Blue carbon dynamics across the Metro Vancouver region: Assessing carbon sequestration under different environmental conditions in tidal marshes

by
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Declaration of Committee

Name:	**Alison Martin**
Degree:	**Master of Science**
Title:	**Blue carbon dynamics across the Metro Vancouver region: Assessing carbon sequestration under different environmental conditions in tidal marshes**
Examining Committee:	**Supervisor and Chair:** **Dr. Marlow Pellatt** Parks Canada **Dr. Ken Ashley** Committee Member BCIT **Dr. Anayansi Cohen-Fernandez** Committee Member BCIT

Abstract

This research project aims to assess the carbon sequestration dynamics of three tidal marshes under different environmental conditions in the Metro Vancouver region. By identifying the site conditions that influence carbon sequestration, areas can be prioritized, and restoration activities can be adapted to increase or maintains the marsh's ability to do so. This project was done in partnership with Parks Canada and will contribute to a larger study of 'blue carbon' across British Columbia. For this project, I collected sediment cores from the eastern portion of Boundary Bay in Delta, BC, Brunswick Point in Ladner, BC, and a constructed salt marsh in Tsawwassen, BC, to assess soil carbon content and carbon stocks. Porewater salinity, vegetation data and depth measurements were collected at these sites as well. Percent carbon content ranged between 3.98 ± 1.48% and 5.78 ± 5.93% between the three marshes and the marsh carbon stock ranged between 93.95 Mg C and 2,994.51 Mg C. Across the three marshes, core carbon stock for the high marsh cores was found to be significantly higher than the core carbon stock for the low marsh cores, suggesting that marsh zonation influences carbon stock. The data analysis and literature review determined that vegetation and porewater salinity had the greatest influence on a marsh's ability to sequester and store carbon. The results indicate that the high marsh with low salinities and a diverse plant community have the highest carbon sequestration potential. As marshes with conditions similar to that of the Boundary Bay marsh as well as polyhaline marshes should be prioritized for restoration. These findings will aid in the development and implementation of restoration projects to increase a marsh's ability to sequester carbon.

Keywords: blue carbon; tidal marsh; carbon stock; British Columbia; coastal management; restoration; marsh restoration

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List of Acronyms

BBE	Boundary Bay East Marsh
BRP	Brunswick Point Marsh
CEC	Commission for Environmental Cooperation
DoR	Depth of Refusal
DBD	Dry Bulk Density
NbS	Nature-based solutions to Climate Change
%IC	Percent Inorganic Carbon
%C	Percent Carbon
%OC	Percent Organic Carbon
SCD	Soil Carbon Density
TSF	Tsawwassen Ferry Terminal Marsh

1. 1.0 Introduction

Tidal marshes are considered to be a natural resource of global significance and have been the focus of conservation for decades. Historically, the high-level biological diversity, especially bird diversity, was the primary reason for marsh protection. More recently these systems have been recognized for their important ecosystem services for both human welfare and sustainable natural resource management (Bobbink et al. 2016). These ecosystem services include providing valuable habitat and supporting numerous species that can benefit the economies of coastal communities, as well as protection against flooding, storm surges and shoreline erosion (Bobbink et al. 2016; Chmura 2013; Siikamaki et al. 2013). In recent years, saltwater tidal marshes have been identified as a global resource as a net sink of carbon dioxide. However, large amounts of carbon that were historically stored have been released due to degradation (Bobbink et al. 2016). As a result, these ecosystems are unable to sequester as much carbon as they would be able to when it is in a pristine state because they emit more greenhouse gasses than they store, transforming them into carbon sources. With this knowledge, it has become more critical for the conservation of these ecosystems and their ability to be carbon sinks in regard to climate change mitigation.

'Blue carbon' refers to the atmospheric carbon that is stored in the vegetation and sediment of coastal and marine ecosystems (Hori et al. 2019). In tidal marshes, marsh vegetation uptakes the atmospheric carbon through respiration and is then stored in the leaves, stems, and roots. As these ecosystems conduct self-maintenance through continuous vertical accretion, the vegetation becomes buried and the carbon within them (Chmura 2013; Drake et al. 2015). As a result, tidal marshes have the ability to store vast amounts of carbon in their soil that remain trapped for very long (centuries to millennia) compared to terrestrial systems (years to decades) (Howard et al. 2014). There has been growing interest in tidal marsh conservation and restoration as a potential nature-based solution (NbS) because it provides human and wildlife with protection from climate change impacts while slowing further warming, supporting biodiversity, and securing ecosystem services (Seddon et al. 2020). Blue carbon ecosystem conservation and restoration are excellent examples of a NbS for their numerous ecosystem services that can mitigate the effects of climate change on a local and global scale. With the growing interest in blue carbon and tidal marshes, there is a need to fill knowledge gaps to better design conservation and restoration activities. There are numerous factors that influence the ecosystem's carbon sequestration ability that must be understood prior to implementing restoration activities.

Despite their valuable ecosystem services, tidal marshes are under high levels of pressure due to anthropogenic stressors. The total global area of tidal marshes has been declining by about 5% per year and more than 50% of the world's marshes have been lost (Grenier et al. 2013). The main anthropogenic stressors responsible for this loss are related to coastal development and land-use change. These ecosystems have proven to be highly valuable agricultural land so many have been drained and converted for agriculture (Siikamaki et al. 2013). As the vegetation is removed and the land is dredged or drained, the sediment becomes exposed to the atmosphere and/or water column, resulting in the stored carbon becoming exposed to the oxygen in the air. As the carbon bonds with the oxygen, it forms carbon dioxide and other greenhouse gasses and is released into the atmosphere or ocean (Howard et al. 2014). As well, coastal squeeze due to diking and sea level change are also major stressors on these ecosystems (Siikamaki et al. 2013). The building of dikes results in the partial or complete separation of the marsh from tidal action, which will dramatically decrease the flow of carbon and nutrients into and out of the system (Drexler et al. 2019). The lack of tidal action and saline water has severe impacts on the marsh's ability to sequester carbon as it alters the plant community composition.

There are multiple drivers, such as vegetation, tidal range, elevation, and sediment supply, that influence the carbon sequestration potential of a tidal marsh (Gailis et al. 2021; Chmura & Hung 2004; Ouyang & Lee 2014; Kelleway et al. 2017). The salinity of the both the seawater and porewater also plays a critical role in carbon sequestration because it influences plant productivity and decomposition, ultimately affecting carbon sequestration rates. Increasing salinity will led to a decrease in plant productivity as it causes a decrease in microbial activity. The decrease in microbial activity leads to slower decomposition rates of dissolved organic carbon (Qu et al. 2018). If carbon inputs remain constant, soil organic carbon can increase under these conditions. As the rate of decomposition decreases, methane production is limited, which reduces the amount of methane that is released into the atmosphere (Gailis et al. 2021).

Marshes are the single largest natural source of methane emission as these ecosystems are responsible for one third of global emissions (Bridgham et al. 2014). Methane is produced in the soil as methanogenic bacteria decompose organic matter in anerobic conditions that are continuously water saturated (Purvaja & Ramesh, 2001). Once the methane is produced, it can become oxidized by aerobic bacteria present in the deep soil layers (Purvaja & Ramesh 2001). The methanogenic bacteria are sensitive to a number of parameters such as water table depth and carbon content. Methane emissions will also vary with salinity and vegetation (Purvaja & Ramesh, 2001). Methanogens have a higher presence in low salinity sites because the presence of sulfate in ocean water reduces methanogenic bacteria as the sulfate reducers out compete and/or inhibit them (Bartlett et al. 1987; Holm et al. 2016). As a result, freshwater marshes are likely to have higher methane fluxes than salt marshes. Tidal marshes with lower porewater salinities have been found to have highly variable methane emissions so if emissions are low enough, these marshes can be considered a net carbon sink (Gailis et al. 2021; Poffenbarger et al. 2011). Understanding the conditions and drivers that influence carbon sequestration at a site-specific level is crucial regarding mitigating climate change through conservation and restoration of these ecosystems.

This project will examine the blue carbon dynamics under different conditions in tidal marshes within the Metro Vancouver region of British Columbia. Within this region, there is about 8,368 ha of estuarine ecosystem and about 7,969 ha of intertidal zone and many have been heavily influenced by anthropogenic activities (Welham & Seely 2019). In 2018, the Metro Vancouver Regional District conducted a survey to develop a carbon storage dataset for the region to help support land use decision-making (Welham & Seely 2019). This dataset identified marsh and estuarine ecosystems within the region as potential carbon storage units, but little is known about the overall condition of the ecosystem and their ability to sequester carbon.

Three tidal marshes within the Metro Vancouver region were identified for this project, each under different environmental conditions, to develop an understanding of the blue carbon dynamics of Metro Vancouver’s marshes. This project will also examine potential restoration strategies to construct, restore and/or conserve tidal marsh ecosystem condition and its ability to sequester carbon. By identifying site specific conditions that influence a marsh’s carbon sequestration ability, sites can be prioritized for restoration based on these conditions and strategies can be developed to best suit a specific site.

This project expanded upon previous research that has focused on carbon sequestration in the Pacific Northwest’s tidal marshes. Gailis et al (2021) quantified the blue carbon storage and accumulation rates in the western portion of Boundary Bay, Delta, BC and identified the need for further research, specifically into porewater, greenhouse gas fluxes and an overall carbon budget for the marsh. The eastern portion of Boundary Bay was selected for this project to expand on this existing research. Chastain (2017) examined carbon stocks and accumulation rates on seven marshes in Clayoquot Sound and Pacific Rim National Park Reserve of Canada, Tofino, BC to address data gaps that were identified by the Commission for Environmental Cooperation (CEC). Crooks (2014) assessed the blue carbon opportunity in the Snohomish Estuary in Washington state to help inform policymakers about greenhouse gas emissions and removals in tidal marshes to better guide management decisions. This project will aim to fill data gaps that have been identified throughout these studies with a focus on the Metro Vancouver region and how restoration can be adapted to converse and maintain tidal marshes in the scope of climate change mitigation.

2. 2.0 Goals & Objectives

The goal of this research project is to develop an understanding of blue carbon dynamics under different environmental conditions in tidal marshes across Metro Vancouver and identifying restoration strategies to maintain or increase carbon sequestration in these ecosystems. By doing so, sites can be identified for restoration and appropriate activities can be tailored for specific site conditions, such as marsh salinity, to increase the ecosystem's ability to sequester carbon. It is expected that the tidal marshes will have different levels of carbon stocks based on site and environmental conditions.

Goal 1: Determine carbon dynamics in tidal marshes with different overall salinities.

Objective 1.1: Determine carbon stock of each marsh by collecting and examining sediment cores and extrapolating to marsh area over a given depth.

Objective 1.2: Identify plant community and composition of each marsh by examining species present and percent cover at coring locations.

Objective 1.3: Determine the relationship between soil properties, vegetation, and carbon stock in each marsh.

Goal 2: Identify restoration strategies to restore the tidal marsh ecosystem's and increase its ability to sequester carbon.

Objective 2.1: Determine how effectively a restored marsh is storing carbon in comparison to a natural marsh.

Objective 2.2: Identify environmental factors (anthropogenic activities, plant community, salinity levels) that may influence the ecosystem condition and carbon dynamics.

Objective 2.3: Develop restoration strategies (site priority, vegetation) that could be implemented to increase the ecosystem's ability to sequester carbon.

3. 3.0 Methods

1. 3.1 Study Sites

1. 3.1.2 Brunswick Point Marsh

The study site is situated on Brunswick Point, Delta, B.C., which is a peninsular point that makes up the lower part of Roberts Bank (**Fig. 1**). The marsh is bounded by Canoe Pass, a minor distributary of the Fraser River on the north and the Strait of Georgia to the west and south (Porter, 1982). The east side is bounded by a man-made dike with agricultural land behind it. The marsh is predominately fresh water influenced along the north side and transitions to brackish on the south side of the peninsula (Porter, 1982). The Fraser River carries large loads of sediment into the delta and deposits it along the banks of the peninsula. Most of the sediment deposition occurs during the annual freshnet (Porter, 1982). The sediment is made up of mostly clay with smaller amounts of sand and silt (Porter, 1982). Brunswick Point has mixed semidiurnal tides with two high and low tide (Porter, 1982).

This marsh is an example of a natural marsh that will demonstrate the influence of salinity and vegetation type on carbon dynamics. The marsh has characteristics of a freshwater marsh on its northern side and a brackish marsh on its southern side. Porewater salinity at this site ranged between 3.55 ppt in the low marsh to 11.34 ppt in the high marsh. The vegetation present at this site was dominated by *Distichlis spicata, Aster subspicatus, Typha angustifolia, Salicornia virgincia, Deschampsia caespitosa, Triglochin maritimum,* and *Potentilla pacifica*.

2. 3.1.2 Boundary Bay East Marsh

The study site is situated in eastern portion of Boundary Bay in Delta, B.C., at the widest part of the marsh (**Fig. 1**). The north edge of the salt marsh is bounded by a large, man-made dike, with multiple farms and a highway behind it. The Serpentine River and the Nicomekl River flow into Boundary Bay approximately 3 km east of the study site. The rivers supply the marsh with small amount of sediment, mainly silt and clay (Porter 1982). The cliffs along the Point Roberts peninsula are the Bay's main source of sediment, which is then transported across the Bay by northward long-shore drift (Swinbanks & Murray 1981). Boundary Bay has mixed semidiurnal tides with two high and low tide (Shepperd 1981).

This marsh is an example of a natural salt marsh that will demonstrate the influence of salinity and vegetation type on carbon dynamics. Porewater salinity at this site ranged between 7.20 ppt in the low marsh to 16.72 ppt in the high marsh. The vegetation in the high marsh was *Distichlis spicata, Atriplex patula,* and *Agrostis stolonifera.* The vegetation in the low marsh was *Salicornia virginica, Suaeda martima* and *Triglochin martima*. The data collected at this marsh will be shared with Hasini Basnayake's Master's thesis study of blue carbon sequestration in Boundary Bay.

3. 3.1.3 Tsawwassen Ferry Terminal Marsh

The study site is situated on the north side at the end of the BC Ferries terminal causeway in Tsawwassen, B.C (**Fig. 1**). This salt marsh was constructed in 1993 to offset the impacts on fish habitat that were associated with the expansion of the north side of the terminal. The marsh is primarily low marsh with some spatial variation due to elevation changes. Vegetation zonation was designed to mimic the plant community and elevation patterns observed at the naturally formed salt marsh at the base of the terminal causeway (Fairhurst 2015). The vegetation, such as *Salicornia virgincia*, were transplanted from the nearby marsh during construction. The marsh is bounded by the causeway to the south and west and the Strait of Georgia to the north and east. The marsh has mixed semidiurnal tides with two high and low tide.

This marsh will provide an understanding of the carbon dynamics of a constructed salt marsh as well as provide insight on potential restoration techniques. Porewater salinity at this site ranged between 23.77 ppt and 27.12 ppt. This marsh was the most saline of the study. The vegetation present at this site was *Agrostis stolonifera* and *Salicornia virgincia*.

2. 3. 2 Fieldwork

At each site, three transects with four stations were chosen for sampling to be representative of the marsh zonation. Marsh zonation was determined through vegetation surveys that were conducted at each station by identifying species present. High and low marsh species were used to differentiated between marsh zones. Sediment cores, vegetation data, and porewater measurements were collected at each station along the transects.

Sediment cores were collected using an AMS sediment corer that was pushed into the ground. PVC piping was placed inside the corer to easily extrude the sediment core. Twelve cores from the Boundary Bay East marsh were collected in October 2020 and twelve cores from the Brunswick Point marsh were collected in November 2020 and January 2021. Twelve cores from the Tsawwassen Ferry Terminal marsh were collected in February 2021. The cores were then brought to the Parks Canada laboratory for analysis.

Vegetation surveys were conducted at each station along the transects. The vegetation data at the Boundary Bay East site was collected in October 2020. The vegetation data at the Brunswick Point site was collected in December 2020 and January 2021. The vegetation data at the Brunswick Point site was collected in December 2020.

Porewater salinities were collected using a syringe and salinity was tested using a handheld YSI conductivity meter. Salinity data was collected at the Boundary Bay East site and the Brunswick Point site in November 2020. Salinity data was collected at the Tsawwassen Ferry Marsh site in February 2021.

Depth measurements were collected by pushing a 4 ft to 6 ft long plasticized metal stakes into the ground until it reached the depth of refusal (DoR) or could no longer be easily pushed. The depths were used to estimate the thickness of the marsh's organic layer for a more robust marsh carbon stock estimation. Depth measurements were collected at all sites in March 2021. The amount of depth measurements collected varied between marshes (**see Appendices A, B & C**). At the Boundary Bay East marsh, 140 depth measurements were collected across 20 transects. At the Brunswick Point marsh, 120 depth measurements were collected across 15 transects. At the Tsawwassen Ferry Terminal marsh, 50 depth measurements were collected across 10 transects.

3. 3. 3 Laboratory Work

For each core (n = 36), a 1 cm^3 volumes of sediment was sampled at 1 cm increments, for the entire length of core. Each sample was weighted to determine wetted weight (g) and then oven-dried for 72 hours at 60°C to determine dry weight (g). Dry bulk density (g/cm^3) was determined by using the mass of the fully dried sample (g) and the original wetted volume (cm^3).

Organic carbon content (%OC) was estimated using loss-on-ignition (%LOI). Each sample was ground using a mortar and pestle, weighted, and placed into a muffle furnace for 4 hours at 550°C to burn off the organic compounds. The samples were then weighed again to calculate %LOI to quantify the fraction of organic carbon lost in each sample:

$$\%LOI_{550} = \left(\frac{DW_i - DW_f}{DW_i}\right) x\ 100$$

Where DW_i is the initial dry weight and DW_f is the dry weight after burning.

A subset of samples (n = 108) was burnt a second time in the muffle furnace for 2 hours at 1000°C to determine inorganic carbon content (%IC) to quantify the fraction of organic carbon more accurately (Heiri et al. 2001):

$$\%LOI_{1000} = \left(\frac{DW_{550} - DW_{1000}}{DW_i}\right) x\ 100$$

Where DW_i is the initial dry weight, DW_{550} is the dry weight after the 500°C burning and DW_{1000} is the dry weight after the 1000°C burning.

%IC was negligible in all the samples analyzed and was assumed to be zero for all percent carbon (%C) calculations (Gailis et al. 2021; Chastain 2017; Howard et al. 2014). Gailis et al. (2021) measured carbon stocks and accumulation rates in western Boundary Bay and the results from the elemental analysis determined the fraction of organic carbon in each sample. The values from this study were used to calculate %C for all sites:

$$\%C = 0.44(\%LOI_{550}) - 1.33$$

Howard et al (2014) recommends using a study location that closely resembles your own locations if it is not possible for an elemental analysis to be completed. As the marshes are in the same region (Distance from Gailis et al. (2021) study site: Boundary Bay marsh: ~ 8.45 km; Tsawwassen Ferry Terminal marsh ~ 8.95 km; Brunswick Point ~ 9.61 km), it is assumed that the values can be used across all sites.

1. 3.3.1 Soil Carbon Density and Carbon Stocks

Carbon stocks were quantified by measuring the soil carbon density (SCD) for each 1 cm sample for the entire length of each core (n = 28, n = 12 for high marsh, n = 16 for low marsh). Soil carbon density (g C/cm^3) is derived from the calculated dry bulk density and percent carbon for each centimeter interval sampled (Gailis et al. 2021; Howard et al. 2014).

$$SCD\left(\frac{g\ C}{cm^3}\right) = \left(\frac{\%C}{100}\right)\ x\ DBD\ \left(\frac{g}{cm^3}\right)$$

The carbon stock for each core (g C cm^3) was calculated by the sum of all 1-cm intervals in each core (Chastain 2017; Howard et al. 2014).

$$Cstock_{core}\ \left(\frac{g\ C}{cm^3}\right) = \sum_{i=0}^{n} \quad SCD_i\ x\ 1\ cm$$

Where *i* is the depth of the top of a 1-cm subsection in cm, *n* is the depth of the core (cm) and *SCD$_i$* is the SCD of each 1 cm interval of soil (g C/cm^3).

Total carbon stocks per core is then converted to the units commonly used in carbon stock assessment (Mg C/ha). The traditional method was used to calculate total carbon stock for the entire marsh area by summing the core carbon stock and then multiplying it by the total area of the marsh (Gailis et al. 2021).

$$Cstock_{Marsh}\,(Mg\ C/ha) = \left(\frac{1}{x}\,x\sum_{i=1}^{x} \quad Cstock_{core}\right)$$

Where *x* is the number of cores in a marsh.

4. 3. 4 Statistical Analysis

All data were tested for normality using the Shapiro-Wilk test for normality. A Kruskal-Wallis test for significance was performed to test for significant differences in percent carbon, soil carbon density and core carbon stock between the high and low marsh zone in all three marshes. The significance level for all tests was set at α = 0.05 and all statistical analyses was performed in R studio.

5.

4. 4.0 Results

1. 4.1 Sediment Properties

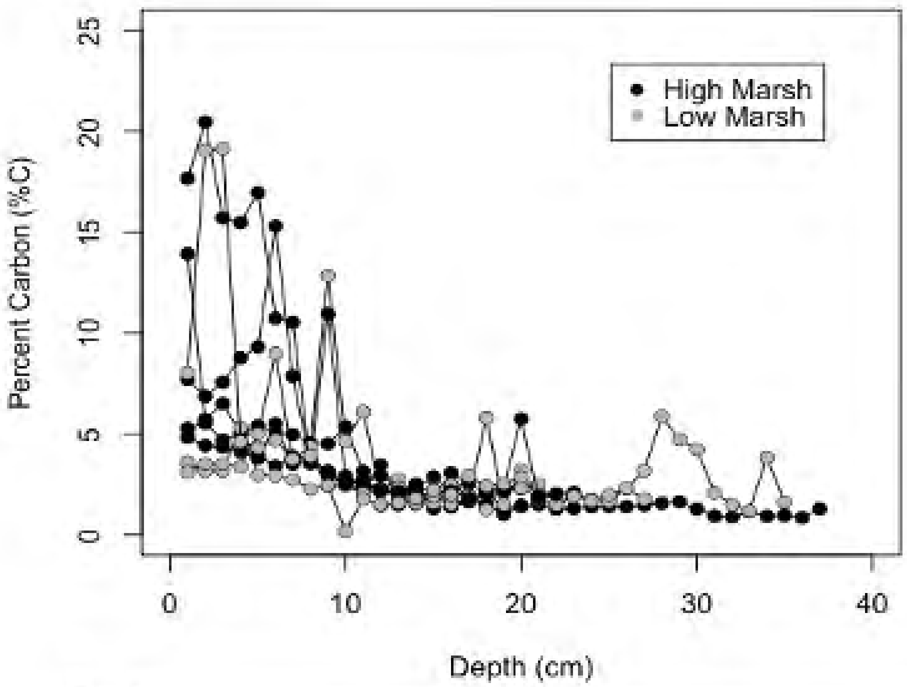
Core depth ranged from 17 to 53 cm and compression occurred in all cores during the field sampling (**Table 1**). Compression varied between the cores but in general, compression occurred highest in the high marsh and lowest in the low marsh cores. The Brunswick Point marsh cores had the highest compression, and the Tsawwassen Ferry Terminal marsh cores had the lowest. The cores consisted of three layers: top organic matter layer, a mixed layer of peat and clay and/or sand and a bottom layer of sand/clay. The top layer had the higher organic material content while the bottom layer had little to no organic material. The estimated average depth profile for the organic matter layer ranged between 34.04 ± 39.35 cm to 89.55 ± 35.92 cm. The Tsawwassen Ferry Terminal marsh had the thinnest depth profile while the Brunswick Point mars had the thickest depth profile. Average dry bulk density ranged from 0.55 ± 0.18 g/cm^3 to 0.88 ± 0.02 g/cm^3. The low marsh at the Boundary Bay East marsh had the highest average dry bulk density (0.88 ± 0.02 g/cm^3), while the low marsh at the Brunswick Point marsh has the lowest average dry bulk density (0.55 ± 0.18 g/cm^3).

Porewater salinities ranged from 3.55 to 27.08 ppt across all sites (**Table 1**). The Tsawwassen Ferry Terminal marsh had the highest salinities ranging between 23.77 ppt and 27.08 ppt. The Brunswick Point marsh had the lowest salinities ranging between 3.55 ppt and 11.34 ppt. At both the Brunswick Point marsh and the Boundary Bay marsh, the high marsh has lower salinities than the low marsh, with the exception of BBE1H2. As the Tsawwassen Ferry Terminal marsh as it is entirely low marsh, there is little variation between cores.

In all cores, %C decreased with depth, with some outliers that can be explained by larger roots and/or woody debris that were present in the sample (**Tables 1, 2 & 3; Figs. 2, 3 & 4**). As the middle and bottom layers of the cores have less organic material, %C decreased while dry bulk density increased. The highest and lowest average %C across all sites can be found at the Boundary Bay East marsh. The highest average is 8.15 ± 6.53% in the high marsh, while the lowest average is 1.83 ± 0.54% in the low marsh. Average soil carbon densities across all marshes are 0.017 ± 0.08 g C/cm^3, ranging from 0.011 ± 0.002 g C/cm^3 in the low marsh of Boundary Bay East to 0.021 ± 0.009 g C/cm^3 in the high marsh of Brunswick Point.

Table 1: Summary of core sediment data (depth of core (cm), porewater salinity (ppt), dry bulk density (DBD), average percent carbon (%C), average soil carbon density (SCD), and core carbon stock (MgC/ha)) collected for cores at the Brunswick Point marsh in Ladner, B.C.

Core ID	Depth of Core (cm)	Porewater Salinity (ppt)	Average DBD (g/cm^3)	Average %C	Average SCD (gC/cm^3)	Core Carbon stock (MgC/ha)
			High Marsh Cores			
BRP1H1	17	7.12	0.58	4.36	0.019	32.2
BRP1M	37	11.34	0.87	2.22	0.017	62.1
BRP2H2	23	2.07	0.30	6.65	0.018	41.8
BRP2H1	20	3.55	0.59	3.06	0.016	32.5
BRP3H1	22	3.58	1.06	4.68	0.037	75.9
Average ± SD	24 ± 8	5.53 ± 3.74	0.68 ± 0.29	4.19 ± 1.69	0.021 ± 0.009	48.9 ± 19.4
			Low Marsh Cores			
BRP2L	28	4.13	0.69	3.45	0.022	77.8
BRP2M	27	3.73	0.60	2.41	0.014	36.9
BRP3M	20	7.01	0.35	4.95	0.014	28.0
Average ± SD	25 ± 4	4.96 ± 1.79	0.55 ± 0.18	3.60 ± 1.28	0.017 ± 0.005	47.6 ± 26.6



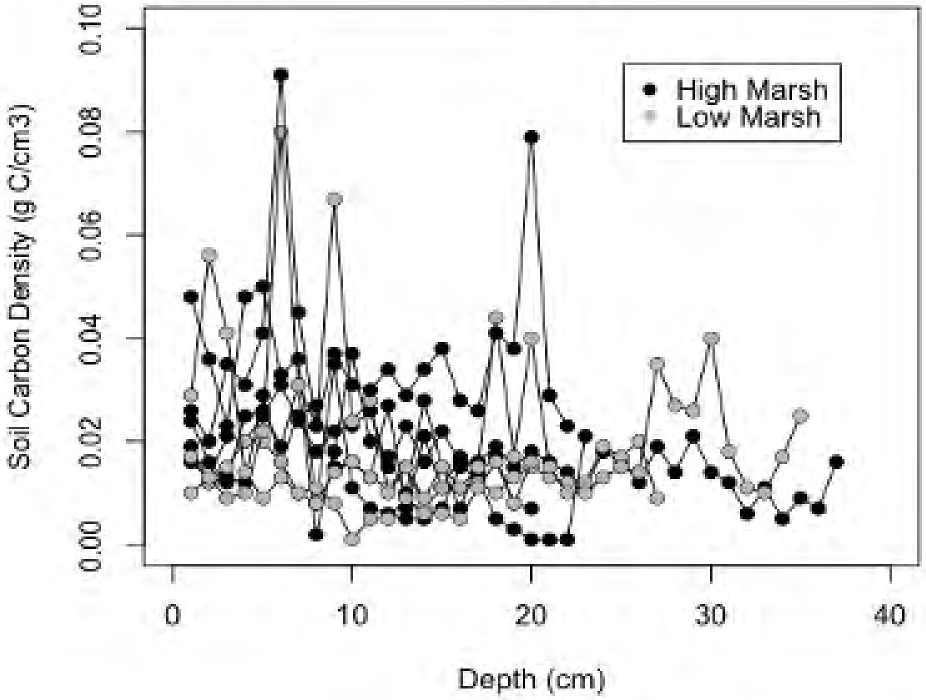
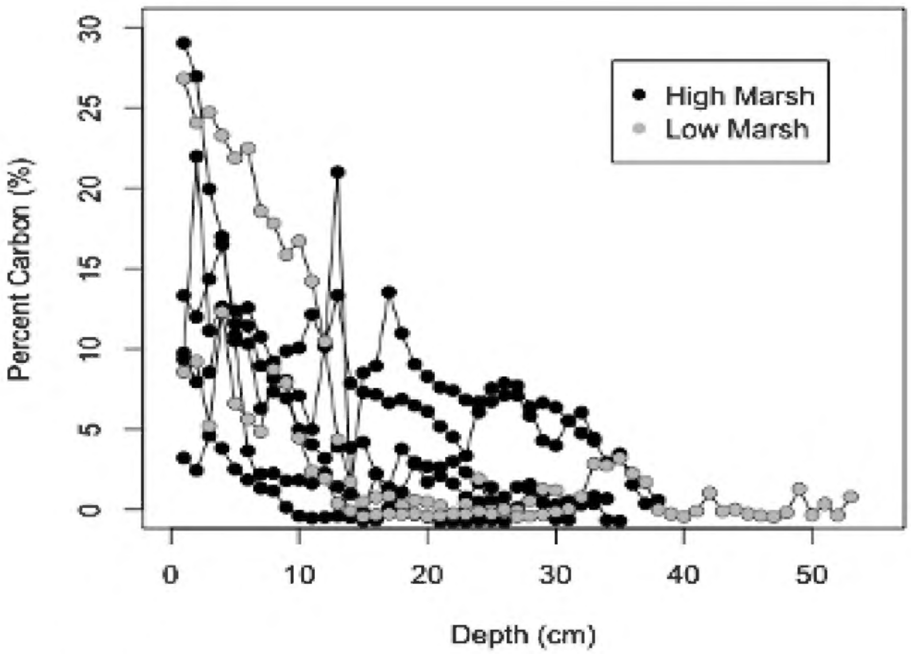


Table 2: Summary of core sediment data (depth of core (cm), porewater salinity (ppt), dry bulk density (DBD), average percent carbon (%C), average soil

carbon density (SCD), and core carbon stock (MgC/ha)) collected for cores at the Boundary Bay East marsh in Delta, B.C.

Core ID	Depth of Core (cm)	Porewater Salinity (ppt)	Average DBD (g/cm^3)	Average %C	Average SCD (gC/cm^3)	Core Carbon stock (MgC/ha)
			High Marsh Cores			
BBE1H2	53	10.74	0.96	4.99	0.013	66.6
BBE2H2	34	7.70	0.40	9.30	0.034	123.3
BBE2H1	43	9.71	0.44	19.08	0.027	101.7
BBE2M	30	7.70	0.80	3.50	0.016	57.7
BBE3H2	26	10.44	1.05	3.87	0.006	10.9
Average ± SD	37 ± 11	9.26 ± 1.47	0.73 ± 0.30	8.15 ± 6.53	0.019 ± 0.011	72.05 ± 43.3
			Low Marsh Cores			
BBE1M	34	16.72	0.90	1.68	0.013	45.7
BBE2L	46	7.20	0.88	1.38	0.009	39.7
BBE3L	30	15.36	0.87	2.43	0.011	27.2
Average ± SD	36 ± 8	13.09 ± 5.15	0.88 ± 0.02	1.83 ± 0.54	0.011 ± 0.002	37.53 ± 9.4



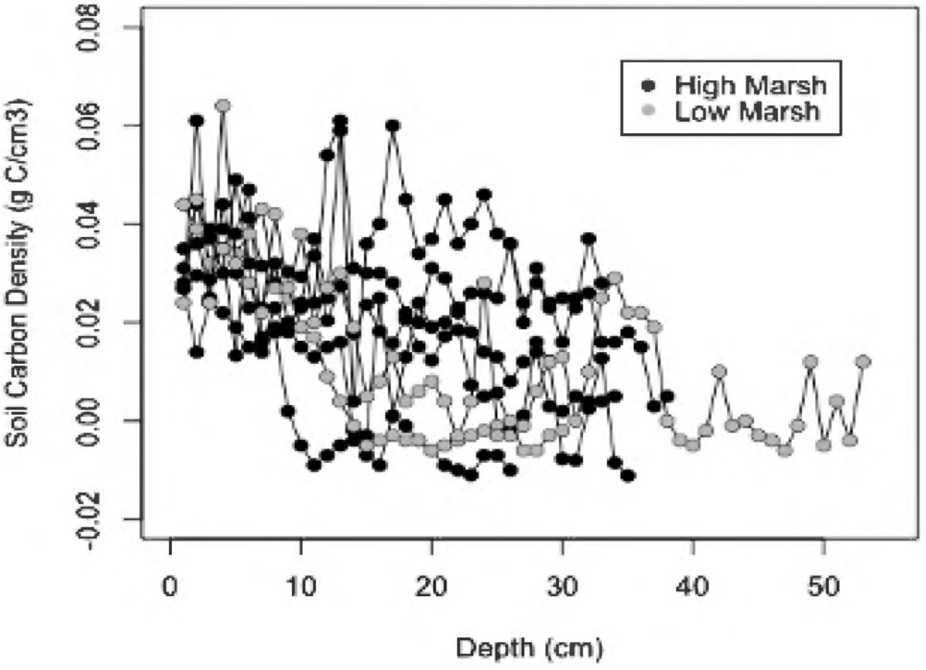
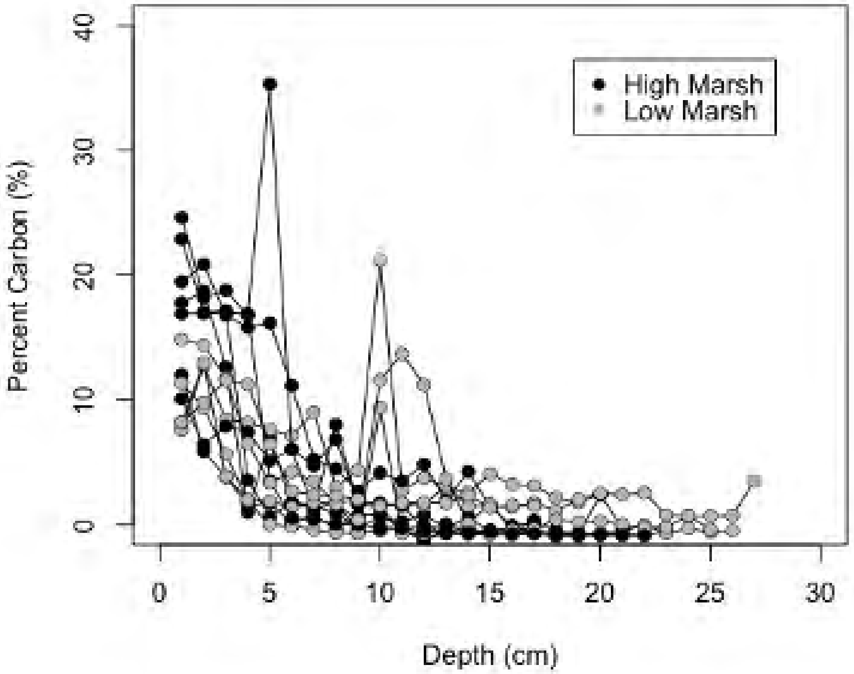


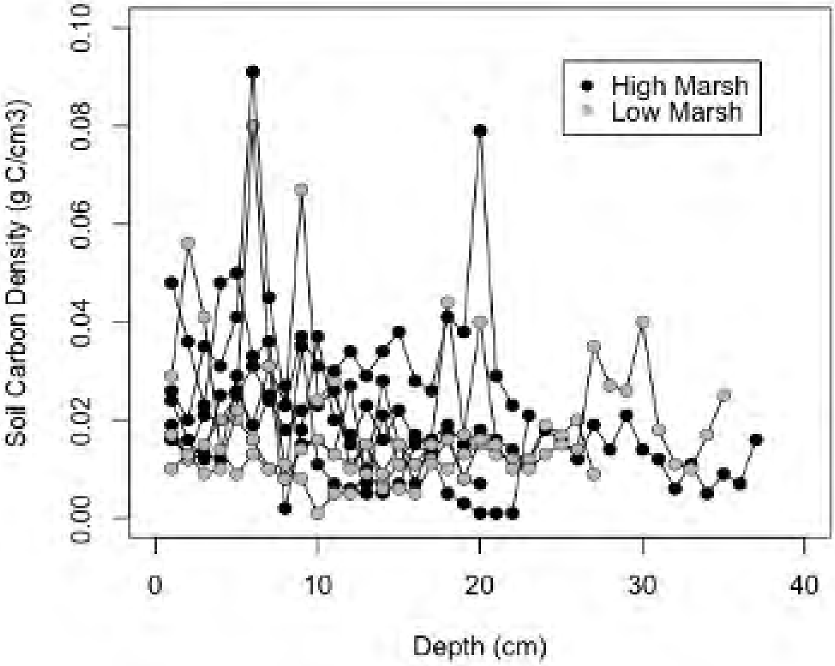
Table 3: Summary of core sediment data (depth of core (cm), porewater salinity (ppt), dry bulk density (DBD), average percent carbon (%C), average soil

carbon density (SCD), and core carbon stock (MgC/ha)) collected for cores at the Tsawwassen Ferry Terminal marsh in Tsawwassen, B.C

Core ID	Depth of Core (cm)	Porewater Salinity (ppt)	Average DBD (g/cm^3)	Average %C	Average SCD (gC/cm^3)	Core Carbon stock (MgC/ha)
			Low Marsh Cores			
TSF1H2	17	27.08	1.252	1.44	0.011	19.2
TSF1H1	23	26.09	1.106	2.63	0.006	13.6
TSF1M	19	25.77	1.112	3.46	0.015	1.50
TSF1L	20	26.09	0.607	5.92	0.033	66.6
TSF2H2	15	25.26	0.889	9.57	0.013	18.9
TSF2H1	25	25.74	1.214	1.01	0.003	6.6
TSF2M	21	26.79	0.883	6.37	0.029	60.4
TSF2L	27	26.63	0.708	2.48	0.016	42.2
TSF3H2	13	23.77	0.737	6.26	0.011	15.9
TSF3H1	25	24.68	0.831	4.11	0.014	35.7
TSF3M	22	25.50	1.079	5.39	0.018	41.7
TSF3L	17	26.54	0.619	4.14	0.018	31.1
Average ± SD	20 ± 4	25.83 ± 0.94	0.82 ± 0.26	4.40 ± 2.44	0.016 ± 0.009	29.5 ± 20.6

2.


● High Marsh
● Low Marsh
Percent Carbon (%)
0
10
20
30
40
0
5
10
15
20
25
30
Depth (cm)


● High Marsh
● Low Marsh
Soil Carbon Density (g C/cm3)
0.00
0.02
0.04
0.06
0.08
0.10
0
10
20
30
40
Depth (cm)

3. 4.2 Vegetation

Marsh zonation was determined by vegetation present (**Tables 4, 5 & 6;** see **Appendix G, H & 1** for more detailed description of the vegetation). Species such as *Salicornia virginia* was identified as a 'low marsh' species and *Agrostis stolonifera* was identified as a 'high marsh' species in more saline conditions (porewater salinity > 7 ppt). *Agrostis stolonifera* and *Typha angustifolia* were identified as 'low marsh' species and *Distichlis spicata* and *Deschampsia caespitosa* were identified as 'high marsh' species in less saline conditions (porewater salinity < 7). *Agrostis stolonifera* was found at all the marshes. The Brunswick Point marsh had the most diverse plant community, which is likely a result of the influence of both the freshwater from the Fraser River and seawater from the Strait of Georgia. The Tsawwassen Ferry Terminal marsh had the least diverse community as the marsh is predominately low marsh. Vegetation did vary throughout the marsh because of elevation differences in the marsh.

Table 4: Species composition and marsh zonation of coring sites at the Brunswick Point marsh in Ladner, B.C.

Core ID	Porewater Salinity (ppt)	Species	Percent Cover (%)	Marsh Zonation
BRP1H2	3.55	*Distichlis spicata*	85	High Marsh
		Aster subspicatus	15	
BRP1H1	7.12	*Distichlis spicata*	90	High Marsh
		Aster subspicatus	5	
		Typha angustifolia	5	
BRP1M	11.34	*Distichlis spicata*	90	High Marsh
		Aster subspicatus	8	
		Typha angustifolia	2	
BRP1L	7.50	*Salicornia virginica*	100	Low Marsh
BRP2H2	2.07	*Deschampsia caespitosa*	80	High Marsh
		Triglochin maritima	10	
		Typha angustifolia	10	
BRP2H1	3.55	*Deschampsia caespitosa*	80	High Marsh
		Triglochin maritima	15	
		Potentilla pacifica	5	
BRP2M	3.73	*Distichlis spicata*	95	Low Marsh
		Typha angustifolia	5	
BRP2L	4.13	*Distichlis spicata*	90	Low Marsh
		Typha angustifolia	5	
		Triglochin maritima	5	
BRP3H2	3.25	*Deschampsia caespitosa*	80	High Marsh
		Triglochin maritima	10	
		Typha angustifolia	10	
BRP3H1	3.58	*Deschampsia caespitosa*	90	High Marsh
		Triglochin maritima	10	
BRP3M	7.01	*Agrostis stolonifera*	80	Low Marsh
		Triglochin maritima	10	
		Typha angustifolia	10	
BRP3L	5.15	*Agrostis stolonifera*	90	Low Marsh
		Triglochin maritima	10	

Table 5: Species composition and marsh zonation of coring sites at the Boundary Bay East marsh in Delta B.C.

Core ID	Porewater Salinity (ppt)	Species	Percent Cover (%)	Marsh Zonation
BBE1H2	10.74	*Distichlis spicata*	100	High Marsh
BBE1H1	6.48	*Atriplex patula*	100	High Marsh
BBE1M	16.72	*Salicornia virginica*	50	Low Marsh
		Triglochin maritima	50	
BBE1L	7.40	*Salicornia virginica*	100	Low Marsh
BBE2H2	7.70	*Agrostis stolonifera*	100	High Marsh
BBE2H1	9.71	*Agrostis stolonifera*	75	High Marsh
		Triglochin maritima	25	
BBE2M	7.70	*Agrostis stolonifera*	50	High Marsh
		Suaeda maritima	50	
BBE2L	7.20	*Salicornia virginica*	100	Low Marsh
BBE3H2	10.44	*Agrostis stolonifera*	100	High Marsh
BBE3H1	9.31	*Agrostis stolonifera*	30	High Marsh
		Distichlis spicata	70	
BBE3M	12.10	*Suaeda maritima*	100	Low Marsh
BBE3L	15.36	*Salicornia virginica*	100	Low Marsh

Table 6: Species composition and marsh zonation of coring sites at the Tsawwassen Ferry marsh in Tsawwassen, B.C.

Core ID	Porewater Salinity (ppt)	Species	Percent Cover (%)	Marsh Zonation
TSF1H2	27.08	*Agrostis stolonifera*	100	Low Marsh
TSF1H1	27.12	*Agrostis stolonifera*	50	Low Marsh
		Salicornia virginica	50	
TSF1M	25.77	*Agrostis stolonifera*	100	Low Marsh
TSF1L	26.09	*Agrostis stolonifera*	100	Low Marsh
TSF2H2	25.26	*Salicornia virginica*	100	Low Marsh
TSF2H1	25.74	*Salicornia virginica*	100	Low Marsh
TSF2M		*Salicornia virginica*	50	Low Marsh
		Agrostis stolonifera	50	
TSF2L	26.63	*Agrostis stolonifera*	100	Low Marsh
TSF3H2	23.77	*Agrostis stolonifera*	100	Low Marsh
TSF3H1	24.68	*Salicornia virginica*	100	Low Marsh
TSF3M	25.50	*Agrostis stolonifera*	100	Low Marsh
TSF3L	26.54	*Agrostis stolonifera*	100	Low Marsh

4. 4.3 Marsh Area, Carbon Stock and Comparisons

Marsh area ranged from 3.19 ha at the Tsawwassen Ferry Terminal marsh to 61.87 ha at the Brunswick Point marsh (**Table 7**) and the average depth profile ranged from 34.04 ± 39.25 cm and 89.55 ± 35.92 cm. Using the traditional method, the estimated total carbon stocks ranged from 93.95 Mg C at the Tsawwassen Ferry Terminal marsh to 2,994.51 Mg C at the Brunswick Point marsh (**Table 7**).

Table 7: Comparison of carbon stock estimates (Mg C) from a specified bounded area of each marsh.

Marsh ID	Average DoR (cm)	Bounded Marsh Area (ha^2)	Average Core Carbon Stock (Mg C/ha)	Area (m^2)	Marsh Carbon Stock (Mg C)
BRP	89.55 ± 35.92	61.87	48.4 ± 20.4	618,700	2,994.51
BBE	50.61 ± 25.15	39.29	53.9 ± 37.6	392,900	2,359.27
TSF	34.04 ± 39.35	3.19	29.5 ± 20.6	319	93.95

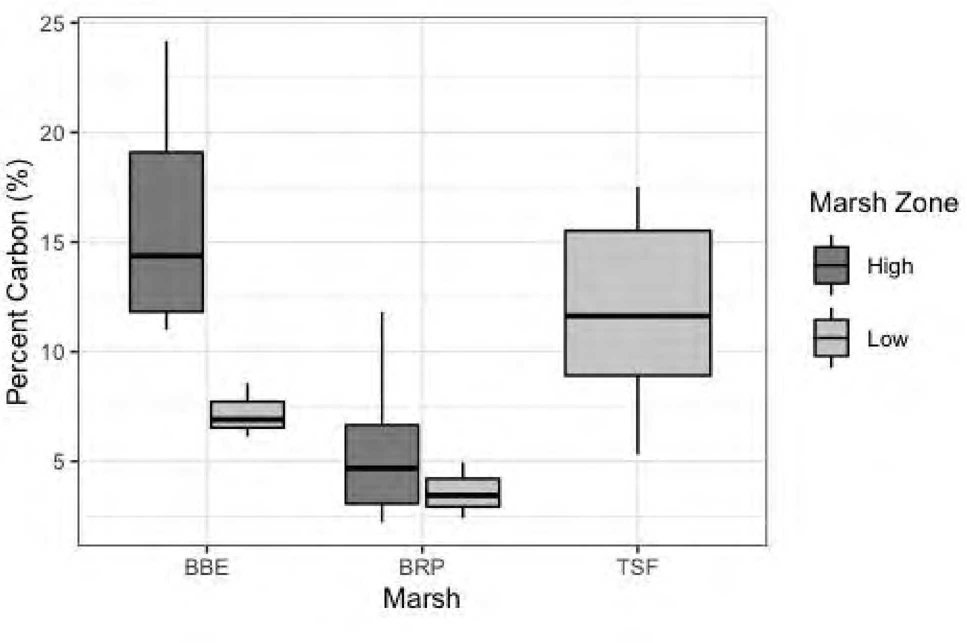
1.

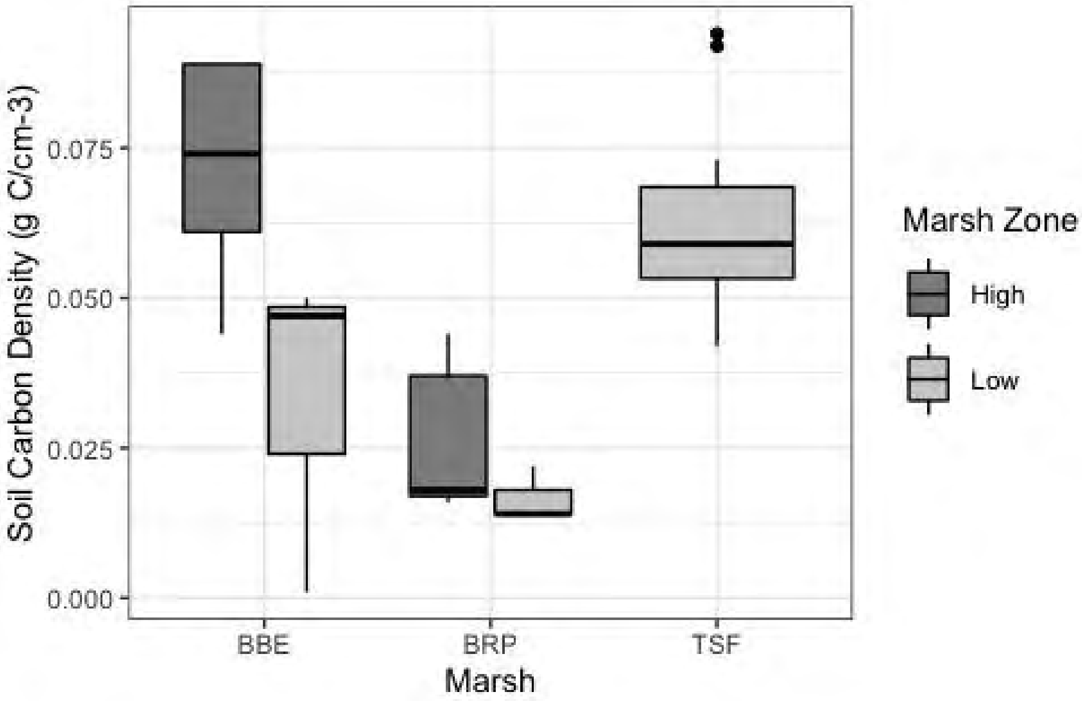
2. 4.3.1 Comparison of Soil Properties

Across the three marshes, the %C and SCD for the high marsh cores was found to be significantly higher compared to the %C and SCD for the low marsh cores ($p < 0.05$) (**Table 8; Figs. 2 & 3**). This is also found the high marsh cores and low marsh cores were compared at the Boundary Bay East marsh and the Brunswick Point marsh, suggesting that marsh zonation has an effect on the soil properties of the marsh. This could be contributed to difference between plant community and porewater salinity between the high and low marsh zone.

Table 8: Comparison of average salinity (ppt), average dry bulk density (g/cm3), average percent carbon (%), average soil carbon density (g C/cm^3), average core carbon stock (Mg C/ha) and estimated marsh carbon stock (Mg C) of each marsh.

Marsh ID	Average Salinity (ppt)	Average DBD (g/cm^3)	Average %C	Average SCD (g C/cm^3)	Average Core Carbon Stock (Mg C/ha)
High Marsh Cores					
BRP	5.32 ± 3.74	0.68 ± 0.29	4.19 ± 1.69	0.021 ± 0.009	48.9 ± 19.37
BBE	9.26 ± 1.47	0.73 ± 0.30	8.15 ± 6.53	0.019 ± 0.011	72.02 ± 43.25
Low Marsh Cores					
BRP	4.96 ± 1.79	0.55 ± 0.18	3.60 ± 1.28	0.017 ± 0.005	47.67 ± 26.56
BBE	13.09 ± 5.15	0.88 ± 0.02	1.83 ± 0.54	0.011 ± 0.002	37.53 ± 9.44
TSF	25.83 ± 0.94	0.82 ± 0.26	4.40 ± 2.44	0.016 ± 0.009	29.5 ± 20.6
All Cores					
BRP	5.32 ± 3.00	0.63 ± 0.20	3.97 ± 1.31	0.019 ± 0.01	48.40 ± 16.67
BBE	10.70 ± 3.57	0.79 ± 0.30	5.78 ± 3.28	0.016 ± 0.005	59.10 ± 18.50
TSF	25.83 ± 0.94	0.82 ± 0.26	4.40 ± 2.44	0.016 ± 0.009	29.5 ± 20.60




Soil Carbon Density (g C/cm-3)
0.075
0.050
0.025
0.000
BBE
BRP
TSF
Marsh
Marsh Zone
High
Low

4.3.2 Comparison of Carbon Stocks

Across the three marshes, the average core carbon stocks for the high marsh cores were found to be significantly higher compared to the average core carbon stock for the low marsh cores ($p<0.05$) (**Table 8; Fig. 4**). As well, the average core carbon stocks for the high marsh cores at the Boundary Bay East marsh (72.04 ± 43.25 Mg C/ha) and the Brunswick Point marsh (48.9 ± 19.37 Mg C/ha) was found to be significantly higher compared to the average core carbon stock for the low marsh (37.53 ± 9.44 Mg C/ha and 47.57 ± 25.56 Mg C/ha, respectively) ($p < 0.05$). These results suggest that marsh zonation has an effect on carbon stock, which is likely contributed to plant community, porewater salinity and the depth profile.

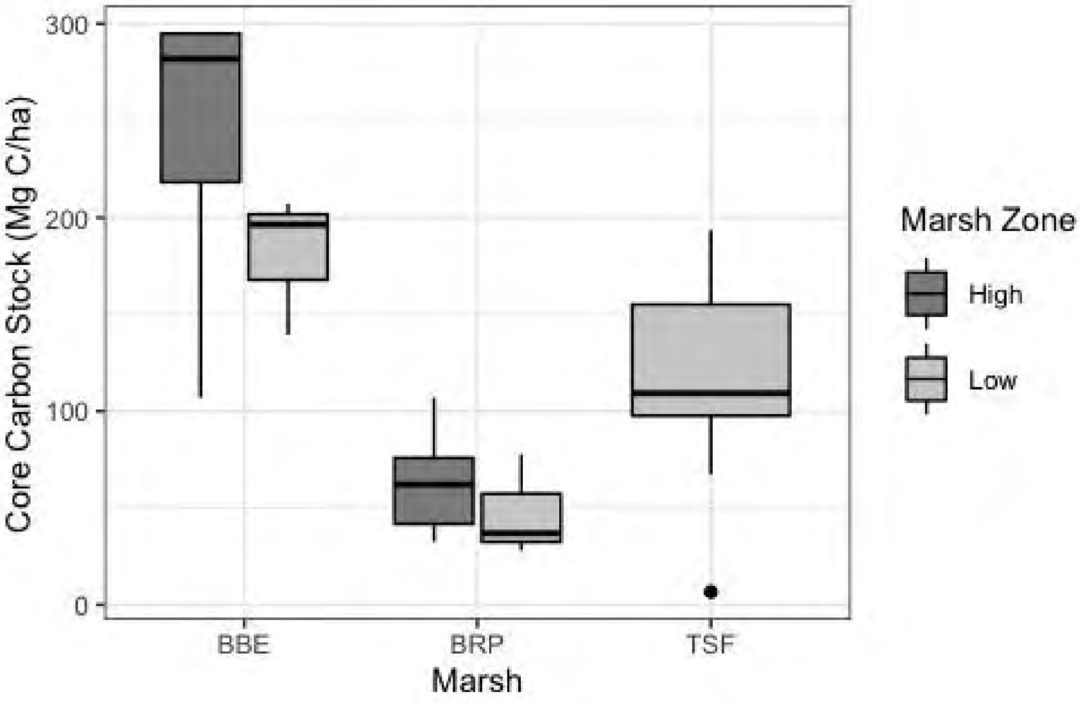


Figure SEQ Figure * ARABIC 7: Core carbon stock (Mg C/ha) comparing high marsh cores (n = 10) to low marsh cores (n = 18) across all marshes. The middle line is the median and the top and bottom of the box are quantiles (Q1 and Q3), and the error bar is the largest and smallest (Chi-squared value = 0.1472, p-value = 0.7012, p < 0.05)

5. 5.0 Discussion

1. 5.1 Sediment Properties & Vegetation

In all the marshes, the average %C is higher in the high marsh than the average %C in the low marsh, with the exception of the Tsawwassen Ferry Terminal marsh. The Tsawwassen Ferry Terminal marsh is considered to be predominately low marsh with higher porewater salinities (23.77 – 27.08 ppt) compared to the other marshes, which limits plant productivity and influences sediment organic carbon content. Setia et al. (2013) suggests that the relative impact of salinity on soil organic carbon content due to reduced plant inputs is greater than the impact of decreased decomposition rates. In saline soils, soil organic carbon content is influenced by plant inputs and rates of decomposition, which is influenced by the sulphate present in the seawater (Setia et al. 2013). The presence of sulphate in the soil allows for sulphate-reducing bacteria to outcompete the methanogen bacteria for energy sources, ultimately inhibiting methane production (Poffenbarger et al. 2011). As salinity increases, decomposition rates will decrease because of this. If carbon input from vegetation and salinity remains unchanged, soil organic carbon content will increase. Salinity affects plant productivity because the accumulation of salts in the root zone has adverse effects on plant growth due to a decrease in availability of water to plants because of a lower osmotic potential of the soil solution (Setia et al. 2013).

Osmotic potential is an alternative approach to measure the effect of salt in soils and takes into account the water content and concentration of salts in the soil solution. As the osmotic potential decreases, the energy that is required by the plants or soil organism to withdraw water increases (Setia et al. 2013). As well, salinity affects microorganisms mainly by decreased osmotic potential because it reduces their activity and alters the microbial community composition (Setia et al. 2013). As the Brunswick Point marsh has an overall lower salinity level due to the freshwater input from the Fraser River, organic matter in the sediment decomposes faster than it does at the Boundary Bay East marsh and Tsawwassen Ferry Terminal marsh. The freshwater input increases soil organic carbon content at Brunswick Point marsh due to decreased salinity, but decomposition rate is increased.

Porewater salinity also has an influence plant species distribution and diversity. Watson and Byrne (2009) investigated the relationship between plant distributions and environmental conditions in the San Francisco Estuary and identified that salinity is the primary control on plant distribution. In more saline marshes, the dominant plant species present was *Salicornia virginica* and was often found to be growing in sediments with high porewater salinity. This trend is seen at the Tsawwassen Ferry Terminal marsh as the dominant vegetation was *Salicornia virginicia* and *Agrostis stolonifera* and the average porewater salinity (20 ± 4 ppt) was the highest among the three marshes. In the Watson and Byrne (2009) study, other species such as *Typha* sp. and *Distichlis spicata* were found adjacent to tidal channels and/or to the shoreline, where porewater salinities are lower. The study also indicates that species diversity was lower in salt marshes and higher in brackish marshes (Watson and Byrne 2009). This trend is seen at the three study marshes as well. The Brunswick Point marsh had the lowest average porewater salinity (5 ± 3 ppt) and had eight species present, while the Tsawwassen Ferry Terminal marsh had highest average porewater salinity (20 ± 4 ppt) but only had two species present across the entire marsh. Watson and Byrne (2009) concluded that salinity played a critical role in tidal marsh plant distribution.

Vegetation growth also plays an important role in marsh elevation and development of the marsh zonation. Changes in marsh elevation is a result of the deposition of mineral sediments and allochthonous organic matter that are deposited during flooding events and the incorporation of in situ produced biomass (Van de Broek et al. 2016). The accumulation of organic matter and mineral sediment results in an elevation gradient across the marsh, which influences tidal inundation duration and salinity levels. The most seaward parts of the marsh will have higher salinities than that of the landward parts, resulting in a longitudinal gradient across the marsh (Van de Broek et al. 2016). The salinity gradient creates a vegetation gradient because plant productivity and macrophyte biomass will be higher in the less saline parts of the marsh. As a result, vegetation plays an important role in marsh elevation by accreting peat and trapping mineral sediment (Kirwan & Mudd 2012). The seaward parts of the marsh will have a lower elevation because the high saline conditions limits plant productivity, which limits the development of a deep organic matter layer through peat accretion. However, the low elevation parts of the marsh will receive more mineral sediment and over time, the sedimentation ate will decrease until the marsh platform elevation is in equilibrium with the mean high-water level (Van de Broek et al. 2016). Once equilibrium is reached, the plant productivity will increase because of the decrease tidal inundation duration and therefore, salinity. The feedback between tidal flooding, plant growth and sediment deposition allow tidal marshes to adapt vertically to a wide range of relative sea-level rates (Blum et al. 2021). Carbon sequestration potential of a marsh is dependent on the relationship between plant growth, sediment deposition and tidal flooding because they dictate the marsh's ability to adapt to sea-level rise.

Vegetation and salinity are important indicators for shifts that may be occurring in the marsh, especially in regard to climate change and sea-level rise. As the sea level continues to rise, marsh zonation will shift and will likely have an impact on soil organic carbon. If the marsh is limited by topography and human-built structures, the high marsh will be converted to low marsh because the marsh is not able to maintain elevation relative to see level rise (Blum et al. 2021). Watson and Byrne (2009) indicate that marsh plant species distribution will depend on whether the sediment accretion can match the rate of sea level rise. The current trend of 'salinization' will continue to increase if sediment accretion does not keep pace with sea level rise (Watson and Byrne 2009). 'Salinization' occurs when salts begin to accumulate in the soil which will, likely result in a shift in vegetation and therefore, soil organic carbon content. As a result of salinization, marsh species diversity will decline in the low salinity areas of the marsh and low marsh species will likely become more common in the high marsh (Watson and Byrne 2009). In addition, the increase in porewater salinity in the high marsh will influence soil organic carbon content due to reduced plant input as vegetation growth becomes limited (Setia et al. 2013). Decomposition will also increase, resulting in an increase of net CO_2 emitted from these systems because of the lower CO_2 uptake by plants (Setia et al. 2013). These findings suggest that as freshwater and brackish marshes, like the Brunswick Point marsh, transition into saltwater marshes as a result of sea-level rise, this will cause a shift in salinity and vegetation. With this shift, there will be an increase of CO_2 emissions. As of CO_2 emissions increase, a positive feedback loop will be created that will amplify the effects of climate change.

Poffenbarger et al. (2011) classified marshes based on the porewater salinity to develop an understanding of the relationship between methane emissions and porewater salinity. Using this classification, the marshes in this study can be grouped and assumptions can be made on their methane emissions. The Boundary Bay East and Brunswick Point marshes can be classified as mesohaline marshes (salinity 8 – 15 ppt) and the Tsawwassen Ferry Terminal marsh is classified as a polyhaline marsh (salinity > 18 ppt). Polyhaline systems had the lowest mean emissions while the mesohaline systems were generally lower than freshwater systems (salinity < 0.5 ppt) and oligohaline systems (salinity 0.5 – 5 ppt) (Poffenbarger et al. 2011). There was more variability in methane emissions within the mesohaline class so methane emissions would need to be determined on a site-by-site basis. For example, the Brunswick Point marsh and the Boundary Bay East marsh can both be classified as mesohaline marsh, but the site-specific conditions likely influence methane emission differently. The Boundary Bay East marsh has the highest %C (5.78 ± 5.93%) and the average salinity is 10.70 ± 3.57 ppt. In contrast, the Brunswick Point marsh has a lowest average salinity (5.32 ± 3.00 ppt) and the lowest average %C (3.98 ± 1.48%) out of the three marshes. The low salinity level increased plant productivity as well as soil organic carbon content but it can be assumed that methane emissions are likely the highest out of the three marshes.

2. 5.2 Carbon Stock

Across all marshes, the average core carbon stock of the high marsh cores was found to be significantly higher than the average core carbon stock for the low marsh cores ($P < 0.05$). This trend was also seen between the high marsh cores and low marsh cores at the Boundary Bay East marsh and the Brunswick Point marsh. This was expected as the high marsh tends to have higher carbon storage because it has deeper rooting plants that has increased production of below ground biomass and the plant canopy is more mature that enables easier storage of organic matter brought in from the tide (Gailis et al. 2021). The interaction between the root systems and plant allocation in the above ground and below ground play a vital role in the distribution and storage of soil organic carbon (Wang et al. 2017). Moreover, many studies have concluded that the top layers of marsh soil content have the highest amount of carbon that declines with depth (Gailis et al. 2021). The cores from the three marshes in this project demonstrated this pattern as %C and SCD in the core declines with depth (**Figs. 2, 3 & 4**).

Vegetation with higher below ground allocation and relatively deep roots tend to create a deeper carbon profile in the soil (Wang et al. 2017). This trend is also seen between the three marshes. The shallow depth profile is one of the main drivers for the Tsawwassen Ferry Terminal marsh having the lowest marsh carbon stock out of the three marshes. The Brunswick Point marsh has the deepest depth profile (89.55 ± 35.92 cm), and it has the lowest average %C but a similar total marsh carbon stock (2,994.51 Mg C) to the Boundary Bay East marsh (2,359.27 Mg C). The conditions at Boundary Bay East marsh allows for higher carbon input through vegetation in the high marsh and reduced decomposition in the soil profile because of the soil salinity, therefore the highest capacity for carbon sequestration. As well, it is likely that the Boundary Bay East marsh has a higher soil organic carbon accumulation rate, which is a result of high carbon input and low carbon output (Wang et al. 2017). It can also be assumed that the Tsawwassen Ferry Terminal marsh has the lowest capacity for carbon sequestration, but the results may be skewed due the difference in size and age between the marshes.

3. 5.3 Comparison Between Natural and Constructed Marshes

It is important to identify the differences between a constructed and restored marsh. Restored marshes refers to the rehabilitation of degraded marshes or re-establishing of a marsh that destroyed. Marsh restoration techniques can include restoration of previously restricted tidal regimes and invasive species removal (Rezek et al. 2017). In comparison, constructed marshes are brand new ecosystems that are created to offset habitat losses associated with coastal development (Rezek et al. 2017). As well, constructed marshes do not have remnants of the ecosystem that is being created, which a restored marsh would have. The Tsawwassen Ferry Terminal marsh is an example of a constructed marsh because it was built to offset the impact on fish habitat that was associated with the expansion of the ferry terminal. Creating and restoring ecosystems to offset the impacts of urbanization and industrialization is a key aspect to ‘habitat banking’. This offsetting approach strives to achieve ‘no not losses’ in biodiversity through the creation of ecosystems while allowing for economic development goals to be reached (Santos et al. 2015). Many of these projects focus more on the offsetting the impacts on species and habitat rather than focusing on creating functioning ecosystems (Santos et al. 2015). The functions of a marsh ecosystems are just as important as offsetting impacts because of the carbon sequestration ability of marsh. By focusing on both offsetting the impacts of the project and creating a functioning marsh ecosystem, the impacts associated with human and economic development can be mitigated while creating a functioning carbon sink to mitigate the effects of climate change.

The differences in %C and carbon stock between the constructed marsh and natural marshes can be contributed to age, size, porewater salinity and vegetation. The initial carbon content of this marsh, which was collected a year after it was construction, is similar to the carbon content calculated for this project (ranged between 1% to 60%). Drexler et al. (2019) identified that restored marshes can quickly begin to accumulate carbon initially, even when the vegetation is sparse, but this does not seem to be occurring. The depth profile, a reasonable proxy for estimating the maximum depth of organic accumulation, is very shallow (34.04 ± 39.35 cm) (Chastain 2017; Howard et al. 2014). This suggests that plant colonization and marsh zonation may be influencing the carbon accumulation rate in this marsh. Drexler et al. (2020) investigated the differences in vertical accretion and carbon accumulation rates between a restored marsh and a relatively undisturbed marsh near Olympia, Washington State. The study identified that the main difference between vertical accretion and carbon accumulation rates was due to a lack of plant community on the recently restored marsh. The lack of plant colonization meant that the carbon the marsh was storing could easily be lost through erosion (Drexler et al. 2019).

Plant colonization may be influenced by low initial elevation due to improper grading or land surface subsidence, poor drainage and post-restoration issues such as compaction and anoxia (Drexler et al. 2019). However, the Tsawwassen Ferry Terminal marsh has an established plant community as the vegetation was transplanted from a nearby marsh during construction, so it is unlikely that erosion has a large impact on carbon storage. Halophytic species, such as *Salicornia virginicia*, can colonize quickly when transplanted and species richness may parallel reference areas within the first 7 years (Sullivan et al. 2017; Bakker et al. 2002). While the plant community does parallel the Boundary Bay East marsh, other characteristics, such as soil organic content, it can take multiple decades to reach the same point as a natural marsh (Drexler et al. 2019; Davis et al. 2015). As well, the Tsawwassen Ferry Terminal marsh does not have any zonation and is considered to be completely low marsh, limiting plant growth. The marsh is dominated by *Salicornia virginicia,* a species that have shallow root systems, therefore, limiting the depth profile and carbon storage.

The Tsawwassen Ferry Terminal marsh and the Boundary Bay East marsh a similar same average SCD (0.016 ± 0.009 g C/cm^3 and 0.016 ± 0.005 g C/cm^3, respectively) and a similar average for %C (4.40 ± 2.44% and 5.78 ± 5.93%, respectively) (**Table 8**). Restored marshes can have similar carbon accumulation rates, even if their marsh formation processes different (Drexler et al. 2019). As previously mentioned, constructed marshes can rapidly become indistinguishable from natural marshes, but this may not occur at the Tsawwassen Ferry Terminal marsh. A key aspect of marsh construction is accommodating space in the tidal frame for the marsh to migrate and grow so that the elevation is not uniform across the entire marsh. The elevation of the marsh must eventually rise enough to provide the necessary conditions for plant growth, especially those with deep roots that can develop a deep depth profile (Drexler et al. 2019). If not, the marsh may continue to accumulate carbon but may not be considered a typical "blue carbon" system as the accumulate will mainly be composed of inorganic sediment (Drexler et al. 2019). The Tsawwassen Ferry Terminal marsh may be susceptible to this because it is bounded by a roadway on its west and south sides and berms along the north and east sides. Without the ability to develop different elevations and zones, the marsh will likely remain uniform and remain predominately low marsh. The development of the high marsh zone is critical for carbon sequestration, which is evident at both the Brunswick Point marsh and the Boundary Bay East marsh as the high marsh zone had significantly higher carbon stocks than the low marsh. The lack of a high marsh zone will likely have a significant negative effect on the marsh's ability to sequester and store carbon.

4. 5.4 Tidal Marsh Restoration & Conservation

There has been a growing interest in blue carbon research and projects as wetland management has been linked to climate change mitigation response. Restoration of coastal ecosystems provides benefits that support both human and coastal ecosystems but also reduces and potentially reserves greenhouse gas emissions from converted wetland (Crooks et al. 2014). As a result, marsh restoration has been identified as a nature-based solution (NbS) to climate change. NbS are emerging as an approach to climate change that help protect us from climate change impacts while slowing further warming, supporting biodiversity, and securing ecosystem services" (Seddon et al. 2020). In addition, the carbon market institutions have begun to recognize wetland restoration and conservation activities as potential carbon projects to offset emissions. While these initiatives are promoting coastal ecosystem restoration activities, more research is necessary to fill knowledge gaps regarding methane emissions.

In many marshes, methane and nitrous oxide can be produced and released into the atmosphere, which may offset the carbon that is being sequestered. These ecosystems can become carbon sources if emissions are higher than carbon uptake. Poffenbarger et al. (2011) identifies that mesohaline systems, like the Boundary Bay East marsh and the Brunswick Point marshes, have the potential to be used in carbon crediting programs but methane emissions must be accounted for. A portion of the carbon sequestration benefit from these types of marsh should be subtracted to account for methane emission, unless it can determine the site has low methane emissions (Poffenbarger et al. 2011).

Crooks et al. (2014) and Poffenbarger et al. (2011) identified the need to fill the significant data gap regarding greenhouse gas emissions. As a result of this knowledge gap, it is important that restoration is conducted properly. This can be achieved by tailoring restoration activities for the site-specific conditions and by understanding the factors that influence a restoration's ability to provide the ecosystem services (Chen 2017). Restoration can be limited by the severity of degradation and the effort involved in re-establishing historical conditions and when these two factors cross, it becomes difficult to restore the marsh (Chen 2017). With this in mind, it is important to identify and address these constraints.

It is also important to consider the integral part that tidal marshes have in the global carbon cycle because of their strong carbon sequestration capacity (Lu et al. 2019). Most efforts have focused on the organic carbon stocks and little attention is given to inorganic carbon despite the important role carbonate dissolution plays on greenhouse gas emissions (Lu et al. 2019). Dissolved inorganic carbon that is released into the tidal water plays an important role in regulating coastal water acid-base properties and buffering capacity (Wang et al. 2016). For these reasons, inorganic carbon storage should be considered in blue carbon research (Lu et al. 2019). As well, organic carbon and inorganic carbon processes could influence one another's effect on carbon stock and carbon dioxide production (Howard et al. 2018). By understanding the inorganic carbon dynamics, restoration can be developed to further increase carbon sequestration potential.

Tidal marshes can play an important role in buffering the effects of climate change by storing carbon, regulating coastal water pH, and protecting against sea-level rise, but it is critical to protect the plant community and increase biomass (Callaway et al. 2012; Wang et al. 2017). A shift in the plant community will also further amplify the effects of climate change. As previously mentioned, if greenhouse gas emissions are being emitted faster than the amount of carbon being sequestered, a positive feedback loop will be created. This will further perpetuate the effects of climate change and should be considered in marsh restoration.

It is also critical to consider the threat from sea-level rise due to climate change as tidal marshes are particularly vulnerable to it. "Coastal squeeze" refers to a marsh's inability to migrate and expand inland as it has been restricted by hardened shorelines, resulting in the seaward edge of the marsh 'retreating' (Chmura 2013). As well, the inability to adapt to rising sea-levels as a result of climate change further puts pressure on these ecosystems. In many cases, the rate of sea-level rise is occurring at a rate faster than or equal to the rate that the marsh is building soil elevation (Kirwan & Megonigal 2013). When marsh elevations are low and rates of relative sea-level rise is high, the increase in duration of tidal inundation limits plant productivity, reducing soil organic content and accelerating erosion (Kirwan & Megonigal 2013).

This shift decreases the marsh's carbon sequestration ability because of the reduced vegetation that is necessary for carbon uptake. Based on regional assessments, a 20-45% loss of salt marshes is expected during the current century (Kirwan & Megonigal 2013). The Boundary Bay East marsh and Brunswick Point marsh are both bounded by dikes that were built to create agricultural land. As both marshes have limited landward migration, their ability to adapt and expand to rising sea-levels will be restricted. The low and uniform elevation and bounded edges at the Tsawwassen Ferry Terminal marsh puts it at risk as well. If the marshes do not have the ability to adapt to climate change and sea-level rise, they will eventually disappear and become unvegetated intertidal mudflat or shallow subtidal open-water systems.

It is difficult to determine how these ecosystems will respond to sea-level rise, though, because the climate, water quality and sediment delivery rates continue to change with human activity (Kirwan & Megonigal 2013). It is important to identify the key aspects of the system that allow it to function and focus restoration activities on those aspects. Mineral and organic sedimentation are key to tidal marsh building because it builds the mudflats to the elevations that emergent tidal marsh vegetation can colonize (Crooks et al. 2016). Appropriate plant colonization is crucial for developing the highly valued ecosystem services and contribute to accumulation of tidal marsh soil (Drexler et al. 2020). If the vegetation is completed properly, the restored marsh can quickly begin to accumulate sediment and store carbon. Even if initial plant colonization is sparse, sediment and carbon will begin to accumulate but the site may be more vulnerable to erosion (Crooks et al. 2016).

As well, different species in the low and high marsh means different levels of accretion as the plant species can cause different rates of accretion to occur throughout the marsh (Weis 2016). This results in marsh zonation and differences in accretion and plant growth, therefore, influencing carbon sequestration throughout the marsh. Across all three study marshes, average %C was highest in the high marsh zone because plant productivity was higher, resulting in higher soil carbon density. As the high marsh zone tends to store the highest amounts of carbon, restoration activities should be focus on maintaining the current conditions of these zones. With this in mind, it is crucial to develop restoration strategies that increase the ecosystem's resiliency to sea level rise.

1. 5.4.1 Identifying Areas of Priority for Restoration

Tidal marsh restoration is complex as these systems are dynamic and can be influenced by numerous external factors, such as climate change. As a result, the ecosystem's response to restoration is unpredictable and the benefits of restoration projects are not constant (Zedler 2020; Boerema et al. 2016). For this reason, it is important to consider site-specific conditions and prioritize specific areas that will be the most successful, especially if the restoration goal is to increase carbon sequestration. Restoration can be just as complex as the disturbance so it is critical to understand the complexities and develop projects that will address them (Zedler 2000).

Gerwing et al. (2020) suggests that monitoring prior to the restoration project is useful as it provides baseline data that can be compared to post-restoration monitoring to determine success of the project. This is important because it is difficult to predict the project's succession trajectory (Boerema et al. 2016). Although it is necessary for marsh restoration to be site-specific, there are a number of ecosystem characteristics that restoration should focus on. Protecting the vegetation community and increasing biodiversity and biomass should be a critical aspect of any marsh restoration as plants are the assurance of organic carbon input (Wang et al. 2017). Without a healthy plant community, the marsh would not be able to sequester and store carbon. Plant and their roots improve the soil structure and develop a deeper soil depth profile, which allows for a deeper carbon profile (Wang et al. 2017).

To further develop the plant community, restoration efforts should focus on maintaining the health of the high marsh zone. Based on the results from this project, the core carbon stock in the high marsh cores was found to be significantly higher than the core carbon stock in the low marsh cores ($p < 0.05$) at the Boundary Bay East marsh and the Brunswick Point marsh. As well, the average %C was found to be significantly higher in the high marsh zone than the low marsh zone at both marshes ($p < 0.05$). When a marsh is bounded by a dike, the high marsh will get smaller due to coastal squeeze, ultimately resulting in a decrease of carbon stock in the marsh. Restoration techniques should focus on minimizing the impact of coastal squeeze on the high marsh zone, which can be achieved by allowing the marsh to migrate and expand inland, rather than seaward. Seaward migration occurs when the landward migration is prevented and will result the loss of marsh plant community and an overall loss of marsh habitat (Wasson et al. 2013).

Marsh elevation is another factor in regard to enhancing the plant community. My results indicate that marsh zonation has significant effect on soil properties and carbon stock across all marshes, suggesting that marsh elevation should be a key consideration for restoration. The differences between marsh zone are likely contributed to marsh elevation because the plant community can thrive at the higher elevation in the high marsh as inundation occurs with the high tides. This allows for high biodiversity in the plant community and encourages the growth of plant species with deep roots. It is important to have a gradual increase in elevation in newly restored marshes to allow for the development of the high marsh plant community. By doing so, soil organic carbon content will increase, therefore, increasing the overall carbon stock of the marsh.

Certain characteristics, such as porewater salinity, influence the ability of the marsh to act as a carbon sink and these characteristics should be considered in restoration planning. As previously mentioned, porewater salinity influences the rate of decomposition in tidal marshes and greenhouse gas emissions (Bastviken 2009). Marsh ecosystems with higher porewater salinities should be the focus of restoration because these systems are considered to be carbon sinks since they store more atmospheric carbon than they release. High salinity marsh systems, such as the Boundary Bay East marsh, tend to have higher levels of soil organic carbon content and lower greenhouse gas emission because of the lower rate of decomposition (Bartlett et al. 1985).

Poffenbarger et al. (2011) determine that the creation of polyhaline systems, like the Tsawwassen Ferry Terminal marsh, will reliably act as a net carbon sink because these systems consistently have low methane emissions. This indicates that these systems can be used in restoration without accounting for methane emissions (Poffenbarger et al. 2011). In mesohaline marshes, like the Brunswick Point marsh and the Boundary Bay East marsh, the methane emissions are not as consistent so there is a need to understand the carbon sequestration dynamics of the specific marsh system. Poffenbarger et al. (2011) concludes that there is a need for site-specific information when planning projects for marsh systems with salinities < 18. It is still important to restore freshwater and brackish marsh, though, to maintain their carbon sequestration potential and maintain methane emission so that they remain a carbon sink. While high salinity marshes are more reliable in terms of predicting methane emissions, low salinity marshes should still be considered for this reason. Marsh restoration that focuses on maintaining or increasing carbon sequestration should focus on the site-specific characteristics and aim to reduce methane emissions and increasing carbon uptake.

2. 5.4.2 Marsh Restoration Techniques

Breaching of hard armoured shorelines, such as dikes, is a common restoration approach to restoring estuaries and tidal marshes to a more natural state. The removal of these will allow for immediate impacts on a multiple spatiotemporal scale and is highly successful in achieving restoration goals. Hardened shorelines limit tidal exchange as they do not contain openings or if they do, they are undersize, poorly placed or malfunction quickly (Gerwing et al. 2020). The restriction of tidal flow modifies flow, water surface elevation, flood volume, salinity, and sediment transport rates (MacBroom & Schiff 2012).

The change in tidal circulation can diminish the marsh’s ability to adapt to sea-level rise and ability to sequester carbon (Gerwing et al. 2020). Without tidal inundation, a salt marsh can shift towards a brackish and freshwater system due to decreased salinity. As the salinity decreases, the plant community will shift towards that of a freshwater system community. The lack of salinity will also increase the rate of organic decomposition in the soil profile, resulting in higher methane emissions. By dike breaching, the tidal circulation and inundation will be re-introduced, allowing for sediment delivery and salinity levels to increase (Crooks et al. 2016). The altered circulation and tidal dynamics increase sediment accumulation and elevation throughout the marsh.

Hood (2014) identified that elevations in breached and reference sites began to equalize after ~15 years but recovery speed can be highly variable (Sullivan et al. 2017). As the dike is breached, it will allow for recolonization of tidal marsh plant species and reactivation of carbon sequestration (Crooks et al. 2016). However, recovery of native species from the seedbank or local seed sources may not be achievable with intervention. Some marsh plant species have a transient or short-term persistent seedbank while others may persist for years (Bakker et al. 2002; Gerwing et al. 2020). Transplanting marsh grasses from local sources and broadcasting seed will allow for recolonization and reduce the risks of sediment loss through erosion. As well, removal of undesirable established species, such as invasive species and terrestrial vegetation, can also speed up recovery (Gerwing et al. 2020).

Monitoring for multiple year post-breach is critical as well so that management plans can be adjusted. For example, if plant colonization does not occur immediately, the elevation of the marsh platform may need to be raised to provide necessary conditions for plant growth (Drexler et al. 2020). Without the hardened shoreline, the marsh will no longer be affected by coastal squeeze as it will be able to continue to grow as it can migrate inland. As the marsh develops and plant colonization continues, it will regain its carbon sequestration ability.

‘Soft armouring’ of shorelines, or living shorelines, is another approach to marsh restoration that refers to techniques that seek to provides shoreline protection while increasing tidal connectivity with minimal disruption to normal coastal processes (Bilkovic et al. 2016). Living shorelines are a type of estuarine habitat shoreline erosion control that incorporates native vegetation and aims to preserve habitat and natural processes (Davis et al. 2015). These shorelines are created through the enhancement or creation of vegetated shoreline habitats through strategic placement of plants, stone, sand fill and other structural or organic materials (Bilkovic et al. 2016). Enhancement or creation of tidal marshes is often a popular approach for living shorelines but there is an important distinction between a created marsh and living shoreline. Living shorelines are often narrow fringing marshes (< 30 m) and do not have an extensive meadow marsh system (Bilkovic et al. 2016). Although these shorelines are typically low marsh, they still have the ability to grow and accumulate carbon in their soil.

Davis et al. (2015) investigated the carbon sequestration potential for living shorelines and restored marshes in the Newport River Estuary, North Carolina, USA. Across the marshes, the carbon sequestration rate that ranged from 58 to 283 g C m^{-2} yr^{-1} and concluded that wide-spread use of the living shoreline approach will likely come with substantial carbon benefits (Davis et al. 2015). The authors highlighted, though, that the impact of an individual living shoreline is small, but the cumulative impact will be substantial as they continue to gain popularity (Davis et al. 2015). This approach balances the need for shoreline protection without impeding the health and natural processes of coastal ecosystems. As well, it benefits both humans and the ecosystem in regard to climate change as it provides humans with protection from rising sea levels while increasing resiliency and adaptability of the marsh ecosystem.

The Boundary Bay East marsh is a part of a pilot project that is aiming to create a natural dike along a 250 km stretch of its shoreline. This creation of a ‘living dike’ will gradually raise the elevation of the marsh decades so that the marsh can survive sea level rise (Wood 2020). The project partners plan to deposit sediment into the marsh over three decades so that the native plant species can adapt to these changes. The goal behind this approach is to provide wave protection for the people who live nearby while allowing for the marsh to migration and expand (Wood 2020). Currently, the dike restricts the landward migration of the marsh and reduces its ability to adapt to sea level rise, resulting in coastal squeeze (SNC-Lavalin 2018). Following the creation of the living dike, the marsh will be able to move landwards as sea levels rise and will redirect wave energy so that marsh vegetation can thrive. This type of approach to climate change utilizes the ‘infrastructure’ features of ecosystems to address societal challenges while sustaining the health of the ecosystem. Nature-based solutions, like the living dike example, are gaining in popularity as it provides solutions for climate change without hampering the ecosystem’s natural processes. Tidal marshes have the ability to be utilized as a climate change mitigation tool but for this to happen it is necessary for their ability to sequester carbon to be maintained. Through adapting the present practices of shoreline protection and restoring degraded marshes, these ecosystems can be used as a nature-based solution to climate change.

6. 6.0 Conclusion

The main purpose of this project was to assess the environmental conditions that influence carbon sequestration in tidal marshes in the Metro Vancouver region. This research will help develop restoration strategies that will increase or maintain marsh carbon sequestration ability by helping to identify areas of priority and site-specific conditions that will influence the success of restoration. Soil properties such as SCD and %C were found to be significantly different between high marsh cores and the low marsh cores across all marshes ($p < 0.05$). As well, the results indicated that carbon stock is significantly higher in the high marsh compared to the low marsh of all three marshes studied, which aligns with the results of other studies. This indicates that areas with a deeper depth profile with vegetation that has deeper roots and lower porewater salinities will result in a higher carbon stock. These findings suggest that restoration efforts should focus on maintaining the plant community, tidal regime (therefore salinity levels) and marsh elevation as these conditions are critical in increasing or maintaining the marsh's carbon sequestration ability.

The literature suggests that restored marshes have the ability to rapidly become indistinguishable from natural marshes, but certain characteristics such as Soil organic carbon content and carbon stock, can take decades to reach the same point. The results from this study indicate that the %C at the restored Tsawwassen Ferry Terminal marsh has remained the same since a year after it was built, even though the marsh is similar to the low marsh of the Boundary Bay East marsh. These findings suggest that the marsh may not be able to develop into a 'blue carbon' system as it is does not have the ability to expand and develop a high marsh zone, which has been identified to store the most carbon. This is likely is a result of the marsh being bounded by hardened shorelines. These findings that indicate that marsh elevation is an important aspect of should be consider when constructing a marsh.

Marsh restoration can be utilized as a nature-based solution to mitigate the impacts of climate change. The findings from this project can be used to tailor restoration strategies to maximize the impact of restoration activities, such as living shorelines and dike breaching. By doing so, restoration activities can be well-informed and designed in a way to best suit the needs of the individual marsh so that restoration can be as successful as possible. The findings suggest that the high marsh zone and polyhaline marshes (salinity > 18 ppt), such as the Tsawwassen Ferry Terminal marsh, should be prioritized for restoration as these environmental conditions are ideal for carbon sequestration. It is still critical to maintain the functioning condition of marshes that have similar conditions as the Brunswick Point marsh, though, to reduce the impact of inundation from rapid sea-level rise due to climate change.

More environmental data, such as carbon accumulation rates and greenhouse gas, can be collected to further inform activities in order to maximize the impact of restoration. By selecting the right areas and conditions for blue carbon dynamics, restoration methods can be more effective at increasing the overall condition of tidal marsh ecosystems and mitigating the impact of climate change by reducing greenhouse gas emissions.

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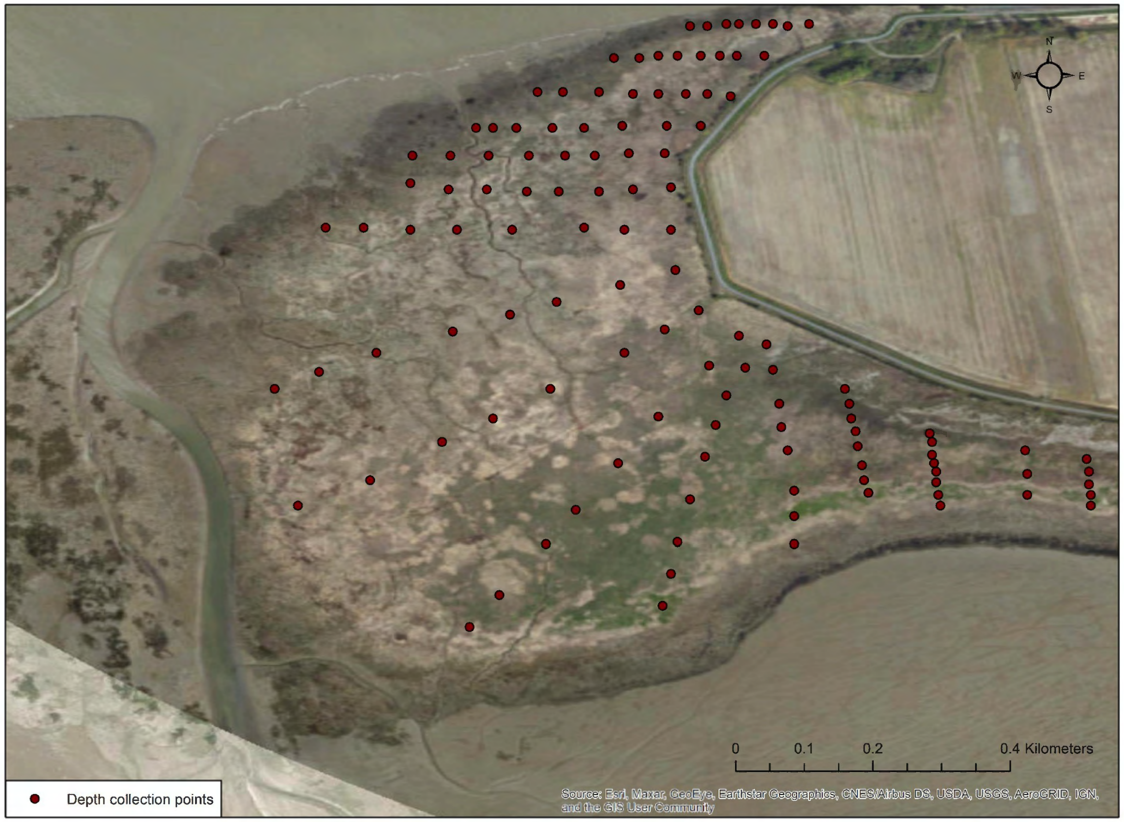
Appendix

Appendix A: Location ID, coordinates, and depth (cm) of the 120 depth measurements taken at the Brunswick Point marsh in Ladner, BC.

Location ID	Latitude	Longitude	Depth (cm)	Location ID	Latitude	Longitude	Depth (cm)
1.1	49°04'04.7"N	123°09'23.8"W	30	5.1	49°03'58.6"N	123°09'30.6"W	60
1.2	49°04'04.6"N	123°09'24.8"W	60	5.2	49°03'58.6"N	123°09'32.3"W	75
1.3	49°04'04.7"N	123°09'25.5"W	69	5.3	49°03'58.5"N	123°09'33.9"W	100
1.4	49°04'04.7"N	123°09'26.3"W	78	5.4	49°03'58.5"N	123°09'35.3"W	100
1.5	49°04'04.7"N	123°09'27.1"W	60	5.5	49°03'58.5"N	123°09'37.0"W	105
1.6	49°04'04.7"N	123°09'27.7"W	57	5.6	49°03'58.5"N	123°09'38.9"W	80
1.7	49°04'04.6"N	123°09'28.6"W	65	5.7	49°03'58.5"N	123°09'40.7"W	90
1.8	49°04'04.6"N	23°09'29.4"W	79	5.8	49°03'58.5"N	123°09'42.5"W	110
2.1	49°04'03.2"N	123°09'25.9"W	40	6.1	49°03'57.0"N	123°09'30.3"W	41
2.2	49°04'03.2"N	123°09'27.2"W	52	6.2	49°03'56.9"N	123°09'32.1"W	66
2.3	49°04'03.2"N	123°09'28.0"W	70	6.3	49°03'56.8"N	123°09'33.7"W	66
2.4	49°04'03.2"N	123°09'28.9"W	92	6.4	49°03'56.8"N	123°09'35.6"W	77
2.5	49°04'03.2"N	123°09'30.0"W	94	6.5	49°03'56.8"N	123°09'37.1"W	100
2.6	49°04'03.2"N	123°09'30.9"W	90	6.6	49°03'56.9"N	123°09'39.0"W	110
2.7	49°04'03.1"N	123°09'31.8"W	79	6.7	49°03'56.9"N	123°09'40.8"W	90
2.8	49°04'03.1"N	123°09'33.0"W	51	6.8	49°03'57.2"N	123°09'42.6"W	84
3.1	49°04'01.3"N	123°09'27.5"W	60	7.1	49°03'55.0"N	123°09'30.3"W	42
3.2	49°04'01.4"N	123°09'28.6"W	59	7.2	49°03'55.0"N	123°09'32.5"W	82
3.3	49°04'01.4"N	123°09'29.6"W	73	7.3	49°03'55.1"N	123°09'34.4"W	80
3.4	49°04'01.4"N	123°09'30.9"W	99	7.4	49°03'55.0"N	123°09'37.8"W	120
3.5	49°04'01.4"N	123°09'32.1"W	108	7.5	49°03'55.0"N	123°09'40.4"W	105
3.6	49°04'01.5"N	123°09'33.7"W	80	7.6	49°03'55.0"N	123°09'42.6"W	95
3.7	49°04'01.5"N	123°09'35.4"W	77	7.7	49°03'55.1"N	123°09'44.8"W	92
3.8	49°04'01.5"N	123°09'36.6"W	70	7.8	49°03'55.1"N	123°09'46.6"W	7
4.1	49°03'59.9"N	123°09'28.9"W	40	8.1	49°03'53.1"N	123°09'30.1"W	15
4.2	49°03'59.9"N	123°09'30.5"W	61	8.2	49°03'52.4"N	123°09'32.7"W	90
4.3	49°03'59.9"N	123°09'32.6"W	94	8.3	49°03'51.6"N	123°09'35.7"W	92
4.4	49°03'59.8"N	123°09'34.4"W	110	8.4	49°03'51.0"N	123°09'37.9"W	84
4.5	49°03'59.8"N	123°09'35.9"W	87	8.5	49°03'50.2"N	123°09'40.6"W	100
4.6	49°03'59.8"N	123°09'37.6"W	89	8.6	49°03'49.2"N	123°09'44.2"W	129
4.7	49°03'59.8"N	123°09'38.7"W	67	8.7	49°03'48.3"N	123°09'46.9"W	106
4.8	49°03'59.8"N	123°09'39.5"W	60	8.8	49°03'47.5"N	123°09'49.0"W	97

Location ID	Latitude	Longitude	Depth (cm)
9.1	49°03'51.2"N	123°09'29.0"W	45
9.2	49°03'50.3"N	123°09'30.6"W	30
9.3	49°03'49.2"N	123°09'32.5"W	90
9.4	49°03'47.5"N	123°09'36.0"W	64
9.5	49°03'46.1"N	123°09'38.7"W	70
9.6	49°03'45.0"N	123°09'41.1"W	170
9.7	49°03'43.2"N	123°09'44.5"W	65
9.8	49°03'42.0"N	123°09'47.9"W	105
10.1	49°03'50.0"N	123°09'27.1"W	20
10.2	49°03'48.6"N	123°09'28.5"W	40
10.3	49°03'46.2"N	123°09'30.9"W	45
10.4	49°03'44.0"N	123°09'32.8"W	95
10.5	49°03'41.8"N	123°09'34.8"W	110
10.6	49°03'40.2"N	123°09'36.2"W	113
10.7	49°03'37.8"N	123°09'38.4"W	115
10.8	49°03'36.3"N	123°09'39.8"W	128
11.1	49°03'48.5"N	123°09'26.8"W	110
11.2	49°03'47.2"N	123°09'27.7"W	55
11.3	49°03'45.8"N	123°09'28.2"W	95
11.4	49°03'44.3"N	123°09'28.7"W	65
11.5	49°03'42.3"N	123°09'29.4"W	175
11.6	49°03'40.3"N	123°09'30.0"W	115
11.7	49°03'38.8"N	123°09'30.3"W	125
11.8	49°03'37.3"N	123°09'30.7"W	140
12.1	49°03'49.6"N	123°09'25.8"W	45
12.2	49°03'48.4"N	123°09'25.5"W	81
12.3	49°03'46.8"N	123°09'25.2"W	40
12.4	49°03'45.7"N	123°09'25.1"W	90
12.5	49°03'44.6"N	123°09'24.8"W	97
12.6	49°03'42.7"N	123°09'24.5"W	105
12.7	49°03'41.5"N	123°09'24.5"W	123
12.8	49°03'40.2"N	123°09'24.5"W	147
13.1	49°03'47.5"N	123°09'22.1"W	52
13.2	49°03'46.8"N	123°09'21.9"W	40
13.3	49°03'46.1"N	123°09'21.8"W	110
13.4	49°03'45.5"N	123°09'21.6"W	90
13.5	49°03'44.8"N	123°09'21.5"W	105
13.6	49°03'43.9"N	123°09'21.3"W	118
13.7	49°03'43.2"N	123°09'21.2"W	153
13.8	49°03'42.6"N	123°09'21.0"W	115
14.1	49°03'45.4"N	123°09'18.1"W	165
14.2	49°03'45.0"N	123°09'18.0"W	160
14.3	49°03'44.4"N	123°09'18.0"W	170
14.4	49°03'44.0"N	123°09'17.9"W	163
14.5	49°03'43.6"N	123°09'17.8"W	110
14.6	49°03'43.1"N	123°09'17.8"W	140
14.7	49°03'42.5"N	123°09'17.7"W	162
14.8	49°03'42.0"N	123°09'17.6"W	65
15.1	49°03'44.6"N	123°09'13.6"W	58
15.2	49°03'43.5"N	123°09'13.5"W	150
15.3	49°03'42.5"N	123°09'13.5"W	155
15.4	49°03'44.2"N	123°09'10.7"W	60
15.5	49°03'43.6"N	123°09'10.6"W	94
15.6	49°03'43.0"N	123°09'10.6"W	153
15.7	49°03'42.5"N	123°09'10.5"W	125
15.8	49°03'42.0"N	123°09'10.5"W	130



Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

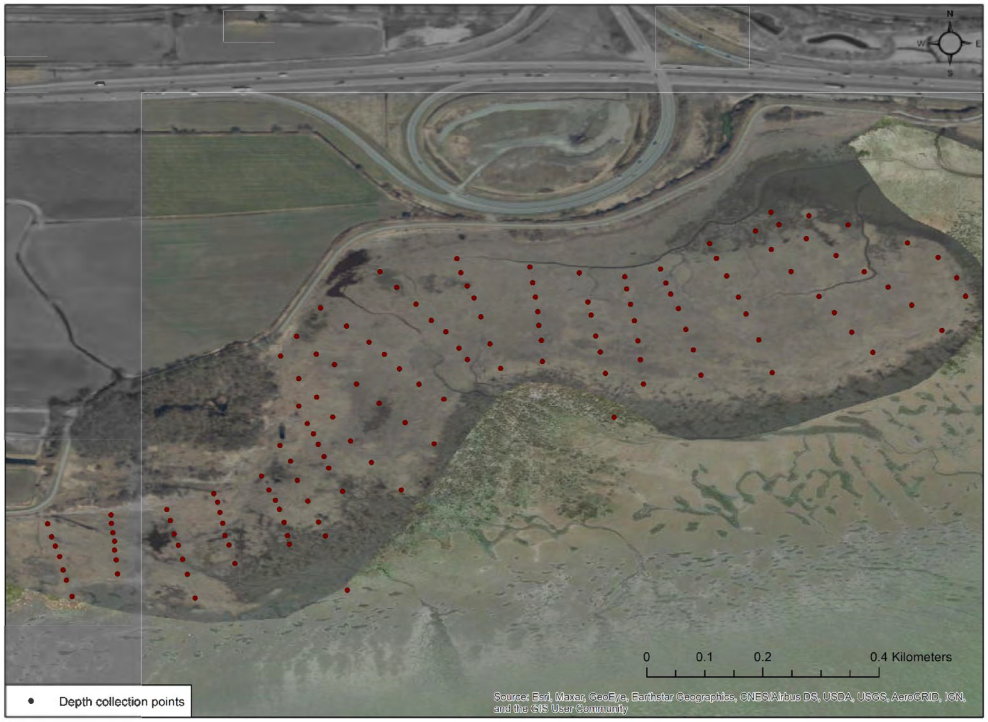
Projection: NAD 1983 UTM 10N
Production: Hasini Basnayake, 2021

Appendix B: Locations of depth measurements completed in ArcMap at the Brunswick Point marsh in Ladner, BC.

Appendix C: Location ID, coordinates, and depth (cm) of the 140 depth measurements taken at the Boundary Bay East marsh in Delta, BC.

Location ID	Latitude	Longitude	Depth (cm)	Location ID	Latitude	Longitude	Depth (cm)
1.1	49°05'24.3"N	122°53'32.2"W	95	6.1	49°05'20.7"N	122°53'40.3"W	80
1.2	49°05'24.1"N	122°53'30.0"W	91	6.2	49°05'20.0"N	122°53'40.2"W	56
1.3	49°05'23.6"N	122°53'27.8"W	29	6.3	49°05'19.2"N	122°53'40.0"W	67
1.4	49°05'22.6"N	122°53'24.5"W	87	6.4	49°05'18.2"N	122°53'39.8"W	68
1.5	49°05'21.8"N	122°53'22.8"W	73	6.5	49°05'17.1"N	122°53'39.6"W	58
1.6	49°05'20.6"N	122°53'21.8"W	70	6.6	49°05'16.1"N	122°53'39.4"W	58
1.7	49°05'19.6"N	122°53'21.3"W	63	6.7	49°05'14.7"N	122°53'39.3"W	61
2.1	49°05'23.6"N	122°53'31.7"W	98	7.1	49°05'20.9"N	122°53'42.8"W	79
2.2	49°05'22.8"N	122°53'30.2"W	82	7.2	49°05'19.3"N	122°53'42.3"W	74
2.3	49°05'21.9"N	122°53'28.5"W	69	7.3	49°05'18.6"N	122°53'42.2"W	75
2.4	49°05'21.0"N	122°53'26.9"W	82	7.4	49°05'17.4"N	122°53'41.9"W	68
2.5	49°05'20.1"N	122°53'25.6"W	48	7.5	49°05'16.5"N	122°53'41.7"W	65
2.6	49°05'19.1"N	122°53'24.3"W	58	7.6	49°05'15.3"N	122°53'41.4"W	59
2.7	49°05'17.7"N	122°53'22.6"W	25	7.7	49°05'12.9"N	122°53'40.9"W	33
3.1	49°05'23.2"N	122°53'33.0"W	91	8.1	49°05'21.2"N	122°53'45.6"W	88
3.2	49°05'22.2"N	122°53'32.1"W	47	8.2	49°05'20.4"N	122°53'45.4"W	76
3.3	49°05'21.0"N	122°53'31.0"W	75	8.3	49°05'19.6"N	122°53'45.3"W	76
3.4	49°05'19.6"N	122°53'29.5"W	35	8.4	49°05'18.7"N	122°53'45.1"W	80
3.5	49°05'18.7"N	122°53'28.6"W	67	8.5	49°05'18.0"N	122°53'45.1"W	85
3.6	49°05'17.6"N	122°53'27.6"W	55	8.6	49°05'17.1"N	122°53'44.9"W	73
3.7	49°05'16.5"N	122°53'26.5"W	48	8.7	49°05'16.0"N	122°53'44.9"W	68
4.1	49°05'22.5"N	122°53'35.6"W	83	9.1	49°05'21.7"N	122°53'49.6"W	32
4.2	49°05'21.7"N	122°53'35.2"W	82	9.2	49°05'20.9"N	122°53'49.4"W	65
4.3	49°05'20.7"N	122°53'34.6"W	81	9.3	49°05'20.2"N	122°53'49.1"W	91
4.4	49°05'19.6"N	122°53'34.0"W	71	9.4	49°05'19.5"N	122°53'48.7"W	85
4.5	49°05'18.6"N	122°53'33.5"W	65	9.5	49°05'18.5"N	122°53'48.3"W	81
4.6	49°05'17.2"N	122°53'32.8"W	69	9.6	49°05'16.9"N	122°53'47.8"W	80
4.7	49°05'15.3"N	122°53'32.1"W	52	9.7	49°05'15.6"N	122°53'47.2"W	75
5.1	49°05'21.1"N	122°53'38.3"W	89	10.1	49°05'21.0"N	122°53'53.9"W	95
5.2	49°05'20.3"N	122°53'38.0"W	85	10.2	49°05'20.1"N	122°53'53.0"W	65
5.3	49°05'19.7"N	122°53'37.7"W	71	10.3	49°05'19.2"N	122°53'51.9"W	89
5.4	49°05'18.9"N	122°53'37.3"W	67	10.4	49°05'18.3"N	122°53'51.1"W	95
5.5	49°05'17.8"N	122°53'36.9"W	68	10.5	49°05'17.6"N	122°53'50.3"W	84
5.6	49°05'16.6"N	122°53'36.5"W	53	10.6	49°05'16.7"N	122°53'49.5"W	85
5.7	49°05'15.2"N	122°53'36.0"W	44	10.7	49°05'16.1"N	122°53'49.1"W	80

Location ID	Latitude	Longitude	Depth (cm)	Location ID	Latitude	Longitude	Depth (cm)
11.1	49°05'18.9"N	122°53'57.2"W	27	16.1	49°05'09.6"N	122°54'00.5"W	16
11.2	49°05'17.9"N	122°53'55.8"W	20	16.2	49°05'08.8"N	122°54'00.1"W	27
11.3	49°05'17.0"N	122°53'54.5"W	25	16.3	49°05'08.2"N	122°53'59.8"W	40
11.4	49°05'16.4"N	122°53'53.7"W	25	16.4	49°05'07.7"N	122°53'59.5"W	35
11.5	49°05'15.6"N	122°53'52.8"W	40	16.5	49°05'07.0"N	122°53'59.3"W	60
11.6	49°05'14.7"N	122°53'51.8"W	45	16.6	49°05'06.3"N	122°53'59.1"W	30
11.7	49°05'13.9"N	122°53'50.4"W	34	16.7	49°05'05.8"N	122°53'59.0"W	35
12.1	49°05'17.4"N	122°53'58.6"W	20	17.1	49°05'08.6"N	122°54'03.2"W	33
12.2	49°05'16.4"N	122°53'57.5"W	16	17.2	49°05'08.1"N	122°54'03.0"W	35
12.3	49°05'15.8"N	122°53'56.5"W	10	17.3	49°05'07.5"N	122°54'02.8"W	35
12.4	49°05'14.7"N	122°53'55.2"W	40	17.4	49°05'06.9"N	122°54'02.7"W	15
12.5	49°05'13.6"N	122°53'54.0"W	20	17.5	49°05'06.3"N	122°54'02.6"W	38
12.6	49°05'12.6"N	122°53'52.5"W	38	17.6	49°05'05.7"N	122°54'02.3"W	35
12.7	49°05'11.4"N	122°53'50.9"W	15	17.7	49°05'04.7"N	122°54'02.0"W	32
13.1	49°05'16.3"N	122°53'59.5"W	12	18.1	49°05'07.7"N	122°54'05.8"W	20
13.2	49°05'15.0"N	122°53'58.5"W	10	18.2	49°05'07.1"N	122°54'05.6"W	22
13.3	49°05'14.0"N	122°53'57.5"W	7	18.3	49°05'06.3"N	122°54'05.4"W	20
13.4	49°05'12.9"N	122°53'56.6"W	7	18.4	49°05'05.7"N	122°54'05.2"W	35
13.5	49°05'11.5"N	122°53'55.6"W	15	18.5	49°05'04.9"N	122°54'04.9"W	35
13.6	49°05'10.3"N	122°53'54.4"W	40	18.6	49°05'04.1"N	122°54'04.7"W	47
13.7	49°05'08.8"N	122°53'52.7"W	40	18.7	49°05'02.8"N	122°54'04.2"W	40
14.1	49°05'13.5"N	122°53'58.5"W	12	19.1	49°05'07.4"N	122°54'08.9"W	40
14.2	49°05'12.5"N	122°53'58.0"W	12	19.2	49°05'06.9"N	122°54'08.9"W	60
14.3	49°05'11.9"N	122°53'57.6"W	10	19.3	49°05'06.4"N	122°54'08.8"W	27
14.4	49°05'11.3"N	122°53'57.4"W	30	19.4	49°05'05.9"N	122°54'08.7"W	46
14.5	49°05'10.7"N	122°53'57.0"W	20	19.5	49°05'05.5"N	122°54'08.7"W	35
14.6	49°05'10.0"N	122°53'56.8"W	70	19.6	49°05'04.9"N	122°54'08.6"W	40
14.7	49°05'08.7"N	122°53'56.0"W	60	19.7	49°05'04.1"N	122°54'08.6"W	40
15.1	49°05'11.3"N	122°53'59.5"W	22	20.1	49°05'06.9"N	122°54'12.5"W	35
15.2	49°05'10.4"N	122°53'58.9"W	13	20.2	49°05'06.2"N	122°54'12.2"W	50
15.3	49°05'09.3"N	122°53'58.5"W	27	20.3	49°05'05.7"N	122°54'12.0"W	25
15.4	49°05'08.2"N	122°53'57.9"W	30	20.4	49°05'05.1"N	122°54'11.8"W	32
15.5	49°05'07.0"N	122°53'57.4"W	28	20.5	49°05'04.3"N	122°54'11.6"W	25
15.6	49°05'06.2"N	122°53'57.0"W	70	20.6	49°05'03.8"N	122°54'11.4"W	30
15.7	49°05'03.2"N	122°53'55.8"W	35	20.7	49°05'02.9"N	122°54'11.1"W	52



Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Projection: NAD 1983 UTM 10N
Production: Hasini Basnayake, 2021

Appendix D: Locations of depth measurements completed in ArcMap for the Boundary Bay East marsh in Delta, BC.

Appendix E: Location ID, Coordinates, and depth (cm) of the 50 depth measurements taken at the Tsawwassen Ferry Terminal marsh in Tsawwassen, BC.

Location ID	Latitude	Longitude	Depth (cm)	Location ID	Latitude	Longitude	Depth (cm)
1.1	49°00'46.1"N	123°07'18.9"W	120	7.1	49°00'42.4"N	123°07'23.7"W	2
1.2	49°00'46.4"N	123°07'19.4"W	80	7.2	49°00'42.7"N	123°07'24.5"W	8
1.3	49°00'46.6"N	123°07'19.9"W	119	7.3	49°00'43.1"N	123°07'25.3"W	5
1.4	49°00'46.8"N	123°07'20.3"W	110	7.4	49°00'43.5"N	123°07'26.0"W	10
1.5	49°00'47.0"N	123°07'20.6"W	105	7.5	49°00'43.7"N	123°07'26.6"W	41
2.1	49°00'45.8"N	123°07'19.3"W	97	8.1	49°00'41.8"N	123°07'24.8"W	1
2.2	49°00'46.0"N	123°07'19.8"W	73	8.2	49°00'42.1"N	123°07'25.4"W	3
2.3	49°00'46.2"N	123°07'20.1"W	92	8.3	49°00'42.4"N	123°07'26.1"W	2
2.4	49°00'46.5"N	123°07'20.9"W	45	8.4	49°00'42.9"N	123°07'27.1"W	2
2.5	49°00'46.9"N	123°07'21.6"W	90	8.5	49°00'43.4"N	123°07'28.2"W	36
3.1	49°00'45.2"N	123°07'20.1"W	13	9.1	49°00'41.5"N	123°07'27.1"W	5
3.2	49°00'45.6"N	123°07'20.7"W	77	9.2	49°00'41.9"N	123°07'27.8"W	7
3.3	49°00'46.0"N	123°07'21.4"W	33	9.3	49°00'42.2"N	123°07'28.3"W	4
3.4	49°00'46.4"N	123°07'22.1"W	93	9.4	49°00'42.5"N	123°07'28.8"W	5
3.5	49°00'46.7"N	123°07'22.7"W	101	9.5	49°00'42.8"N	123°07'29.3"W	13
4.1	49°00'44.5"N	123°07'21.1"W	20	10.1	49°00'41.4"N	123°07'29.9"W	9
4.2	49°00'44.9"N	123°07'21.8"W	9	10.2	49°00'41.6"N	123°07'30.2"W	8
4.3	49°00'45.3"N	123°07'22.5"W	10	10.3	49°00'41.8"N	123°07'30.5"W	8
4.4	49°00'45.7"N	123°07'23.1"W	80	10.4	49°00'42.1"N	123°07'30.8"W	6
4.5	49°00'46.0"N	123°07'23.8"W	63	10.5	49°00'42.3"N	123°07'31.1"W	20
5.1	49°00'43.7"N	123°07'22.3"W	13				
5.2	49°00'44.1"N	123°07'23.3"W	10				
5.3	49°00'44.4"N	123°07'23.8"W	2				
5.4	49°00'44.7"N	123°07'24.4"W	8				
5.5	49°00'45.1"N	123°07'25.3"W	30				
6.1	49°00'43.0"N	123°07'22.8"W	3				
6.2	49°00'43.5"N	123°07'23.7"W	5				
6.3	49°00'43.8"N	123°07'24.5"W	1				
6.4	49°00'44.2"N	123°07'25.3"W	2				
6.5	49°00'44.6"N	123°07'26.1"W	3				

Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

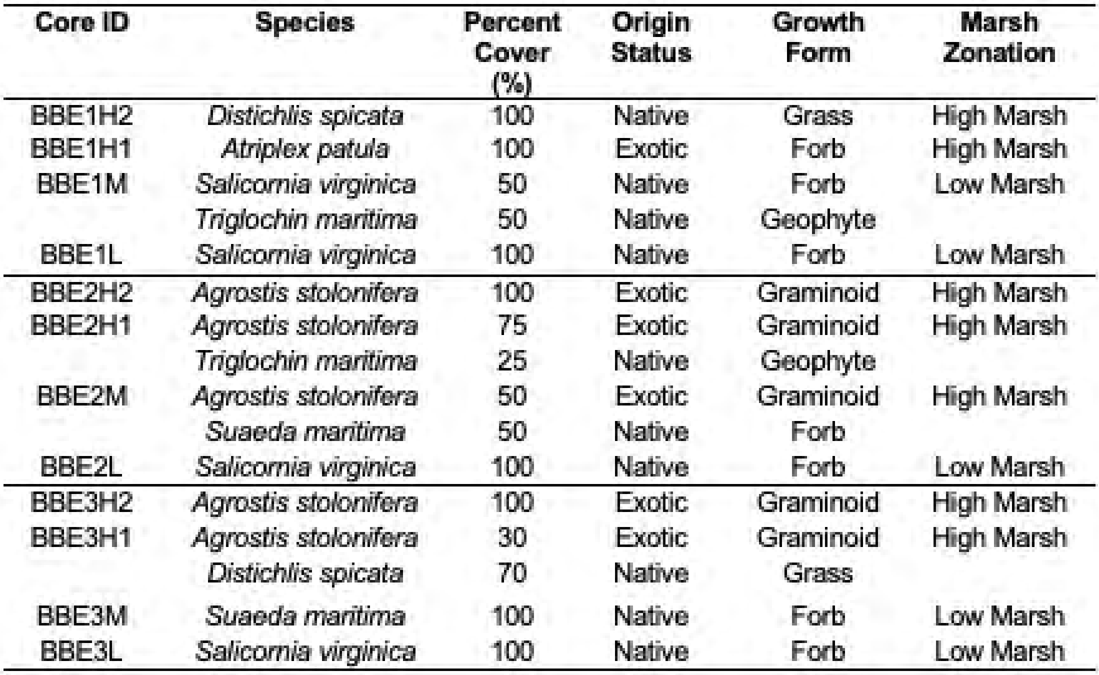
Projection: NAD 1983 UTM 10N
Production: Hasini Basnayake, 2021

Appendix F: Locations of depth measurements completed ArcMap at the Tsawwassen Ferry Terminal marsh in Tsawwassen, BC.

Appendix G: Species composition, percent cover, origin status, growth form and marsh zonation of coring sites at the Brunswick Point marsh in Ladner, B.C.

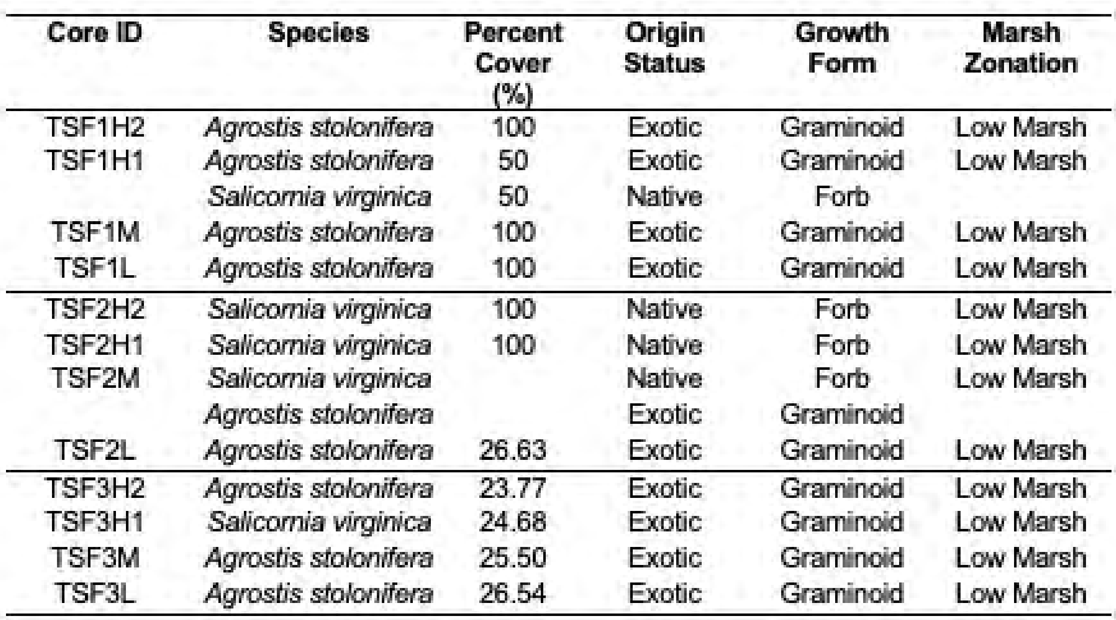
Core ID	Species	Percent Cover (%)	Origin Status	Growth Form	Marsh Zonation
BRP1H2	*Distichlis spicata*	85	Native	Grass	High Marsh
	Aster subspicatus	15	Native	Forb	
BRP1H1	*Distichlis spicata*	90	Native	Grass	High Marsh
	Aster subspicatus	5	Native	Forb	
	Typha angustifolia	5	Exotic	Graminoid	
BRP1M	*Distichlis spicata*	90	Native	Grass	High Marsh
	Aster subspicatus	8	Native	Forb	
	Typha angustifolia	2	Exotic	Graminoid	
BRP1L	*Salicornia virginica*	100	Native	Forb	Low Marsh
BRP2H2	*Deschampsia caespitosa*	80	Native	Graminoid	High Marsh
	Triglochin maritima	10	Native	Geophyte	
	Typha angustifolia	10	Exotic	Graminoid	
BRP2H1	*Deschampsia caespitosa*	80	Native	Graminoid	High Marsh
	Triglochin maritima	15	Native	Geophyte	
	Potentilla pacifica	5	Native	Forb	
BRP2M	*Distichlis spicata*	95	Native	Grass	Low Marsh
	Typha angustifolia	5	Exotic	Graminoid	
BRP2L	*Distichlis spicata*	90	Native	Grass	Low Marsh
	Typha angustifolia	5	Exotic	Graminoid	
	Triglochin maritima	5	Native	Geophyte	
BRP3H2	*Deschampsia caespitosa*	80	Native	Graminoid	High Marsh
	Triglochin maritima	10	Native	Geophyte	
	Typha angustifolia	10	Exotic	Graminoid	
BRP3H1	*Deschampsia caespitosa*	90	Native	Graminoid	High Marsh
	Triglochin maritima	10	Native	Geophyte	
BRP3M	*Agrostis stolonifera*	80	Exotic	Graminoid	Low Marsh
	Triglochin maritima	10	Native	Geophyte	
	Typha angustifolia	10	Exotic	Graminoid	
BRP3L	*Agrostis stolonifera*	90	Exotic	Graminoid	Low Marsh
	Triglochin maritima	10	Native	Geophyte	

Appendix H: Species composition, percent cover, origin status, growth form and marsh zonation of coring sites at the Boundary Bay East marsh in Delta B.C.



Core ID	Species	Percent Cover (%)	Origin Status	Growth Form	Marsh Zonation
BBE1H2	*Distichlis spicata*	100	Native	Grass	High Marsh
BBE1H1	*Atriplex patula*	100	Exotic	Forb	High Marsh
BBE1M	*Salicornia virginica*	50	Native	Forb	Low Marsh
	Triglochin maritima	50	Native	Geophyte	
BBE1L	*Salicornia virginica*	100	Native	Forb	Low Marsh
BBE2H2	*Agrostis stolonifera*	100	Exotic	Graminoid	High Marsh
BBE2H1	*Agrostis stolonifera*	75	Exotic	Graminoid	High Marsh
	Triglochin maritima	25	Native	Geophyte	
BBE2M	*Agrostis stolonifera*	50	Exotic	Graminoid	High Marsh
	Suaeda maritima	50	Native	Forb	
BBE2L	*Salicornia virginica*	100	Native	Forb	Low Marsh
BBE3H2	*Agrostis stolonifera*	100	Exotic	Graminoid	High Marsh
BBE3H1	*Agrostis stolonifera*	30	Exotic	Graminoid	High Marsh
	Distichlis spicata	70	Native	Grass	
BBE3M	*Suaeda maritima*	100	Native	Forb	Low Marsh
BBE3L	*Salicornia virginica*	100	Native	Forb	Low Marsh

Appendix I: Species composition, percent cover, origin status, growth form and marsh zonation of coring sites at the Tsawwassen Ferry marsh in Tsawwassen, B.C.



Core ID	Species	Percent Cover (%)	Origin Status	Growth Form	Marsh Zonation
TSF1H2	*Agrostis stolonifera*	100	Exotic	Graminoid	Low Marsh
TSF1H1	*Agrostis stolonifera*	50	Exotic	Graminoid	Low Marsh
	Salicornia virginica	50	Native	Forb	
TSF1M	*Agrostis stolonifera*	100	Exotic	Graminoid	Low Marsh
TSF1L	*Agrostis stolonifera*	100	Exotic	Graminoid	Low Marsh
TSF2H2	*Salicornia virginica*	100	Native	Forb	Low Marsh
TSF2H1	*Salicornia virginica*	100	Native	Forb	Low Marsh
TSF2M	*Salicornia virginica*		Native	Forb	Low Marsh
	Agrostis stolonifera		Exotic	Graminoid	
TSF2L	*Agrostis stolonifera*	26.63	Exotic	Graminoid	Low Marsh
TSF3H2	*Agrostis stolonifera*	23.77	Exotic	Graminoid	Low Marsh
TSF3H1	*Salicornia virginica*	24.68	Exotic	Graminoid	Low Marsh
TSF3M	*Agrostis stolonifera*	25.50	Exotic	Graminoid	Low Marsh
TSF3L	*Agrostis stolonifera*	26.54	Exotic	Graminoid	Low Marsh