Carbon Stocks and Accumulation Rates in Salt Marshes of the Pacific Coast of Canada

by

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Abstract

We estimated carbon stocks and carbon accumulation rates using 34 sediment cores collected from seven salt marshes within the Clayoquot Sound UNESCO Biosphere Reserve and Pacific Rim National Park Reserve of Canada (49.2° N, 125.80° W). Carbon stocks averaged 80.6 ± 43.8 Mg C ha^{-1} between the seven salt marshes, and carbon accumulation rates averaged 146 ± 102 g C m^{-2} yr $^{-1}$. These rates are comparable to those found in salt marshes further south along the Pacific coast of North America (32.5-38.2° N) and at similar latitudes in Eastern Canada and Northern Europe (43.6-55.5° N). The seven Clayoquot Sound salt marshes currently accumulate carbon at a rate of 54.28 Mg C yr^{-1} over an area of 46.94 ha, 87 % of which occurs in the high marsh zone. On a per-hectare basis, Clayoquot Sound salt marsh soils accumulate carbon at least one order of magnitude more quickly than the average of global boreal forest soils. This carbon accumulation capacity provides a climate mitigation co-benefit when conserving for other salt marsh ecosystem services.

Keywords: Tidal marsh; Clayoquot Sound; blue carbon; carbon accumulation rate; soil carbon stock

For "Grammy" Josephine, Uncle Chandler, and Marc- all loved and never forgotten. You taught me the importance of dedication, self-discipline, keeping an open mind, and most importantly, to enjoy what life has to offer.

Acknowledgements

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Chapter 1.

Introduction

Coastal, vegetated ecosystems, such as eelgrass meadows, mangroves, and tidal salt marshes, have recently been recognized for their ability to store large amounts of carbon, or "blue carbon," within their soils and sediments (IPCC 2014; Howard et al. 2014). While blue carbon ecosystems cover approximately 0.2 % of the ocean surface, previous studies have suggested that they could be responsible for up to 50 % of total ocean carbon burial (Duarte et al. 2005). The estimated, average per-area carbon sequestration rate is between 30 to 50 times greater than that of terrestrial forests (McLeod et al. 2011). Globally, blue carbon ecosystems have been estimated to sequester between 75.3 and 224.2 Tg C yr^{-1} (Duarte et al. 2013).

The high carbon storage and accumulation capacity per-area of coastal ecosystems have been investigated because of the potential for blue carbon to provide climate mitigation co-benefits, when managed for other ecosystem services provided by coastal wetlands, such as storm surge attenuation, coastal erosion control, habitat for commercially important species, and ecotourism (Howard et al. 2017). Climate change mitigation refers to efforts to reduce the negative impacts of anthropogenic climate change by either reducing carbon dioxide (CO_2) and other greenhouse gas emissions or enhancing natural carbon sinks to increase the rate at which CO_2 is removed from the atmosphere. Climate change mitigation for blue carbon resources the limitation of habitat destruction by human activity, because blue carbon ecosystems naturally store accumulated carbon in their soils for centuries or millennia (Duarte et al. 2005). This carbon can be released when the ecosystem is degraded (McLeod et al. 2011, Pendleton et al 2012). To better inform policies that identify priority areas for conservation, more precise measurement of carbon stocks and accumulation potential are needed (Howard et al. 2017).

Global estimates of salt marsh area, carbon stocks, and carbon accumulation rates (CAR) are subject to large uncertainties. Duarte et al. (2013) noted a 20-fold

uncertainty in global estimates of salt marsh area, ranging from 22,000-to 400,000 km^2. This uncertainty is attributed to ambiguous classification schemes for wetlands. For example, some classification systems consider freshwater and saltwater marshes in the same category (Duarte et al. 2013). Similarly, the estimated, global soil carbon stock of all salt marshes ranges between 0.4 and 6.5 Pg C, a 16-fold range (Duarte et al. 2013).

Currently, the average global CAR estimate for salt marshes is 244.7 ± 26.1 g C m^{-2} yr^{-1} (Ouyang and Lee 2014), but recent reviews of salt marsh CAR estimates disproportionately represent certain areas of the world (Ouyang and Lee 2014; Chmura 2003). Some areas, such as Europe and eastern North America, have dozens of CAR data points, while others, such as western North America, East Asia, and Australia, have fewer than 10 estimates per region. Regions such as Africa, India, and South America have no data.

The Commission for Environmental Cooperation (CEC), a tri-national governmental organization promoting scientific cooperation between Canada, the United States, and Mexico, identified the Pacific coast of Canada as a significant blue carbon data gap. Additionally, a review of global salt marsh CAR data identified 64 studies on the northwestern Atlantic coast of North America but only eight on the entire Pacific coast of the continent, none of which were north of 38.2 °N (Ouyang and Lee 2014). This lack of data coverage is problematic when considering the proposed, latitudinal controls on variability in CAR estimates (Ouyang and Lee 2014). The high variability in CAR from site to site combined with the 20-fold uncertainty in global marsh area estimates result in global salt marsh CAR estimates ranging from 0.9 to 31.4 Tg C yr^{-1} (Ouyang and Lee 2014). This 35-fold range is 7 times greater than the global range for mangroves (Ouyang and Lee 2014; Donato et al. 2011). Thus, quantification of the role of salt marshes in the global carbon cycle remains uncertain, and without further sampling from understudied regions, global estimates cannot yet be assumed to reflect the true global carbon sequestration value of salt marshes, leaving an incomplete picture of their importance for greenhouse gas mitigation.

An additional factor that limits CAR quantification is the extensive use of ^{137}Cs radioisotope dating or a marker horizon method, which have the potential for producing overestimates of sediment accumulation rates when compared to radioisotope dating methods such as ^{210}Pb (e.g. Callaway et al. 2012; Johannessen and MacDonald 2016).

For example, of 143 studies reviewed by Ouyang and Lee (2014), only three did not use either a ^{137}Cs or marker horizon method, not including studies which did not specify. Dating using these methods have been demonstrated to produce CAR estimates up to 26 % higher than ^{210}Pb in California salt marshes (Callaway et al. 2012). Using ^{210}Pb dating for producing new estimates on the Pacific coast of Canada allows comparisons with these studies while minimizing overestimation.

This study aims to address the data gap identified by the CEC by providing CAR and carbon stock measurements from the Pacific Coast of Canada as a part of the government of Canada's contribution to a continent-wide assessment of blue carbon mitigation potential. We utilize ^{210}Pb dating to produce CAR estimates and carbon stock measurements from seven salt marshes within the United Nations Educational, Scientific, and Cultural Organization (UNESCO) Clayoquot Sound Biosphere Reserve, British Columbia's Tofino Mudflats Wildlife Management Area, and Pacific Rim National Park Reserve of Canada on Vancouver Island, British Columbia. We calculated soil carbon density (SCD) from dry bulk density (DBD), and percent carbon (% C) on sediment cores collected across the high and low marsh zones of each marsh, and used ^{210}Pb dating in a subset of these cores to quantify carbon accumulation rates. We also used aerial imagery to estimate the extent of high marsh and low marsh areas and estimate carbon stocks and total annual carbon accumulation for each marsh studied. Finally, we compare these new data with CAR data from the Pacific coast of the United States and with marshes at similar latitudes on Canada's eastern coast and in Northern Europe, to better identify spatial trends on controls of CAR and marsh carbon stocks. For greenhouse gas mitigation and accounting purposes, we note the importance of methane emissions from wetlands with low salinities (IPCC 2013). We attempted to choose sites with salinity >5 where such emissions are low enough to result in net carbon sequestration (IPCC 2013), but otherwise we focus solely on soil carbon storage and accumulation.

Chapter 2.   Methods

2.1. Study Area

Clayoquot Sound is a sparsely populated inlet on the west coast of Vancouver Island, British Columbia, Canada, and consists of many islands and peninsulas within mountainous topography. Clayoquot Sound is home to several protected area designations, including Long Beach Unit of Pacific Rim National Park Reserve of Canada, the Province of British Columbia's Tofino Mudflats Wildlife Management Area, and the UNESCO Clayoquot Sound Biosphere Reserve, which protects 366,000 hectares of the west coast of Vancouver Island (Figure 1). The region is part of the temperate rainforest biome with high annual rainfall (3270 mm y^{-1}) and average annual temperature of 9.5 °C (Environment Canada, 1981-2010 averages). The mean tidal range in Tofino is 2.14 m (Fisheries and Oceans 2016).

We collected 34 sediment cores from seven marshes during Summer, 2016, to determine their carbon storage and accumulation rates (Table 1; Figure 1). These marshes include: (1) Cannery Bay East (CBE), a 4 ha marsh surrounding Kenn Falls Creek, immediately north of the Kennedy River mouth; (2) Cannery Bay West (CBW), a 0.51 ha marsh at the mouth of a creek flowing south into Kennedy Cove, (3) Cypress River Flats (CRF), a 27.42 ha tidal marsh and mud flat, partially within two Indian Reserves of the Ahousaht Nation and immediately north of the Cypress River mouth; (4) Grice Bay at Kootowis Creek (GBK)**,** an 11.69 ha salt marsh located in southeast Grice Bay; (5) Kennedy Cove South (KCS), a 0.78 ha marsh located at a creek mouth on the south shore of Kennedy Cove; (6) "Shipwreck Cove" (SWC), a 1.02 ha marsh in a cove approximately 2.5 km southwest of Kennedy Cove; and (7) Tofino Mudflats (TMF), a 1.5 ha marsh at a creek mouth within the Tofino Mudflats Wildlife Management Area. These sites were identified as typical of salt marshes along Canada's Pacific coast because they include small, pocket marshes encompassing an enclosed, semi-circular area of coastline as well as larger, estuarine marshes. Surface water salinity ranged from 5.9 at KCS to 24 in Grice Bay, and 29 at Roberts Point 6 km south of CRF (Postlethwaite and McGowan 2016, submitted).
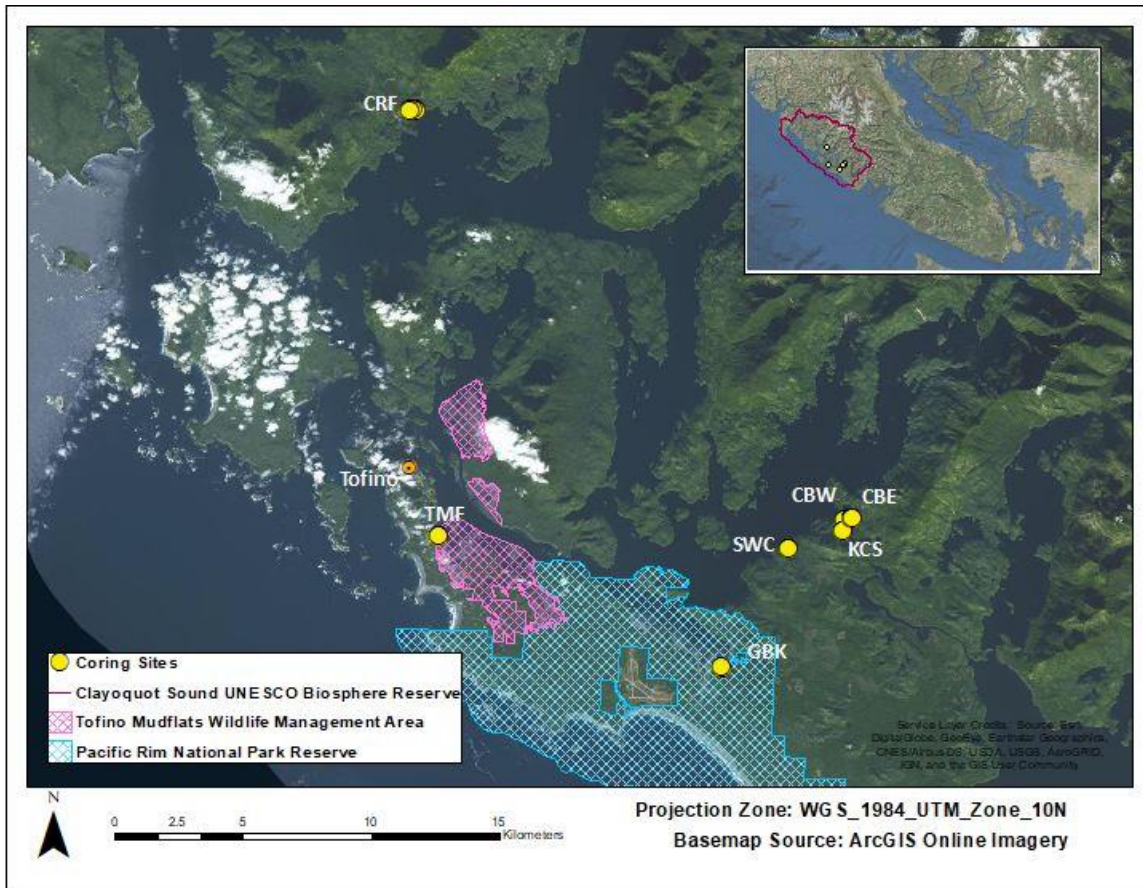
Figure 1. Study area and marsh locations shown within Clayoquot Sound on the west coast of Vancouver Island (inset), British Columbia, Canada. Site locations clockwise from upper left: Cypress River Flats (CRF), Cannery Bay East (CBE), Cannery Bay West (CBW), Kennedy Cove South (KCS), Shipwreck Cove (SWC), Grice Bay at Kootowis Creek (GBK), and Tofino Mudflats (TMF). Pacific Rim National Park Reserve (blue crosshatching) covers the southern portion of the map and the Tofino Mudflats Wildlife Management Area (pink crosshatching) covers portions of the southwestern area. The entire region lies within the Clayoquot Sound UNESCO Biosphere Reserve (purple outline, see inset). Tide and climate measurements were recorded at the town of Tofino (orange dot).

2.2. Field Sampling

Within each marsh, sediment cores were extracted along linear transects perpendicular to the low tide shoreline following the methodology of Howard et al. (2014). Coring spots were approximately evenly spaced along the transect (between nine and 24 meters apart) from land to sea, and attempted to sample from both the low and high marsh zones (Chmura et al. 2011). Core locations were chosen to avoid

ditches and channels without organic soil accumulation which comprised a relatively small portion of total marsh surface area (see section 4.4.3).

Vegetation composition was recorded as an indicator of 'low' vs 'high' marsh zones. A 50 x 50 cm quadrat was placed over each coring spot, the overhead view was photographed, and the species composition noted. Coring spots were considered low marsh if the species *Triglochin maritima*, *Salicornia spp., Fucus ssp.* or *Ditschilis spicata* were present. A coring spot would be considered high marsh if it included *Plantago maritima, Deschampsia caespitosa, Grindelia integrifolia, Potentilla anserina, Glaux maritima,* or *Eleocharis ssp*. If a spot contained a mixture of these species, the majority percent cover of high or low marsh species was used to determine whether the spot was low or high marsh. *Carex lyngbyei* were often found throughout both strata and so were not considered unique to one zone. These designations are defined by the presence or absence of low marsh or high marsh vegetation-- particularly the high marsh plants *Grindelia integrifolia* and *Potentilla anserina*, which grow in a narrow elevation range in Clayoquot Sound (Jefferson 1973). The high marsh species' ranges align approximately with the mean extreme high-water line of estuarine marshes in Clayoquot Sound, while low marsh encompasses elevations between the mean lower high water and the mean extreme high-water lines (Jefferson 1973 as cited in Deur 2000; Weinmann et al. 1984). This method was groundtruthed using detrended correspondence analysis to verify that vegetation assemblages reflected distinct low and high marsh zones (Hill and Gauch 1980; see section 4.4.1).

Sediment cores were collected using a simple percussion coring technique in which a length of two-inch (57 mm) diameter, PVC vacuum tubing fitted with a plastic core catcher (AMS Inc.) was hammered into the ground until the depth of refusal. Depth of refusal (DoR) is considered a reasonable proxy for sampling to the maximum depth of organic accumulation (Fourqurean et al. 2014b). At one site (GBK) a steel sledge corer (AMS Inc.) was used to extract four cores, but mechanical problems required switching to the simpler method described above. All cores were stored upright between sampling until their return to the laboratory where they were photographed, logged, and stored under refrigeration at a Parks Canada laboratory in Vancouver, British Columbia.

2.3. Estimating Marsh Areas

ArcMap 10.3 tools were used with 50 x 50 cm resolution aerial orthophotos taken in July 2014 (Government of British Columbia) to obtain area estimates of high and low marsh zones. The difference between high marsh and low marsh was delineated by eye between darker-green, denser high marsh vegetation and lighter-green, salt-tolerant, and less-dense low marsh vegetation. This method was groundtruthed using the detrended correspondence analysis (e.g. Hill and Gauch 1980) of vegetation survey data and was found to accurately categorize 94 % of the cores into the correct marsh zone (see Discussion section 4.4.1).

2.4. Soil Carbon Density and Carbon Stocks

For each marsh, average carbon stocks (Mg C ha^{-1}) were estimated in each sediment core by first measuring the soil carbon density (SCD, g C cm^{-3}, Eq. (1)) on one-cm thick sample intervals over the length of each core. SCD is the mass of carbon found in a cubic centimetre of soil at a given depth and is the product of the organic carbon content % C and the dry bulk density (DBD):

$$SCD \left(\frac{g\ C}{cm^3}\right) = \left(\frac{\%C}{100}\right) \times DBD \tag{1}$$

where DBD represents the weight of one cc volume of soil that was dried for no less than 72 hours at 60°C.

Organic carbon content (%C) was estimated either using loss-on-ignition (LOI, Eq. (2)) or using CN Elemental and coulometric analysis (Froehlich 1980). An LOI test was performed on every 1 cm subsample by homogenizing samples with a mortar and pestle, combusting them at 550°C for four hours, weighing, and combusting again at 1000°C for two hours (Heiri et al. 2001). The percentage mass loss-on-ignition (%LOI) was estimated as:

$$\% \text{LOI} = (DW_i - DW_f)/DW_i * 100 \tag{2}$$

where DW_i is initial dry weight and DW_f is the dry weight after burning. The %C was also estimated by measuring total carbon (%TC) and inorganic carbon (%IC) on a

subset of 93 samples. %TC was measured on these homogenized subsamples using dry combustion elemental analysis with an Elementar Elemental Analyzer for CN analysis at the University of British Columbia's Department of Earth, Ocean, and Atmospheric Sciences. The same subsamples were then analyzed for %IC using a UIC CM5014 CO_2 coulometer connected to a UIC CM5130 acidification module in the Climate, Oceans, and Paleo-Environments (COPE) laboratory at Simon Fraser University. Measurements of %IC were subtracted from the %TC measurements to estimate %C (Hodgson and Spooner 2016; Hedges and Stern 1984; Schumacher 2002; Howard et al. 2014). Inorganic carbon was negligible in all 93 of the subsamples analysed (max: 0.015 %) and assumed to be zero for all carbon calculation purposes. The relationship between %LOI and %C for these 93 samples was then used to convert %LOI to %C for all sediment samples (Eq. (3), see Appendix A, Figure A1):

$$\%C = 0.44(\%LOI) - 1.80 \tag{3}$$

Next, the carbon stock of a core was estimated from the sum of all 1-cm intervals in each core (Eq 4):

$$C\ stock_{core}(g\ C\ cm^{-2}) = \sum_{i=0}^{n} SCD_i \times 1\ cm \tag{4}$$

Where i = the depth of the top of a 1-cm subsection in cm, n = the depth of the top of the deepest subsection of the core (cm), and SCD_i = the SCD of each subsection i in grams C cm^{-3}.

Carbon stocks were calculated both in megagrams per hectare (Mg C ha^{-1}) -- the typical unit used in carbon stock assessment (Fourqurean et al. 2014a) -- and in total Mg C for high and low marsh to compare the estimates for each marsh zone.

First, to calculate the average carbon stock for all marshes in megagrams C per hectare, all core C stock estimates were averaged across each marsh and scaled up:

$$C\ stock_{Marsh}(Mg\ C\ ha^{-1}) = \left(\frac{1}{x} \times \sum_{i=1}^{x} C\ stock_{core} \right) \tag{5}$$

Where x = the number of cores in a marsh.

A Kruskal-Wallis test of significance for sample groups of unequal variances was used to test for significant differences between *C stock$_{Marsh}$* (Mg C ha^{-1}) between the seven marshes studied. Lastly, the Clayoquot Sound average C stock, *C stock$_{CS,}$* was computed by averaging the C stock$_{marsh}$ estimates from all seven marshes.

Characteristics for low and high marshes were estimated and compared, including total C stock, DBD, %C, SCD, and DoR (Welch's t test). Lastly, the total C stock for low marsh *C stock$_{LowCS}$* was estimated by averaging each site's low marsh core C stock estimates and multiplying by the total estimated low marsh area in Clayoquot Sound. The same was done to estimate the total high marsh C stock, *C stock$_{HighCS}$*.

2.5.   Carbon Accumulation Rate

Carbon accumulation rates (CARs) were estimated in five cores from the CBE, CRF, GBK (2), and TMF sites, by multiplying the sediment accumulation rates (SAR) by the SCD (Eq. (6)):

$$CAR \left(\frac{g\ C}{m^2 yr}\right) = SAR \left(\frac{m}{yr}\right) \times SCD \left(\frac{g\ C}{m^3}\right) \qquad (6)$$

SARs were calculated from age models determined using ^{210}Pb dating. Subsamples from each of the five cores were dated using Polonium-210 alpha counting by Core Scientific International (Winnipeg, Canada) and MyCore Scientific (Dunrobin, Canada). Using a constant rate of supply model, age-depth models were constructed, and SARs estimated (Oldfield and Appleby 1984; Rowan et al. 1994; see Appendix B). Some core compaction (maximum 40 %) occurred during the coring process, which would affect our estimated accumulation rates. We corrected for this compaction by applying a correction factor for each core (Eq. (7)):

$$correction\ factor = \frac{recovered\ core\ length\ (cm)}{length\ of\ core\ penetration\ (cm)} \qquad (7)$$

and used it to find the uncompacted depth (Eq. 8)) of any given subsample (Fourqurean et al. 2014a):

$$uncompacted\ depth = \ sample\ depth\ (cm)\ \times correction\ factor\ (8)$$

The uncompacted depths were used only to calculate SAR (cm yr^{-1}), which was then used to calculate CAR (see equation 6).

The regional average CAR in from Clayoquot Sound, CAR_{CS}, was calculated as the average of all five cores with ^{210}Pb dating. The total CAR for a marsh with a dated core was calculated by multiplying the high marsh core CAR times the high marsh area. Low marsh CAR for each site used the one low marsh dated core multiplied by the site's low marsh area. Regional average CAR for the high and low marsh zones specifically were estimated using the average of the four, ^{210}Pb dated high marsh cores to represent the high marsh and the one low marsh core to represent the low marsh zone.

Chapter 3.   Results

3.1. Soil Properties

Depths of refusal ranged from five cm in the low marsh of SWC to a maximum of 60 cm in the high marsh of CBE. With few exceptions, marsh soils in Clayoquot Sound consisted of three layers separated by defined horizons: topsoil, peat, and sand/clay layers. In all cores, organic carbon concentrations were highest in the surface layers (10-45 %) and decreased to lowest values (~ 2 %) in the deepest parts of the cores (Figure 2). Topsoil layers ranged between two and 18 cm in depth, with moisture content above ~80 % by mass and a typical, wet Munsell of 10YR 2/1. Topsoil had the lowest average DBD (0.16 ± 0.11 g cm^{-3}) and highest average %C (28.0 ± 8.2 %). Second, peat layers were found between two and 31 cm depth, with intermediate moisture content and a typical wet Munsell of 10YR 3/3 or 10YR 3/4. Peat layers had an intermediate average DBD (0.29 ± 0.23 g cm^{-3}) and %C (19.1 ± 10.2 %). Finally, sand and clay layers near the DoR had highest average DBD (0.83 ± 0.22 g cm^{-3}) and lowest average %C (2.4 ± 2.7 %C). Both the sand and clay had the lowest moisture content and typical wet Munsell of GLEY 2/N or GLEY 3/N.

Soil carbon densities averaged 0.037 ± 0.17 g C cm^{-3} for all sites, and site-wide average SCDs ranged from 0.020 to 0.055 g C cm^{-3} (Table 1). With few exceptions, SCDs remained relatively constant in the upper parts of the cores and decreased towards the base of the cores where lowest % C values were encountered (Figure 3).
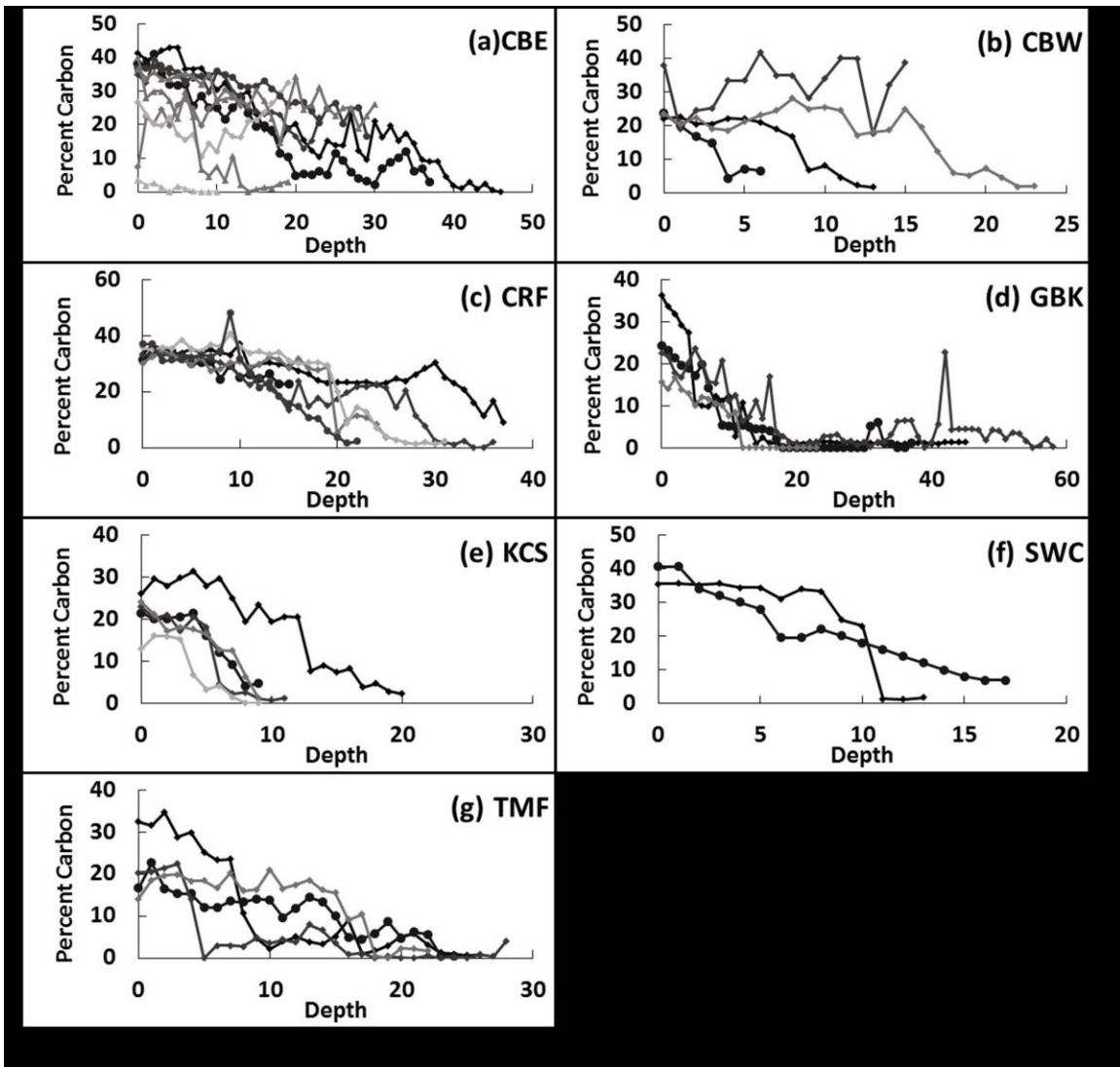
Figure 2 Percent Carbon (vertical axis) by depth in centimetres (horizontal axis) for all cores, divided by site. Lightest grey cores are closest to the shoreline while darkest grey cores are furthest.
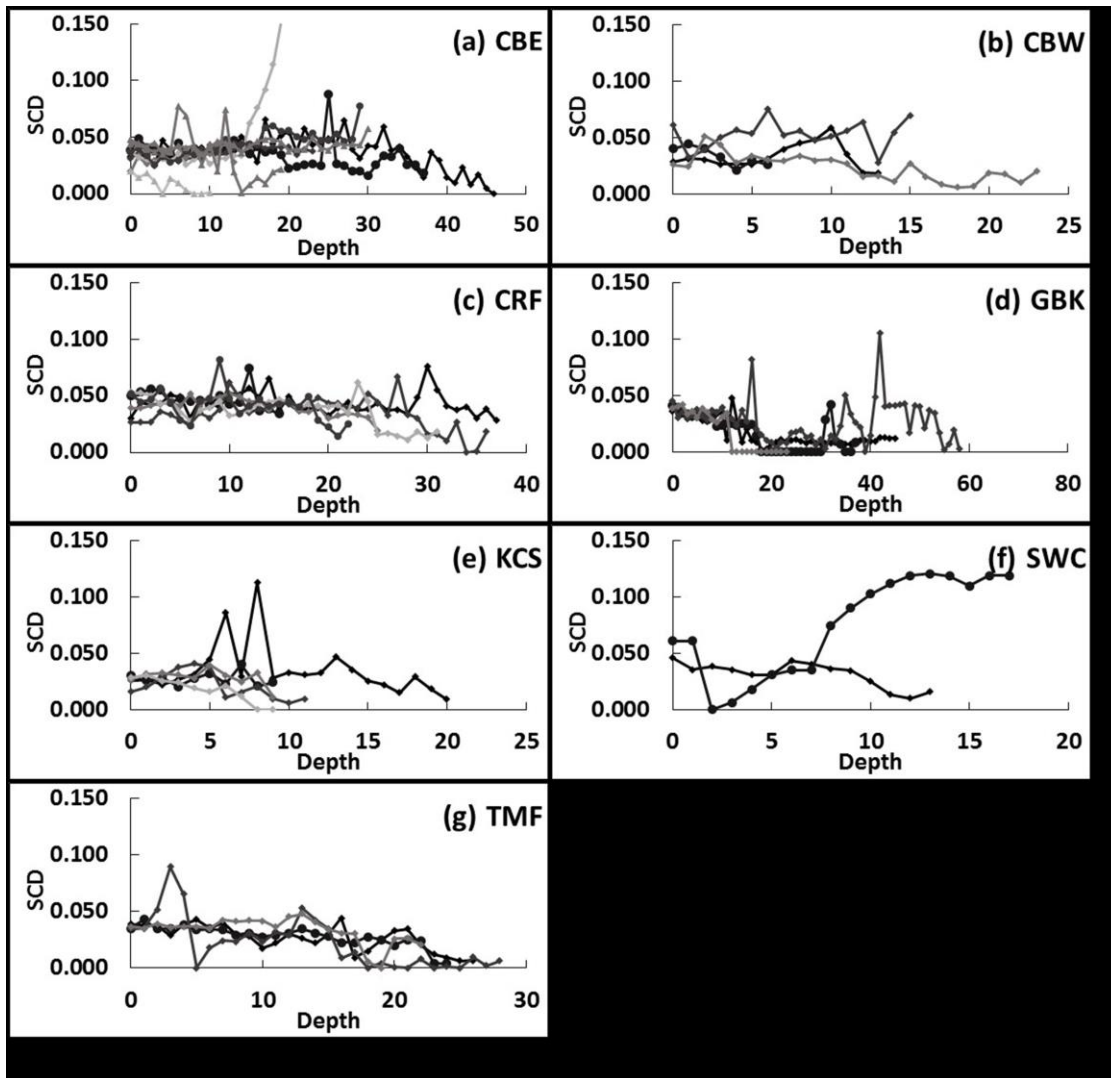
Figure 3 Soil Carbon Density in grams C cm-3 (vertical axis) by depth in centimetres (horizontal axis) for all cores, divided by site. Lightest grey cores are closest to the shoreline while darkest grey cores are furthest.

Table 1 Core information for samples from Clayoquot Sound.

Site, Core ID	Latitude (49.--- ° N)	Longitude (125.--- ° W)	Marsh stratum (High, Low)	Ave DBD (g cm^{-3})	Ave %C	Ave SCD (g C cm^{-3})	Depth (cm)	C Stock Estimate (Mg C ha^{-1})
			Grice Bay Kootowis Creek					
GBK 1-1	.08754	.73238	High	0.64 ± 0.28	6.1 ± 9.8	0.016 ± 0.011	46	73.0
GBK 1-2	.08756	.73261	High	0.67 ± 0.35	5.9 ± 7.8	0.016 ± 0.015	60	60.8
GBK 1-3	.08763	.73271	High	0.68 ± 0.32	6.7 ± 7.2	0.027 ± 0.019	59	158
GBK 1-4	.08771	.73283	Low	0.66 ± 0.37	6.0 ± 6.4	0.017 ± 0.017	24	41.6
Average ± SD	NA	NA	NA	0.66 ± 0.32	6.3 ± 8.0	0.020 ± 0.017	47.3 ± 16.8	83.3 ± 51.4
			Cannery Bay West					
CBW 1-1	.14115	.66983	High	0.40 ± 0.34	15.0 ± 8.3	0.033 ± 0.011	16	46.7
CBW 1-2	.14115	.66982	Low	0.31 ± 0.12	13.4 ± 7.4	0.033 ± 0.003	7	23.5
CBW 1-3	.14113	.66962	Low	0.17 ± 0.01	32.3 ± 7.4	0.053 ± 0.012	16	84.9
CBW 1-4	.14112	.66955	High	0.19 ± 0.20	17.2 ± 8.3	0.023 ± 0.012	24	56.3
Average ± SD	NA	NA	NA	0.24 ± 0.22	20.2 ± 10.7	0.035 ± 0.016	15.8 ± 7.0	52.8 ± 25.4
			Cannery Bay East					
CBE 1-1	.14139	.66620	High	0.32 ± 0.26	19.8 ± 13.1	0.036 ± 0.014	47	169
CBE 1-2	.14142	.66629	High	0.31 ± 0.17	17.0 ± 11.9	0.034 ± 0.012	38	130
CBE 1-3	.14147	.66636	High	0.15 ± 0.06	28.3 ± 7.7	0.038 ± 0.004	24	90.3
CBE 1-4	.14152	.66639	Low	0.15 ± 0.04	23.5 ± 5.6	0.035 ± 0.007	14	48.4
CBE 1-5	.14155	.66644	Low	0.23 ± 0.09	20.2 ± 5.7	0.048 ± 0.034	20	96.4
CBE 2-2	.14140	.66618	High	0.16 ± 0.08	30.3 ± 5.7	0.045 ± 0.011	30	133
CBE 2-3	.14142	.66614	High	0.16 ± 0.05	28.4 ± 5.4	0.043 ± 0.004	30	132
CBE 2-4	.14144	.66609	Low	0.53 ± 0.33	13.6 ± 13.2	0.035 ± 0.022	20	69.8
CBE 2-5	.14151	.66602	Low	0.95 ± 0.23	1.1 ± 1.2	0.008 ± 0.008	30	9.16
Average ± SD	NA	NA	NA	0.29 ± 0.26	21.5 ± 11.8	0.037 ± 0.017	28.1 ± 10.1	97.7 ± 49.7
			Cypress River Flats					
CRF 1-1	.27905	.90754	High	0.17 ± 0.05	26.9 ± 6.7	0.043 ± 0.010	38	163

CRF 1-2	.27896	.90758	Low	0.17 ± 0.04	28.7 ± 4.1	0.048 ± 0.009	16	76.1
CRF 2-1	.27935	.90932	High	0.34 ± 0.31	19.1 ± 11.0	0.034 ± 0.014	37	126
CRF 2-2	.27916	.90926	Low	0.20 ± 0.13	25.3 ± 9.8	0.040 ± 0.007	26	105
CRF 3-1	.27890	.91100	High	0.31 ± 0.29	23.9 ± 14.3	0.036 ± 0.013	32	117
CRF 3-2	.27882	.91087	Low	0.29 ± 0.27	23.3 ± 13.0	0.041 ± 0.014	23	94.8
Average ± SD	NA	NA	NA	0.25 ± 0.23	24.1 ± 10.9	0.040 ± 0.012	28.7 ± 8.6	113 ± 30.0
Kennedy Cove South								
KCS 1-1	.13696	.67082	High	0.28 ± 0.20	17.9 ± 10.5	0.035 ± 0.023	24	73.5
KCS 1-2	.13707	.67085	High	0.25 ± 0.17	15.0 ± 6.9	0.027 ± 0.006	14	27.4
KCS 1-3	.13714	.67093	High	0.42 ± 0.32	11.1 ± 9.5	0.021 ± 0.012	16	25.6
KCS 1-4	.13719	.67096	High	0.30 ± 0.27	14.7 ± 6.8	0.029 ± 0.009	10	29
KCS 1-5	.13720	.67107	Low	0.51 ± 0.39	7.6 ± 6.8	0.018 ± 0.011	10	17.8
Average ± SD	NA	NA	NA	0.34 ± 0.28	14.0 ± 9.3	0.027 ± 0.017	14.8 ± 5.8	34.6 ± 22.1
Shipwreck Cove								
SWC 1-1	.12995	.69943	High	0.30 ± 0.37	25.8 ± 13.8	0.031 ± 0.011	29	43.9
SWC 2-1	.13014	.69908	High	0.60 ± 0.59	21.0 ± 10.1	0.074 ± 0.044	18	133
Average ± SD	NA	NA	NA	0.47 ± 0.52	23.1 ± 12.3	0.055 ± 0.040	23.5 ± 7.8	88.6 ± 63.3
Tofino Mud Flats								
TMF 1-1	.13014	.88689	High	0.54 ± 0.32	11.0 ± 12.0	0.027 ± 0.012	27	72.0
TMF 1-2	.13020	.88688	Low	0.33 ± 0.16	10.6 ± 5.4	0.028 ± 0.009	26	70.5
TMF 2-1	.12989	.88661	High	0.72 ± 0.35	5.2 ± 7.2	0.022 ± 0.023	28	64.2
TMF 2-2	.13017	.88665	Low	0.43 ± 0.38	13.5 ± 7.1	0.033 ± 0.012	27	76.8
Average ± SD	NA	NA	NA	0.52 ± 0.34	9.9 ± 8.8	0.027 ± 0.015	27.0 ± 0.8	70.9 ± 5.2
REGION AVERAGE ± SD	NA	NA	NA	0.39 ± 0.33	17.0 ± 12.4	0.037 ± 0.017	26.6 ± 12.7	80.6 ± 43.8

3.2. Carbon Storage and Marsh Area

The seven marshes ranged in size from 0.51 to 27.42 ha, with a total area of 46.93 ha (Table 2). The high marsh made up 19-63% of each individual marsh and 58% (27.39 of 46.94 ha) of the seven marshes we sampled.

The average C $stock_{CS}$ for the seven salt marshes is 80.6 ± 43.8 Mg C ha^{-1}, ranging from 34.6 ± 22.1 Mg C ha^{-1} at KCS to 113 ± 30 Mg C ha^{-1} at CRF (Table 1). The average C $stock_{LowCS}$ is 53.8 ± 23.0 Mg C ha^{-1}, based on 16 cores from the low marsh zone. The average C $stock_{HighCS}$ is 94.9 ± 28.0 Mg C ha^{-1}, based on 18 cores (Table 2; Figure 5). Using our estimates of marsh area, we calculate that C $stock_{CS}$ is 4709 ± 136 Mg C, 70 % of which is stored in the high marsh.

Table 2 Marsh area, carbon stocks, and accumulation rates.

Site	Marsh Area (ha)			Carbon Stock per hectare (Mg C ha^{-1})		Marsh Carbon Stock (Mg C)			Carbon Accumulation Rate			
									Per unit area (g C m^{-2} yr^{-1})		Per marsh (Mg C yr^{-1})	
	Low Marsh	High Marsh	Total	Low Marsh	High Marsh	Low Marsh	High Marsh	Total	Low Marsh	High Marsh	Low Marsh	High Marsh
Cannery Bay East	2.57	1.42	4	55.9	131	144	187	331 ± 46.3	-	264	-	10.6
Cannery Bay West	0.23	0.27	0.51	35.1	70.6	8.18	19.3	27.5 ± 26.0	-	-	-	
Cypress River Flats	10.11	17.31	27.42	92	135	930	2340	3270 ± 28.5	-	156	-	42.8
Grice Bay-Kootowis Creek	4.79	6.9	11.69	41.6	97.3	199	671	870 ± 67.3	37	198	1.72	13.7
Kennedy Cove South	0.32	0.47	0.78	25	73.5	7.93	34.4	42.3 ± 73.7	-	-	-	
Shipwreck Cove	0.83	0.2	1.02	53.6	88.7	44.3	17.6	61.8 ± 69.5	-	-	-	
Tofino Mud Flats	0.69	0.82	1.51	73.7	68.1	51.1	55.7	107 ± 7.08	-	75	-	1.13
AVERAGE	-	-	-	53.8 ± 23.0	94.9 ± 28.0	-	-	-	37	173 ± 79	-	-
SUM	19.54	27.39	46.93	-	-	1385	3321	**4709 ± 136**	-	**-**	54.78	

Totals may not match exactly due to rounding.

3.3. Carbon Accumulation Rates

Carbon accumulation rates averaged 146 ± 102 g C m^{-2} yr^{-1} at the four sites from which ^{210}Pb dating was completed. The low marsh core at GBK had the lowest CAR of 37 g C m^{-2} yr^{-1}. CAR in the four high marsh cores ranged from 75 g C m^{-2} yr^{-1} at TMF to 264 g C m^{-2} yr^{-1} at CBE (Figure 5). The SAR ranged from 0.142 cm yr^{-1} at the GBK low marsh to 1.322 cm yr^{-1} at GBK high marsh (Table 3).

Using the CAR from GBK's low marsh as the proxy for all low marsh CAR and the average of the four high marsh cores to estimate the high marsh CAR, we estimate that CAR$_{CS}$ is 54.78 ± 22.58 Mg C yr^{-1}. Of this, the 19.54 ha of low marsh accumulate 7.18 ± 6.24 Mg C yr^{-1}, and the 27.39 ha of high marsh accumulate 47.6 ± 21.7 Mg C yr^{-1}. Approximately 87 % of the total, annual CAR is in the high marsh, while this area represents only 58% of the total marsh area.

Table 3 Maximum corrected depth of excess ^{210}Pb activity in centimetres, Age at max ^{210}Pb depth in years, average vertical, linear sediment accumulation rate in centimetres per year, average mass accumulation rate in grams per square centimetre per year, and carbon accumulation rate in grams of organic carbon per square meter per year for cores from four different sites.

Core ID	Maximum Uncompacted Depth of ^{210}Pb Activity (cm)	Age at Max ^{210}Pb Depth (yr before June 2016)	Average Sediment Accumulation Rate (cm yr^{-1})	Average Mass Accumulation Rate (g cm^{-2} yr^{-1})	Carbon Accumulation Rate (g C m^{-2} yr^{-1})
CBE 1-1 (High Marsh)	48.81	113.8	0.757 ± 0.187	0.0731 ± 0.019	264
GBK 1-2 (High Marsh)	45.00	81.9	1.322 ± 0.462	0.251 ± 0.038	198
GBK 1-4 (Low Marsh)	9.41	135.54	0.142 ± 0.084	0.0312 ± 0.014	37
TMF 2-1 (High Marsh)	17.71	81.9	0.360 ± 0.161	0.214 ± 0.025	75
CRF 2-1 (High Marsh)	34.46	83.8	0.460 ± 0.197	0.066 ± 0.008	156
Average	31.08	99.4	0.725 ± 0.432	0.151 ± 0.095	146 ± 102

Compaction factor for GBK 1-4 is average of the other 3 from GBK because hole depth was not measured due to infilling after the corer was withdrawn. No significant difference in CAR was found when using the minimum (0 %) and maximum (40 %) compaction from other cores ($p > 0.05$).

3.4. Comparisons between marshes and strata

C $stock_{HighCS}$ is significantly higher than C $stock_{LowCS}$ ($p < 0.05$). This is largely attributable to differences in the DoR between high and low marshes (Figure 5). While the average DoR of high marsh cores is significantly higher than the average DoR of low marsh cores ($p < 0.05$), no significant differences were found between average DBD, average % C, or a core's average SCD in high versus low marsh cores ($p > 0.05$) (Figure 5).

The Kruskal-Wallis test found significant differences between each of the seven C $stock_{Marsh}$ estimates ($p < 0.05$; K = 12.67). This result shows that each of the marsh average carbon stock estimates vary enough from one another that a single site average cannot be assumed to represent the average carbon stocks of all marshes in the region.
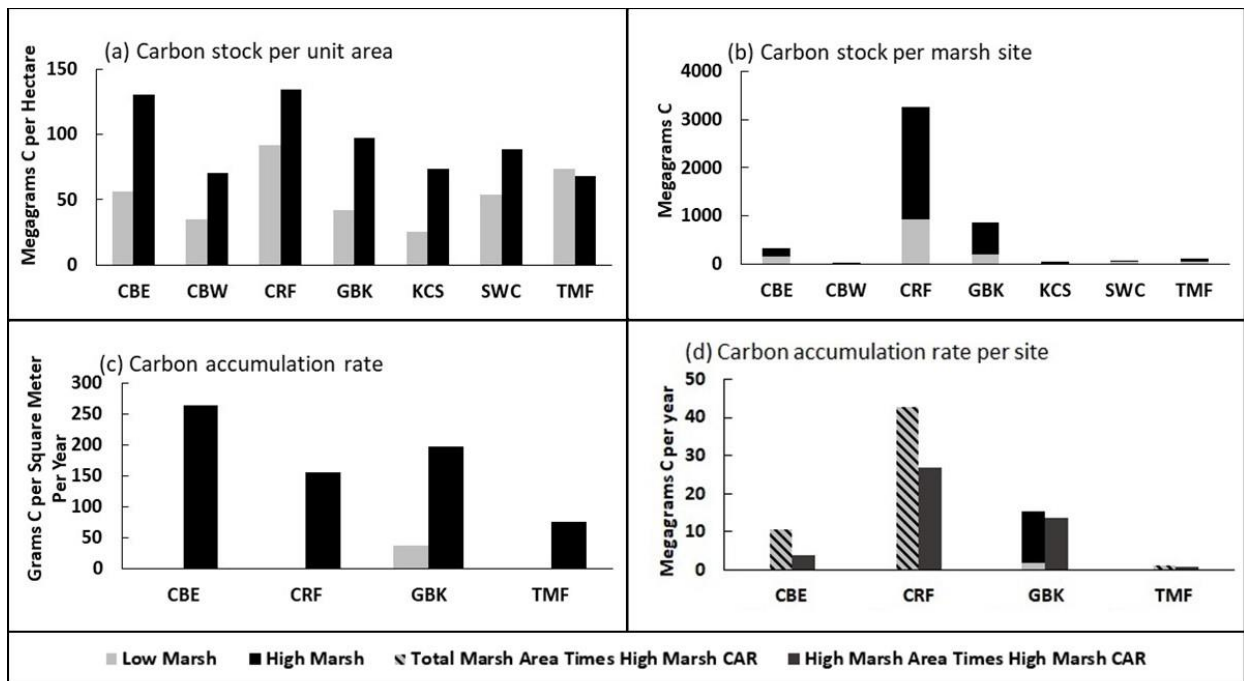
Figure 4 Carbon stocks and accumulation rates from Clayoquot Sound: (a) stock per hectare (Mg); (b) stock per marsh site (Mg C); (c) Carbon accumulation rates; (d) Annual carbon accumulation for each marsh zone and as contributions to total. In Figure 4(d), known high marsh and low marsh CAR are used to calculate the total, annual CAR for GBK. For the other sites, the high marsh CAR is extrapolated to the entire marsh area (crosshatched column) and calculated only for the high marsh area (dark gray).
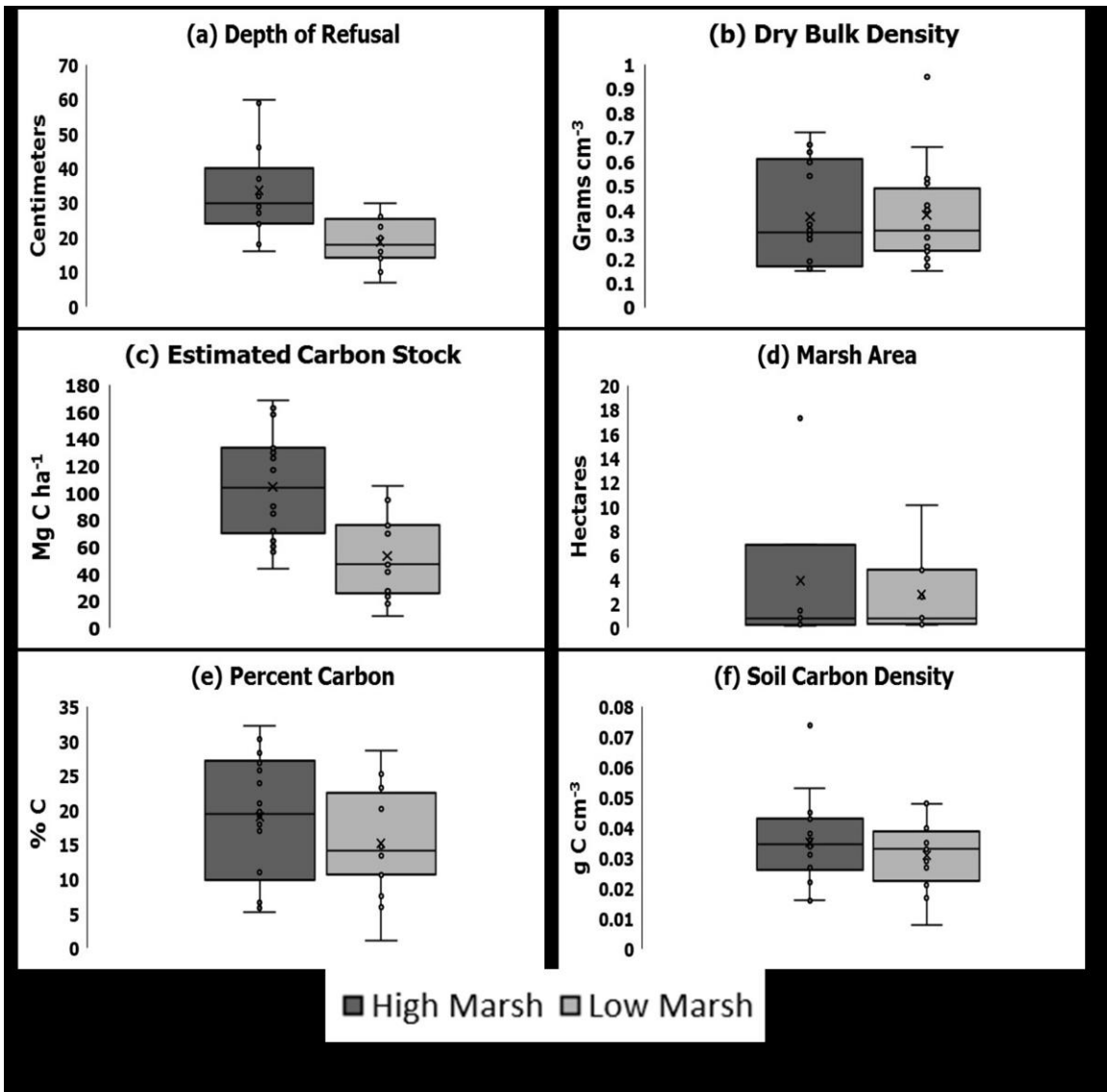
Figure 5 Comparison of high marsh and low marsh soil characteristics across all cores in Clayoquot Sound. Only DoR and carbon stock estimates were significantly different (Welch's t test, p < 0.05). high marsh n=18, low marsh n=16 (graphs a, b, c, e, & f). For graph (d), n=7 marshes.

Chapter 4.   Discussion

4.1. Carbon Stocks- Comparisons

The *C stock$_{CS}$* averaged 80.6 ± 43.8 Mg C ha^{-1}, which is roughly half the global estimate for the top meter of salt marsh soils of 162 Mg C ha^{-1} (Duarte et al. 2013). These global estimates are computed from samples to a depth of one m, while cores from Clayoquot Sound averaged 26.7 cm to DoR. While additional carbon might be stored in deeper, fossil layers below the DOR in Clayoquot Sound marshes, such as in a layer of paleosols buried by tsunami deposits approximately 300 years ago (Clague and Bobrowsky 1994), the large reduction in %C observed at or near the DoR suggests that the majority of soil carbon is found above the DoR.

The shallower depth of accumulation, as approximated by DoR, is likely the main driver of the lower carbon stocks of Clayoquot Sound marshes compared with the global average. The Clayoquot Sound stocks are comparable to those of three natural marsh sites in Everett, Washington, USA, which range from 71.7 to 98.5 Mg C ha^{-1} (Crooks et al. 2014). This region experiences a similar climate to Clayoquot Sound and lies within the same latitude band. Likewise, carbon stocks from marshes in Everett are estimated for the top 30 cm of the marsh soils, which is comparable to the average DoR of 26.7 cm at Clayoquot Sound. At the same time, the 0.037 g C cm^{-3} average SCD of Clayoquot Sound is close to the average of 0.030 g C cm^{-3} calculated from eight National Estuarine Research Reserves in the United States, which includes a site in San Francisco Bay with median SCD of approximately 0.040 g C cm^{-3} (Grimes and Smith 2016). Thus, the carbon stocks in Clayoquot Sound are lower than global averages because high-carbon soil accumulation occurs over depths substantially shallower than one meter.

4.2. Carbon Accumulation Rates- World Comparisons

While the Clayoquot Sound regional average CAR of 146 g C m^{-2} yr^{-1} appears lower than the global average of 245 g C m^{-2} yr^{-1}, this difference is not statistically significant (Welch's t-test, $p > 0.05$). Clayoquot Sound's average CAR is also comparable to CAR estimates from both its latitude band and the other sites within its biogeographical region. Even though Clayoquot Sound's CAR appears lower than the

estimate of 315 g C m^{-2} yr^{-1} calculated for the latitude range 48.4-58.4° N (Ouyang and Lee 2014), this difference is not statistically significant, most likely due to the high variability within this latitude range (SEM ± 62.9 g C m^{-2} yr^{-1}). The median value for the 48.4-58.4° N range (153.5 g C m^{-2} yr^{-1}) is comparable to Clayoquot Sound's average CAR. The latitudinal average appears to be inflated by two high CAR estimates of 793 and 1133 g C m^{-2} yr^{-1} (Andrews et al. 2008). At the same time, the average Clayoquot Sound CAR is also not significantly different (Welch's t test, p < 0.05) from the NE Pacific average of 174 g C m^{-2} yr^{-1} (SEM ± 45.1 g C m^{-2} yr^{-1}), which were estimated from eight data points in California, USA (Ouyang and Lee 2014). These results both underscore that while there is site-to-site variability in CAR, on the scale of 10-degree latitude bands or biogeographical region, Clayoquot Sound's average CAR is close to expected values for its region and its latitude.

The average CARs from Clayoquot Sound are also not significantly different from the average CARs for the Atlantic coast of North America or Northern Europe (Welch's t test, p > 0.05). This includes the NW Atlantic region (172.2 g C m^{-2} yr^{-1}; n=64; 35.0-47.4 °N), and the subset of the NW Atlantic region in Atlantic Canada which is closer in latitude to Clayoquot Sound (188 g C m^{-2} yr^{-1}; n=40; 43.6-47.4 °N) (Ouyang and Lee 2014). While the northern European salt marshes have a higher average CAR (315.2 g C m^{-2} yr^{-1}; n=20; 51.5-55.5 °N) (Ouyang and Lee 2014), this difference is also not a statistically significant difference due to high variability. The North European salt marsh average consists entirely of the same sites as the global estimate for the 48.4-58.4° N range, a result of the unequal geographic distribution of CAR datasets. Therefore, this N. European dataset is biased high by the same outliers as the 48.4-58.4° N dataset mentioned above.

4.3. ^{210}Pb and ^{137}Cs Dating

Clayoquot Sound's average CAR is slightly- but not significantly- lower than the other regions of North America and its latitude band, and some of this difference may be attributable to the method used to measure sediment accumulation rate. Previous researchers have argued that using ^{137}Cs dating to establish age models can result in elevated SARs, and therefore also CARs that are biased high (Johannessen and MacDonald 2016). This overestimation can be a point of concern when making global estimates of salt marsh CAR because the dating method may artificially elevate

estimated carbon sequestration potential. All of the accumulation rates from the NE Pacific, NW Atlantic, and the 48.4-58.4 °N latitude band in the Ouyang and Lee (2014) compilation except for three of the 64 in the NW Atlantic were generated using either ^{137}Cs dating or a marker horizon method.

This inflation can occur because ^{137}Cs dating relies on comparing radionuclide concentrations down the core in relation to the peak atmospheric concentration in 1963, which can result in overestimates due to post-depositional soil turbation (Johannessen and MacDonald 2016). Marker horizons can also be subjected to the same post-depositional soil turbation. Dating methods using ^{137}Cs have been shown to produce slightly - but not significantly- higher CAR estimates in salt marsh CAR estimates, with CAR calculated with ^{210}Pb an average of 26 % lower (SAR 29 % lower) than the same sites dated using ^{137}Cs (Callaway et al. 2012). Because of this potential bias toward higher CAR estimates and the statistical outliers affecting the average CAR from the 48.4-58.4 °N dataset, the Clayoquot Sound CAR is likely close to the true average for both the 48.4-58.4° N latitude range and the NE Pacific biogeographical region.
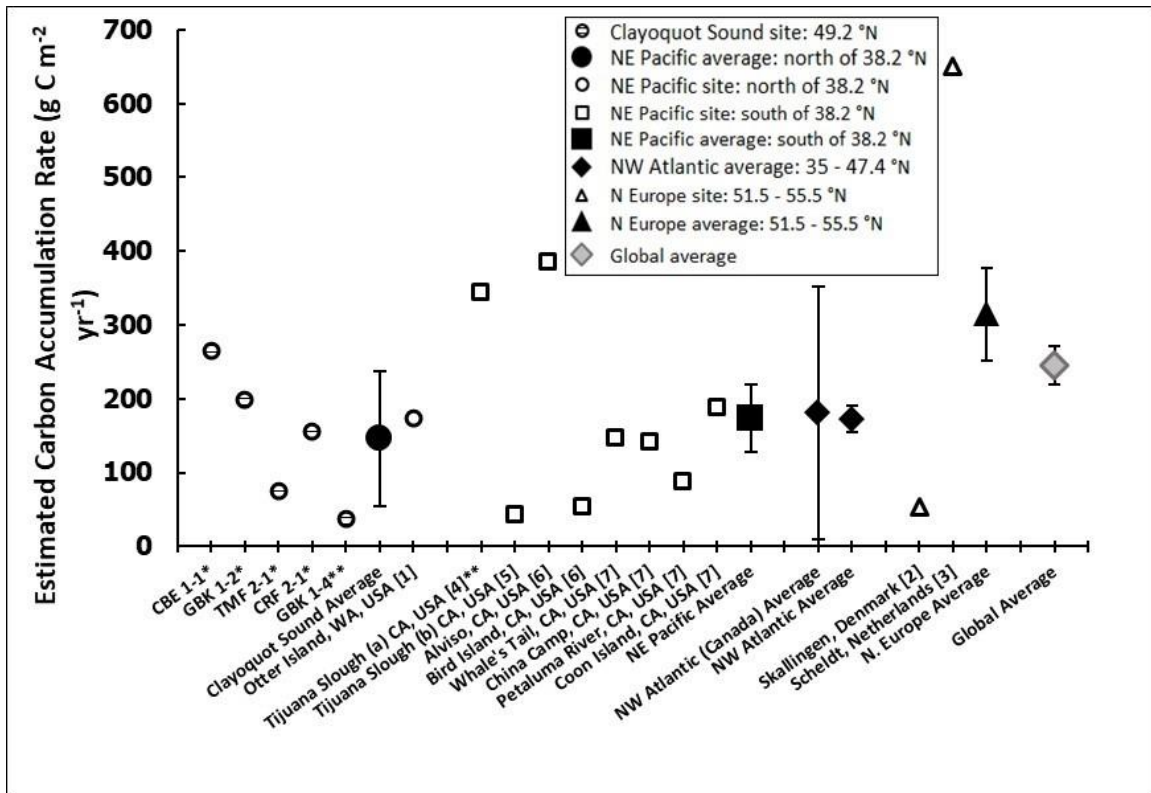
Figure 6 Comparison of Clayoquot Sound CAR with other salt marsh studies compiled by Ouyang and Lee (2014) grouped by regions as defined by that study.

All eight available data points from the NE Pacific region south of 38.2 °N are shown; North Europe data points are the minimum (Skallingen, Denmark) and maximum of that dataset (Scheldt, Netherlands). Data from single sites are unfilled shapes, while filled-in shapes represent averages. *= high marsh; **= low marsh; No asterisks= not specified.

[1] Crooks et al. 2014; [2] Callaway et al. 1996; [3] Oenema and Delaune 1988; [4] Cahoon et al. 1996; [5] Chmura et al. 2003; [6] Patrick and Delaune 1990; [7] Callaway et al. 2012. All regional averages aside Clayoquot Sound's, global average, and region definitions from Ouyang and Lee 2014.

The CAR results we obtained are likely applicable to mesotidal (tidal range 2-4 m; Kirwan and Gunterspergen 2010) estuarine and pocket marshes throughout the west coast of Vancouver Island and potentially throughout the coast of British Columbia. This could include an area of up to 60 square kilometers (Ryder et al. 2007). Additionally, the organic carbon values we encountered in peat and sand (ranging from 0-48 %C) layers are similar to those found in previous studies of paleosediments in salt marshes both

within Pacific Rim National Park Reserve and from the Ucluelet peninsula approximately 30 km to the south (ranging from 12-62 %C) (Clague and Bobrowsky 1994), suggesting that soil carbon content in British Columbia salt marshes does not vary substantially over short distances.

4.4. Uncertainties

4.4.1. Low Marsh CAR

Our low marsh core exhibits anomalously low CAR, however a single core does not posses sufficient statistical power to draw conclusions about differences between average low and high marsh CAR in Clayoquot Sound. While previous studies have found that low marsh CARs are consistently higher than CARs from high marsh areas (Adams et al. 2012; Callaway et al. 1996; Connor et al. 2001; Elsey-Quirk et al. 2011), our results show that CARs were significantly *lower* in the low marsh at GBK when compared with the high marsh at GBK, and with the high marsh cores from the other sites. A power analysis showed that at least nine total cores measured for CAR would be required to confidently compare the means of low marsh and high marsh cores. This was beyond the resources of our study, but future studies should consider this to investigate whether the low marsh CAR in Clayoquot Sound is consistently lower. Evidence from past studies suggests that organic sediment accumulation drives marsh accretion, and that this biomass accumulation would be greater in the high marsh than the low marsh. Marsh soil accretion is the result of both organic deposition and inorganic sediment supply, and the relative contribution of each can vary over time (Drexler 2011). A study from the US Pacific Northwest found a strong relationship between marsh standing biomass and soil carbon (Thom 1992). Additionally, a study of Louisiana salt marshes found that sediment accumulation varied with organic sediment input but not with inorganic input (Nyman et al. 2006). These both suggest that low marshes may experience higher inorganic sediment input, but the CAR would be lower because accretion would be driven by low-carbon, inorganic sediment.

Falling relative sea level (RSL) in Clayoquot Sound may influence marsh accretion dynamics in a way that has yet to be studied and would require additional work to quantify. Low marshes accumulate inorganic sediment primarily from tidal inundation, as particles fall out of suspension in the water or become trapped by the roots of low

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marsh vegetation (e.g. Connor et al. 2001). Salt marshes thus accumulate vertically in response to rising sea levels (Morris et al. 2002). The tide gauge at Tofino has measured a steadily falling relative sea level since observations began in 1905 (NOAA 2013a), which is most likely a consequence of tectonic uplift in the region (Mazzotti et al. 2008). Therefore, the mechanism of vertical accretion may be different from that observed in marshes experiencing rising sea level.

Lastly, the low marsh core's low CAR could simply be the product of small-scale variability of SAR and CAR due to variables we could not control. Previous studies of marsh accretion dynamics have demonstrated variability in SAR on scales as small as one meter due to such influences as recent ecological disturbance (Webb et al. 2013), water table height and soil drainage (Craft 2007), and variable mineral sediment deposition from freshwater drainage (Callaway et al. 2012).

4.4.2. Marsh Areas and Vegetation Survey

Some inaccuracy was expected when ground-truthing the area estimation method using vegetation survey, but this was minor. This approach to differentiating high and low marsh matched with vegetation data for 32 of 34 (94 %) of cores. Both CRF 1-2 and CRF 2-2 were classified as low marsh by vegetation survey but fell within the high marsh using the visual orthophotography method. These cores lie 16 m (CRF 1-2) and 12 m (CRF 2-2) away from the boundary with low marsh as measured using orthophotos, which is less than their distances from the nearest high marsh cores (17 m and 23 m, respectively). All other cores fell within the correct marsh zone.

A detrended correspondence analysis (Hill and Gauch 1980) of the accuracy of vegetation data showed a reasonably accurate fit of low marsh cores with low marsh vegetation and high marsh cores with high marsh vegetation, plus the addition of a somewhat indistinct, third cluster of vegetation possibly representing the backshore. The classification of marsh strata by presence/absence and percent cover of low marsh or high marsh vegetation was groundtruthed using Canoco v4.5 software. This square root-transformed model accounted for 33.2% of all variance in the vegetation dataset (sum of eigenvalues = 3.29). Cores with low marsh vegetation clustered together while high marsh cores clustered separately. An additional, slightly distinct third cluster of backshore vegetation indicates that some high marsh cores may have been extracted

from close to the boundary with a freshwater-dominated backshore or salt-tolerant meadow. The distinction between a salt marsh and a bordering freshwater area has complicated efforts to classify marshes by salinity (Duarte et al. 2013), but this result shows that clustering of vegetation type corresponds reasonably well with each site's designation as high or low marsh (Figure 7). Additional work could clarify this high marsh-backshore boundary with greater precision (See recommendations section).

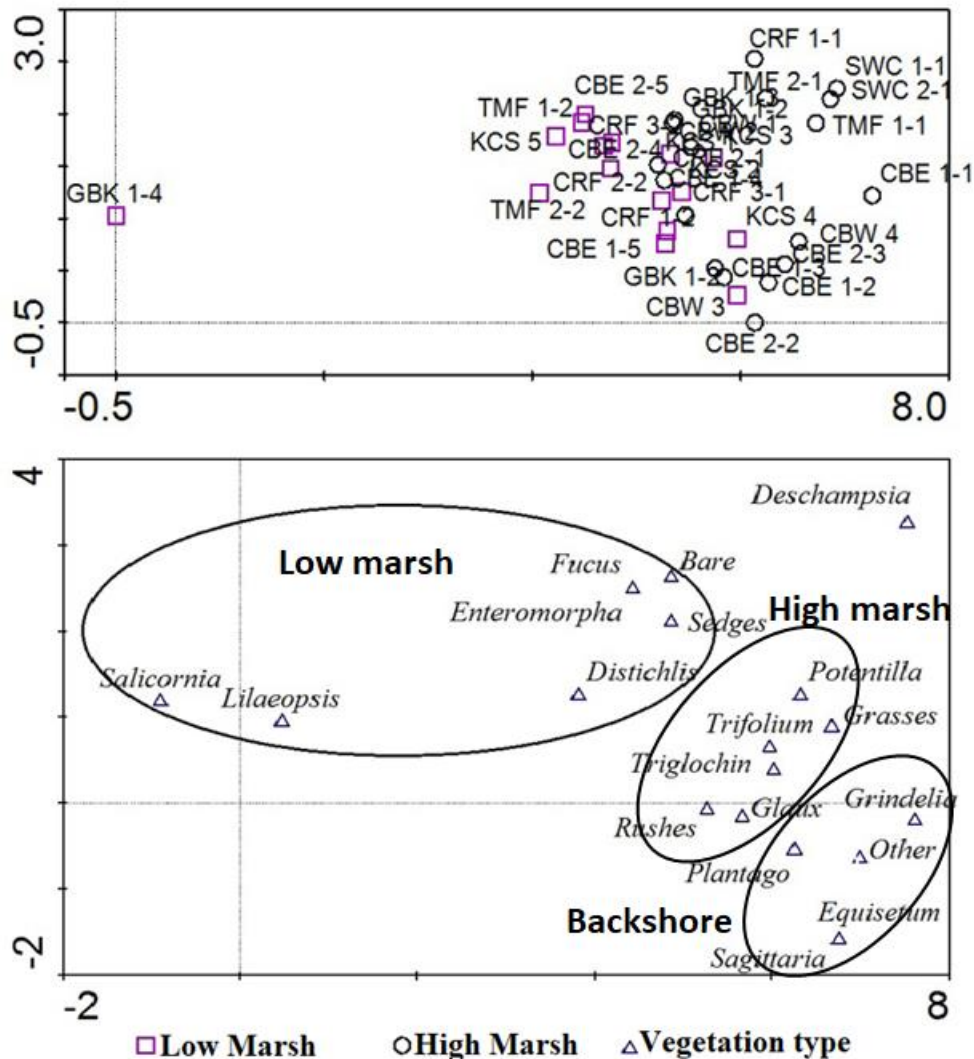**Figure 7 Detrended correspondence analysis results for Marsh vegetation data.** Low marsh cores (top, purple squares) corresponded reasonably well with vegetation identified as low marsh, and high marsh cores corresponded with a distinct cluster of high marsh vegetation The far bottom-right may indicate a population of less salt-tolerant, backshore vegetation but it is indistinct from the high marsh.

4.4.3. Identifying Measurement uncertainties

This study produced qualitative estimates of carbon stocks and accumulation rates using surface area and inferred depth as a proxy for the total volume of soil carbon stocks. These estimates are reasonably reliable but should not be considered a comprehensive account of carbon stocks, but rather a summary estimate of inferred carbon stock and accumulation rates based on the 34 samples recovered. This is true of both our overall estimates and our comparisons between high and low marsh. For example, a sufficiently powerful number of cores for statistical comparisons between high and low marsh SCD is 135, which was beyond the means of this study.

SCD estimates were the main source of uncertainty for carbon calculations. While SCD was not estimated with a high degree of power, the significant difference in high and low marsh core depths was estimated with power approaching 1. This was most likely due to the relatively small differences in both DBD and %C between low and high marsh. While a much larger number of cores would be required to confirm if any significant difference exists between low and high marsh SCD, the difference in low marsh and high marsh core depths can be interpreted with a high degree of confidence.

C stock$_{core}$ and accumulation rate values reported here include uncertainty propagation because each core's carbon stock was computed from uncertain SCD values and CAR were computed from SCD and uncertain, core-average SAR values. In turn, each C stock$_{marsh}$ average also includes uncertainty propagation, as do the regional averages estimated for both stocks and accumulation rates.

Several other factors of the calculation of carbon stock and accumulation rate estimates contributed to the uncertainties in calculated values: avoiding channels and ditches while sampling, the accuracy of the method used for marsh area estimates (see section 4.4.2), and the relationship between %TC and %LOI (see Appendix A).

Avoiding ditches and channels likely biased our carbon stock estimates slightly high by roughly 5 %, however this is difficult to quantify. Vegetation survey data shows an overall average of 5 ± 9 % coverage classified as "bare" without vegetation, however this varied substantially between cores (ranging from 0 % to 30 % bare). Using

unvegetated surface area as a rough estimate for the surface area of channels is not ideal, as in some places, particularly the low marsh, bare spots without vegetation were still covered with organic accumulation.

Lastly, the calculated relationship between %LOI and %TC relied upon a strong relationship between %LOI and %TC as measured by elemental analyzer (r^2 =0.97), which is a minor source of potential uncertainty. Measuring soil C by %LOI alone tends to overestimate because some compounds other than carbon, as well as structural water in clay minerals are volatilized at high temperatures (Schumacher 2002). This method produced a small amount of uncertainty, but the strength of the linear relationship between the measured %LOI and calculated %C quantities shows that this was minimal.

4.5. Implications

4.5.1. Blue Carbon vs. Boreal Forest for Climate Mitigation in Canada

The carbon storage potential of blue carbon ecosystems such as the salt marshes of Clayoquot Sound have been touted as a reason to conserve marshes against future degradation as part of a climate change mitigation strategy (Canadell and Raupach 2008). Blue carbon ecosystems have been argued to accumulate and store carbon at rates several times higher than terrestrial forests per unit area (McLeod et al. 2011). Conservation of blue carbon ecosystems such as Canada's salt marshes presents an opportunity not only to protect a significant carbon stock but also to ensure that these marshes continue to accumulate significant amounts of carbon. Given the tremendous importance of saltmarshes as fish habitat, nursery areas, and coastal buffer zone, carbon storage is an excellent co-benefit to other management activities.

Total soil C stocks per unit area from Clayoquot Sound salt marshes are lower than those of boreal forests. Clayoquot Sound salt marsh soil C stocks average 80.6 Mg C ha^{-1}, which is similar to the approximately 80 Mg C ha^{-1} estimated for Canada's boreal forest (Kurz et al. 2013). However, this estimate does not include the other C stock pools in forests, such as aboveground biomass; the soil pool is estimated to account for only 40 % of total forest carbon. This estimate for soil C stock also does not include organic

material on the ground such as leaf litter, which, when included, brings the total soil C stock estimate up to 123 Mg C ha^{-1}.

However, salt marsh carbon accumulation rates are substantially higher per hectare. Boreal forest soils are estimated to accumulate 4.6 ± 2.1 g C m^{-2} yr^{-1} globally (Zehetner 2010 as cited in McLeod et al. 2011), while Clayoquot Sound marshes accumulate 146 ± 102 g C m^{-2} yr^{-1}. Canada's boreal forest is estimated at 270 million hectares in area (Kurz et al. 2013), and total marsh area in Canada is approximately 44,000 ha (Bridgham et al. 2006). If the CAR estimate from Clayoquot Sound is assumed to approximate the average for all tidal salt marshes in Canada (see section 4.2 for comparison with Eastern Canada marsh sites), Canada's marshes accumulate between 19,400-109,100 Mg C yr^{-1}. Assuming the global estimate represents Canadian boreal forests, the boreal forest accumulates 6,750,000-18,090,000 Mg C annually. Therefore, salt marshes accumulate 0.1 % as much carbon in 0.016 % as much land area; even a conservative estimate of Canadian salt marsh CAR shows CAR one order of magnitude higher than Canada's boreal forest, per unit area. This higher CAR is similar to previous studies comparing blue carbon with terrestrial forests (McLeod et al. 2011).

4.5.2. Ecosystem Services and Carbon Valuation

Conserving blue carbon habitats for climate mitigation purposes could be incentivized through the use of a price on carbon, which would place a monetary value on managing blue carbon. Two examples of this type of approach are (a) a system modifying British Columbia's existing carbon tax to pay dividends to landowners incentivizing conservation of high carbon-accumulating ecosystems, and (b) incorporating blue carbon into voluntary carbon markets.

The first option is to price blue carbon conservation based on the British Columbia carbon tax. This approach values carbon more highly but may require a greater amount of political willpower to implement. Presently, the carbon tax charges $30 per ton of CO_2 equivalent emissions (Government of British Columbia 2017). Using the ratio of 3.67 tons CO_2 per ton of C, this study's estimate of 4709 tons of C would result in approximately 17,280 tons CO_2 equivalent if it were all to be lost as CO_2, with a total value of $518,400 over a study area of approximately 47 hectares. This places the

total value of the carbon stored in all seven study sites at approximately $11,000 per hectare. Additionally, the total carbon sequestration across all seven study sites amounts to 54.3 additional tons of C per year, the equivalent of slightly less than 200 tons CO_2. If the value of this annual carbon sequestration was paid in dividends based on BC's current carbon tax rate, the seven marshes in sum would sequester $6000 worth of CO_2 equivalent per year, or about $160 per hectare per year. The primary benefit of this dividend system would be to align the economic incentives of local landowners and caretakers with larger-scale political ambitions to mitigate climate change. This would most likely require political willpower to implement because of its centralized structure with relatively few direct beneficiaries, but the urgency of action on climate change may allow an opportunity.

Such a "climate dividend" system has been piloted on small scales elsewhere in the world (e.g. Herr et al. 2015) as a potentially significant opportunity for isolated, rural, or otherwise economically disadvantaged communities living in or near blue carbon ecosystems. For example, the Socio Bosque program in Ecuador uses a similar model of payment for ecosystem services to incentivize local conservation of forests including mangroves. These payments are managed through the UN's Reduce Emissions through Deforestation and Degradation (REDD) program. While thus far the payments average $3 per hectare, this price does not yet include the full value of carbon accumulated by the forest reserves (Herr et al. 2015). A similar project in Madagascar has secured management rights for indigenous people to sustainably manage a 10,000-ha area of mangroves for carbon credits.

The second option is to open BC's blue carbon resources to the voluntary carbon market. In a voluntary carbon market, emission offset credits are traded amongst entities wishing to reduce their share of greenhouse gas emissions to fit under a "cap" of total emission credits set by legislation at the provincial, national, or international level. The price of an emissions offset (equivalent to 1-ton CO_2 equivalent of emissions) would be free to vary with the market and therefore subject to change.

Carbon markets would be more politically feasible to implement than the carbon dividend approach, however carbon markets have been shown to undervalue the true cost of carbon. For example, a carbon credit cost $13.50 on California's market in early 2017 (Bear 2017), while the US Environmental Protection Agency estimated that the true

cost of a ton of CO_2 to society is $42 per ton CO_2, as of 2015 (Environmental Protection Agency 2015). Nevertheless, creating a voluntary carbon market would be more politically feasible than distributing carbon tax revenue to land conservators, because it would not involve the redistribution of government resources to specific constituencies.

Regulatory frameworks should be implemented to encourage the monetary valuation of carbon sequestration as a co-benefit to the other wetlands ecosystem services (Howard et al. 2017), because the value of blue carbon by itself is not especially high when compared with the monetary values of other salt marsh ecosystem services. Additionally, the relatively small area of salt marshes, both in Canada and in Clayoquot Sound, limits their potential for climate mitigation. Even with a price on carbon, the benefit of conserving blue carbon alone is relatively small- $11,000 per hectare. Rather, the high carbon sequestration potential of blue carbon ecosystems is one of the several important ecosystem services provided by coastal wetlands. For comparison, the storm protection ecosystem services alone provided by coastal wetlands have an average estimated value of $8,240 USD ha^{-1} yr^{-1} (Costanza et al. 2008). In addition to this, Breaux et al. (1995) estimate that the capitalized value of water purification from salt marshes can reach up to $15,000 USD ha^{-1} when compared with artificial water treatment. Habitat for recreational fishing is estimated to be worth $2,420 ha^{-1} (Bell 1997). The commercial salmon fishery relies upon salt marsh habitat for juvenile salmon. While estimates of the per-hectare value of this ecosystem service are difficult due to the complex nature of salmon's use of estuarine ecosystems during their lifecycle, the total Pacific commercial salmon catch in 2015 had an estimated wholesale value of $172 million (Government of British Columbia 2015). The habitat provided by salt marshes is a vital part of this major economic sector

Methane emissions from freshwater wetlands have a significant impact on the GHG balance of these carbon-sequestering habitats, and properly accounting for the methane flux from wetlands is vital to valuing their climate regulation services accurately. Marshes with salinity between 5-18 emit enough methane in CO2 equivalent units to offset part of the CO_2 equivalent value of carbon sequestration (Poffenbarger et al. 2011), while marshes with salinity >18 can be assumed to represent net carbon sinks with no significant methane emissions (Poffenbarger et al. 2011).Freshwater wetlands emit methane due to metabolic activity from methanogenic bacteria in the soil, but these

bacteria are outcompeted by sulphate-reducing bacteria in saline soils, negating their methane emissions (Bartlett et al. 1987).

We endeavored to select sites with low salinities but could not verify the salinity of every site with precision and chose instead to focus solely on soil carbon stock and sequestration. The soil salinity of marshes in Clayoquot Sound are likely similar to known surface water salinity measured offshore near several sites. These measurements—taken in late May 2016 after a three-week period of low rainfall-- range from 5.9, in Kennedy Cove approximately 100 m northwest of KCS (Postlethwaite et al. 2016, submitted) to 24 in Grice Bay near GBK.).

4.6. Recommendations

Further research into Clayoquot Sound carbon stocks and CAR can address the shortcomings of this study and inform future carbon dividend or offset policies. We recommend the following topics as research priorities for future work to quantify carbon in Clayoquot Sound:

1. Groundtruthing area estimates and marsh strata designations with a statistically powerful number of absolute elevation measurements

2. Collecting a greater number of dated cores from the low marsh to investigate differences between low marsh and high marsh CAR

3. Measuring methane emissions throughout the marsh using gas collection chambers, which could both quantify the GHG balance of salt marshes and assess the reliability of salinity as a proxy for methane emissions in the region.

Measuring absolute elevation using surveying equipment such as a tripod-mounted level with a stadia rod would permit more precise groundtruthing of marsh area estimates and the designation of high and low marsh strata. Using measurements of absolute elevation would permit the definitions of high and low marsh strata to be directly related to their tidal inundation exposure. Results of these data, in turn, would provide a much more precise way to estimate the surface areas of high and low marsh, and to delineate the boundary between the high marsh and the backshore.

As stated in section 4.4.1, a greater number of low marsh cores would be required to establish a statistical difference in CAR between low and high marsh with confidence, so a future research plan wishing to investigate this should incorporate a larger number of dated cores for CAR analysis. The minimum number required would be 9 cores, based on the variability of other factors involved in computing CAR, but low marsh cores should be dated alongside a high marsh core from the same marsh or transect. This would help to control for site-specific factors affecting CAR. This work could also be compared against similar studies from areas of rising relative sea level to investigate the way marshes might respond to the falling sea level in Clayoquot Sound.

Lastly, quantifying methane emission from salt marshes is an important final step for determining the viability of carbon dividends or offset credits trading. This would require periodic, direct measurement of methane emissions from a number of sites in the region because methane emissions can vary over both short and long time periods (Bridgham et al. 2013).

Relating these methane emissions to salinity measurements would also help to verify the strength of that relationship in marsh soils, especially because soil salinity is also likely to fluctuate substantially through time based on the seasonality of precipitation in Clayoquot Sound. 82 % of annual rainfall in Tofino falls between the months of October and April (Environment Canada, 1981-2010 averages), and soil salinity of marshes can vary by a factor of 10 through time (Bartlett et al. 1987). Quantifying salinity alongside methane would be vital for ensuring that carbon dividends or credits are not misallocated, and could also inform the use of salinity as a proxy in future blue carbon studies elsewhere in BC. This would help to avoid overvaluing of blue carbon's net soil carbon accumulation and, as a result, a net increase in anthropogenic carbon emissions resulting from implementing policy.

Chapter 5.   Conclusions

Our work provides estimates of soil carbon stocks and accumulation rates from salt marshes on the Pacific coast of Canada, addressing the data gap within North American blue carbon identified by the CEC. The results show that carbon stocks are lower than the global average but are close to values from Everett, USA nearby in the NE Pacific region. This lower carbon stock is most likely due to shallow depths of accumulation rather than any property of the soil itself. Soil CAR in Clayoquot Sound is also not significantly different ($p < 0.05$) from the global average, other studies in the NE Pacific region, the Atlantic coast of Canada, Northern Europe, and the 48.4-58.4 °N latitude band. This information should be of value for future first-order estimates of carbon in the northern part of the NE Pacific region, as it provides evidence that carbon stock and CAR are indistinguishable from other sites in this region as well as at similar latitude on the Atlantic coast.

We found lower carbon stock in the low marsh and an anomalously low CAR in the low marsh when compared with the high marsh, however we cannot determine if this CAR result is representative of the region's low marsh in general because it comes from only a single core. Soil properties such as SCD, DBD, and %C are not statistically different between marsh elevation zones. The anomalously low CAR may be due to chance because of small-scale variability in SAR, greater soil formation in the high marsh, or other region-specific factors such as a falling RSL may also influence CAR due to differences in vertical accretion dynamics within areas of emergent coastline.

While providing an important climate regulation ecosystem service, blue carbon alone does not provide a sufficient monetary incentive for marsh conservation, and should be regarded as a co-benefit of marsh conservation that seeks to preserve other, more valuable ecosystem services. Carbon storage in Clayoquot Sound marsh soils is valued at approximately \$11,000 ha^{-1} when estimated with the current British Columbia carbon tax, however this is only 43 % of the estimated per-hectare value of storm and erosion management, habitat for commercially important species, and ecotourism provided by salt marshes. Despite it's relatively low value, blue carbon ecosystems should be regarded as carbon accumulation 'hot spots,' and the value of their carbon accumulation should be factored into management decision-making.

Lastly, further investigation of groundtruthing methods for area estimates and high and low marsh designations would allow more precise calculations of carbon storage and accumulation in marshes. This knowledge, alongside greater understanding of any variability between high and low marsh CAR and understanding of methane emissions, would help to inform the role of blue carbon in both local ecosystem services management and the larger global carbon cycle.

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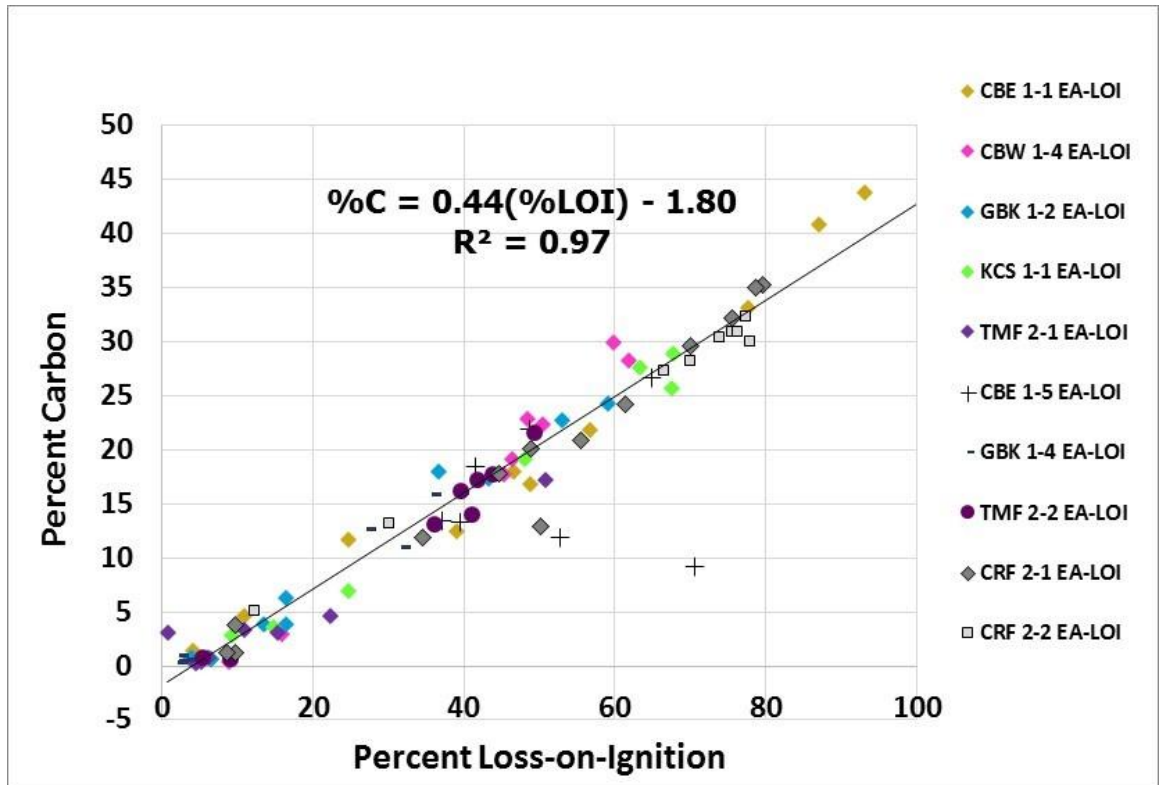
Appendix A

Figure 8 Relationship between measured LOI values and calculated %C, using elemental analyser EA data on set of 93 subsamples.
Measurements from core CBE 1-5 were not used for calculating this relationship due to suspected measurement error.

Appendix B 210Pb Dating Data

Table 4 ^{210}Pb data for core CBE 1-1.

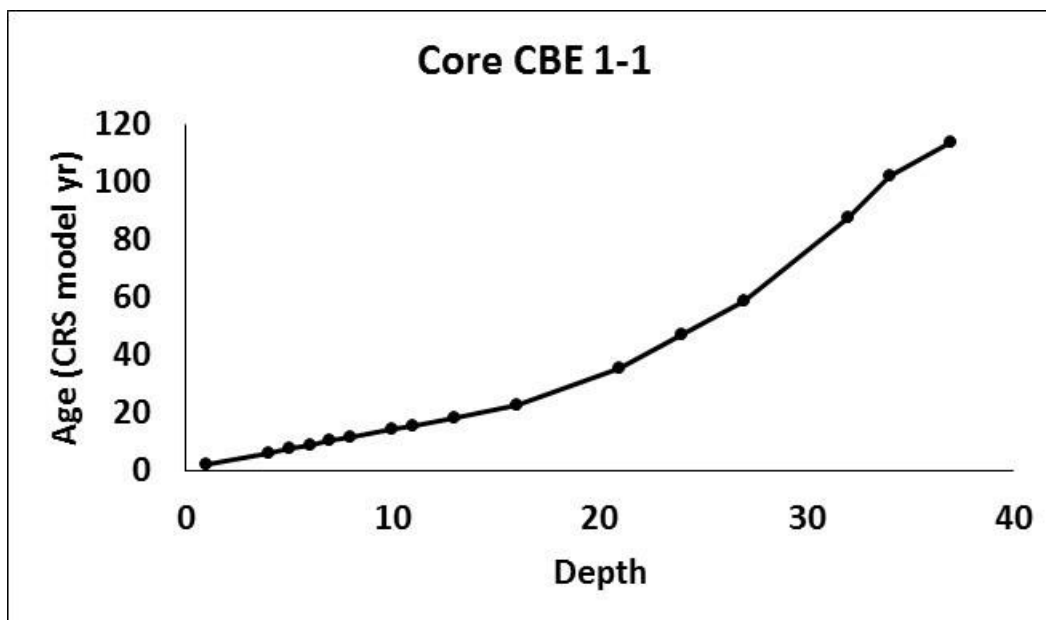| Sample ID	DBD (g cm^{-3})	Upper Depth (cm)	Lower Depth (cm)	Extrapolated Upper Section Depth (cm)	Extrapolated Lower Section Depth (cm)	Age at Bottom of Extrapolated Section (yr)	CRS Sediment Accumulation Rate (g cm^{-2} yr^{-1})
0+1	0.17	0	1	0	1	**2.1**	0.0795
4	0.11	1	4	1	4	**6.3**	0.076
5	0.09	4	5	4	5	**8**	0.0511
6	0.08	5	6	5	6	**9**	0.0719
7	0.1	6	7	6	7	**10.3**	0.0781
8	0.11	7	8	7	8	**11.6**	0.0806
10	0.12	8	10	8	10	**14.4**	0.0835
11	0.11	10	11	10	11	**15.7**	0.0887
13	0.11	11	13	11	13	**18.1**	0.0948
16	0.15	13	16	13	16	**22.7**	0.0963
21	0.24	16	21	16	21	**35.6**	0.0932
24	0.3	21	24	21	24	**47.4**	0.0755
27	0.28	24	27	24	27	**58.8**	0.0729
32	0.3	27	32	27	32	**87.9**	0.0518
34	0.24	32	34	32	34	**102.2**	0.0337
37	0.16	34	37	34	37	**113.8**	0.0411
42	0.78	37	42	37	42		
46	0.92	42	46	42	46		

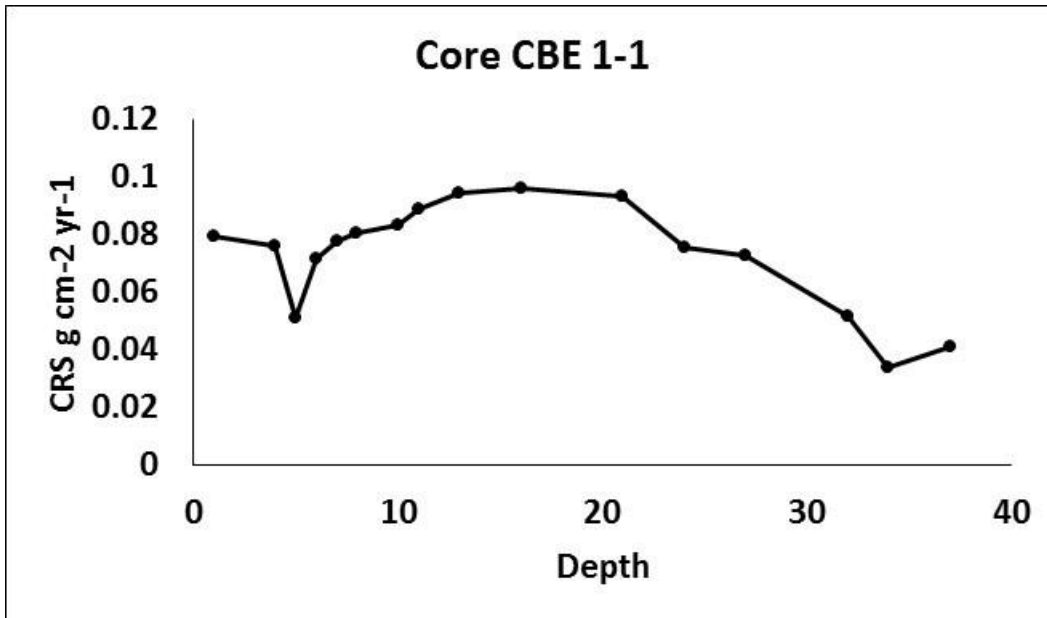**Figure 9 Core CBE 1-1 Age (yr) vs Depth (cm)**

Figure 10 Core CBE 1-1 Sediment Accumulation Rate (CRS g cm^{-2} yr^{-1}) vs Depth (cm)

Table 5 ^{210}Pb data for core CRF 2-1.

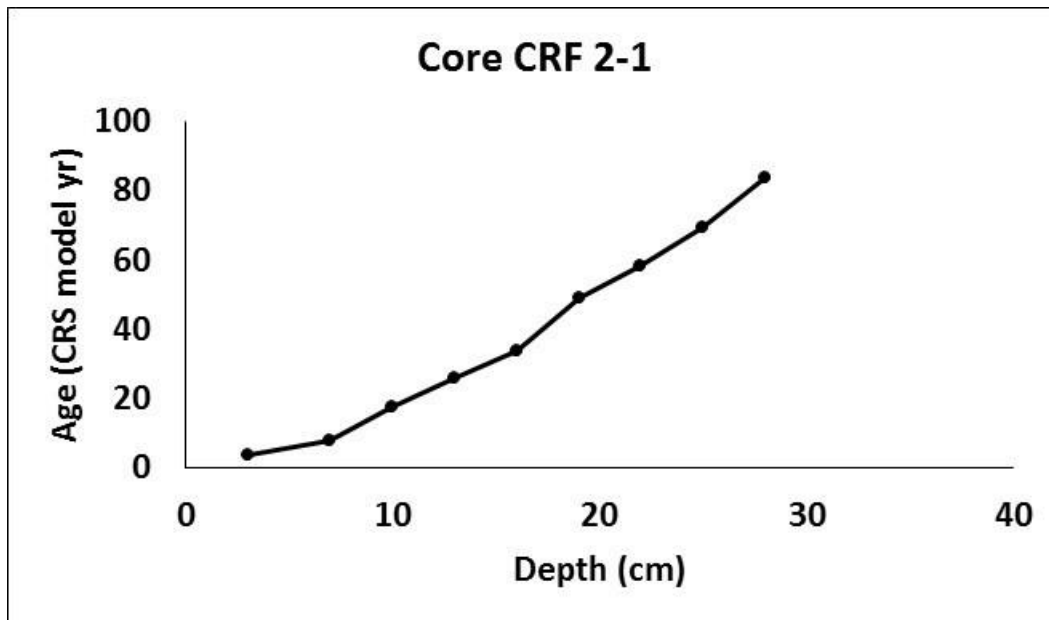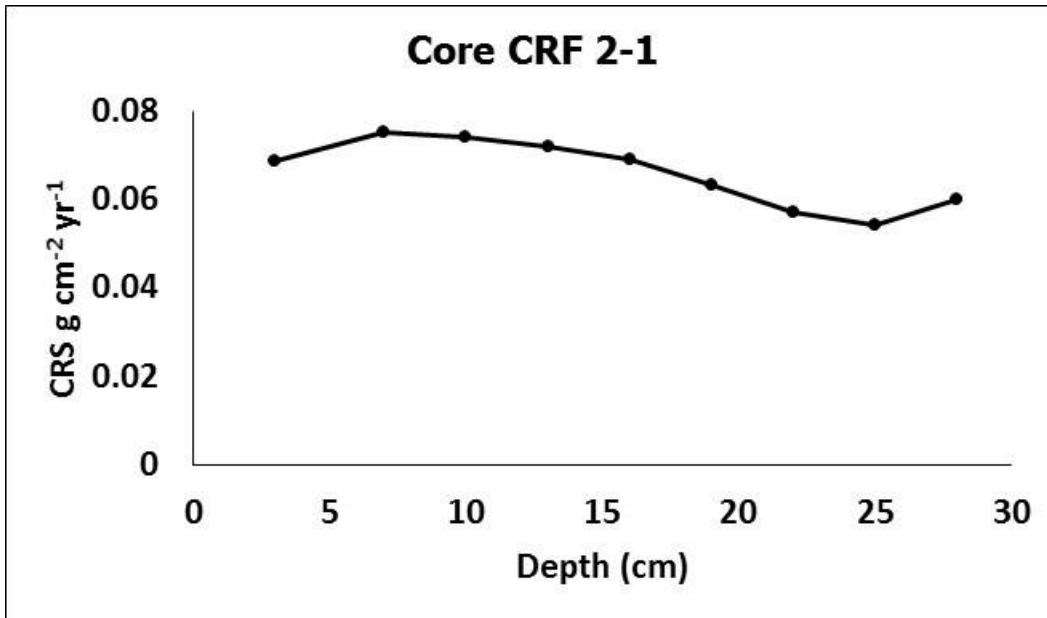| Sample ID	DBD (g cm^{-3})	Upper Depth (cm)	Lower Depth (cm)	Extrapolated Upper Section Depth (cm)	Extrapolated Lower Section Depth (cm)	Age at Bottom of Extrapolated Section (yr)	CRS Sediment Accumulation Rate (g cm^{-2} yr^{-1})
0+1+2	0.08	0	2	0	3	3.440742	0.0688
4+5+6	0.08	4	6	3	7	7.854617	0.0752
8+9+10	0.24	8	10	7	10	17.732	0.0744
13	0.18	10	13	10	13	25.74563	0.0721
16	0.18	13	16	13	16	33.75461	0.0691
19	0.32	16	19	16	19	48.95086	0.0632
22	0.18	19	22	19	22	58.15044	0.0572
25	0.21	22	25	22	25	69.56789	0.0544
28	0.29	25	28	25	28	83.7887	0.0602
31	0.91	28	31	28	31		
34	1.02	31	34	31	34		

Figure 11 Core CRF 2-1 Age (yr) vs Depth (cm)

Figure 12 Core CRF 2-1 Sediment Accumulation Rate (CRS g cm^{-2} yr^{-1}) vs Depth (cm)

Table 6 ^{210}Pb data for core GBK 1-2.

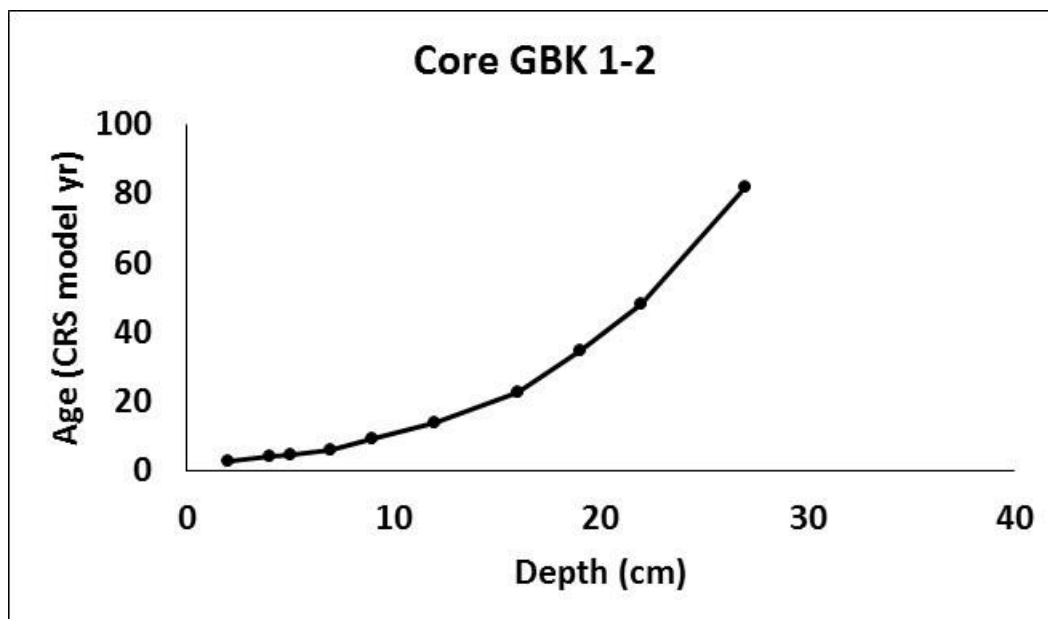| Sample ID	DBD (g cm^{-3})	Upper Depth (cm)	Lower Depth (cm)	Extrapolated Upper Section Depth (cm)	Extrapolated Lower Section Depth (cm)	Age at Bottom of Extrapolated Section (yr)	CRS Sediment Accumulation Rate (g cm^{-2} yr^{-1})
0+ 2	0.3275	0	2	0	2	2.559908	0.255869
4	0.173833	2	4	2	4	3.910491	0.25742
5	0.192733	4	5	4	5	4.635432	0.265861
7	0.2041	5	7	5	7	6.152198	0.260655
9	0.4064	7	9	7	9	9.037745	0.28168
12	0.455	9	12	9	12	13.80398	0.286389
16	0.5945	12	16	12	16	22.47162	0.274354
19	0.997333	16	19	16	19	34.68199	0.245038
22	1.0045	19	22	19	22	47.96489	0.226871
27	1.060833	22	27	22	27	81.87581	0.156415
33	0.8173	27	33	27	33		
37	0.818467	33	37	33	37		

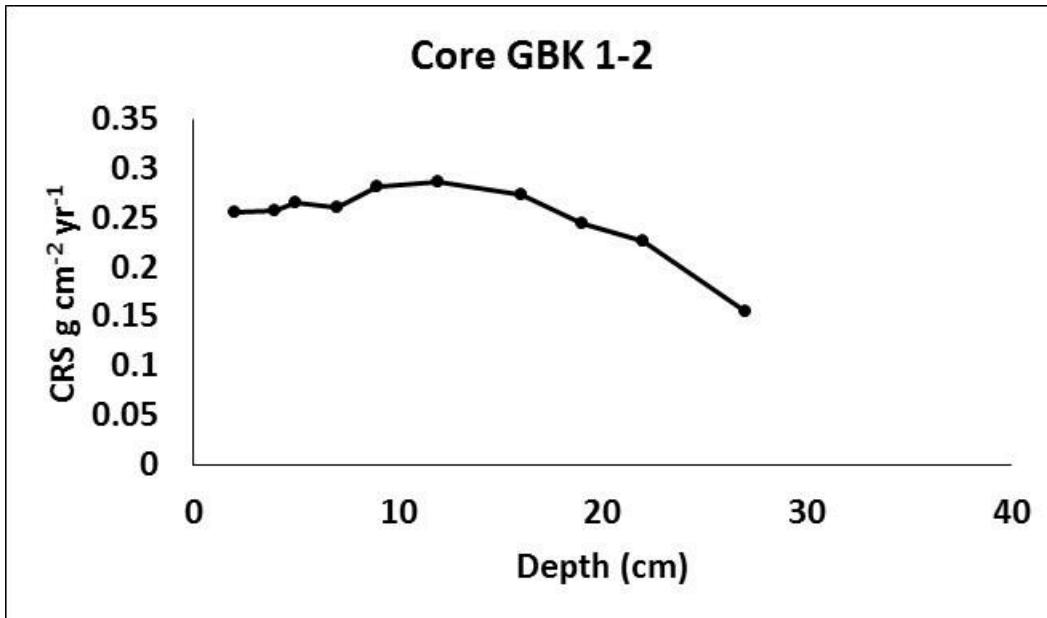**Figure 13 Core GBK 1-2 Age (yr) vs Depth (cm)**

Figure 14 Core GBK 1-2 Sediment Accumulation Rate (CRS g cm^{-2} yr^{-1}) vs Depth (cm).

Table 7 ^{210}Pb data for core GBK 1-4.

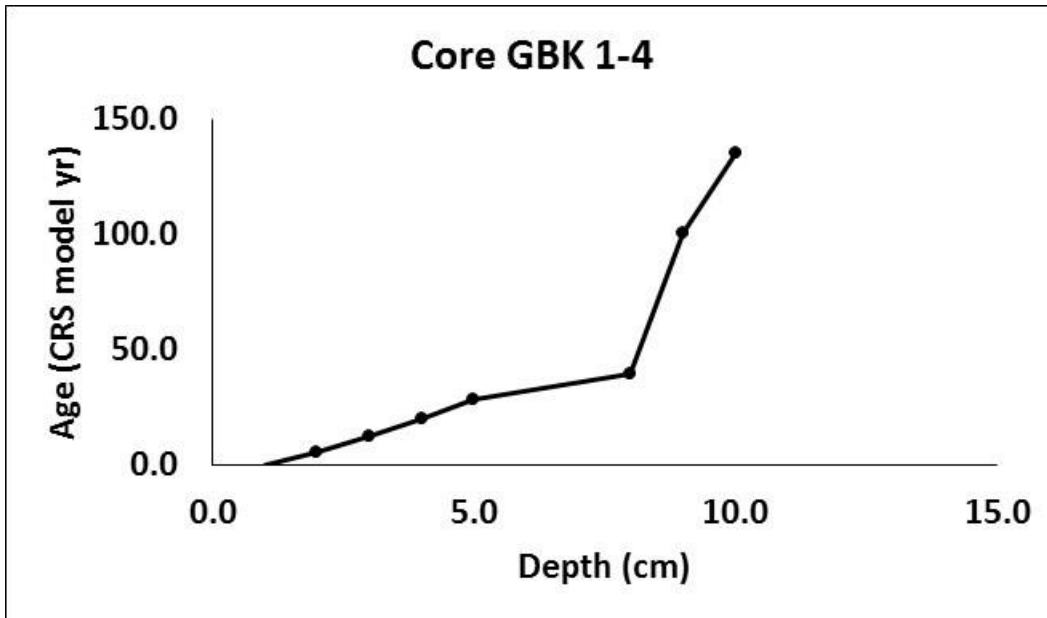| Sample ID	Depth of Top of Section (cm)	Depth of Bottom of Section (cm)	DBD (g cm^{-3})	Sediment Accumulation Rate (g cm^{-2} yr^{-1})	Age at top of section (yr)
"GBK 1-4 0cm"	0.0	1.0	0.254	0.050	0.0
	1.0	2.0	0.288	0.045	5
"GBK 1-4 2cm"	2.0	3.0	0.248	0.038	13
	3.0	4.0	0.240	0.033	20
"GBK 1-4 4cm"	4.0	5.0	0.283	0.030	28
	5.0	8.0	0.914	0.033	39
"GBK 1-4 8cm"	8.0	9.0	0.265	0.012	101
	9.0	10.0	0.260	0.008	136
"GBK 1-4 10cm"	10.0	11.0	0.411		
	11.0	12.0	0.413		
GBK 1-4 12cm"	12.0	13.0	0.944		
	13.0	14.0	1.120		
GBK 1-4 14cm"	14.0	15.0	0.990		
	15.0	16.0	1.055		
GBK 1-4 16cm"	16.0	17.0	1.028		
	17.0	18.0	0.999		
GBK 1-4 18cm"	18.0	19.0	0.974		
	19.0	20.0	1.067		
"GBK 1-4 20cm"	20.0	21.0	0.961		
	21.0	22.0	1.020		
"GBK 1-4 bottom"	22.0	23.0	1.023		
"GBK 1-4 bottom"	23.0	24.0	1.089		

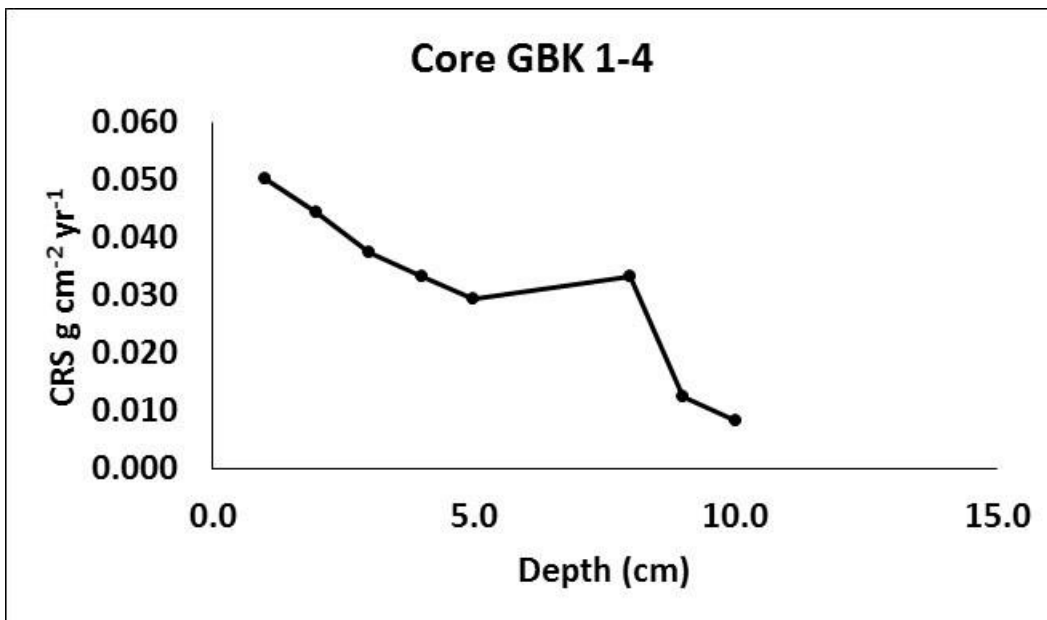**Figure 15 Core GBK 1-4 Age (yr) vs Depth (cm).**

Figure 16 Core GBK 1-4 Sediment Accumulation Rate (CRS g cm^{-2} yr^{-1}) vs Depth (cm)

Table 8 ^{210}Pb data for core TMF 2-1.

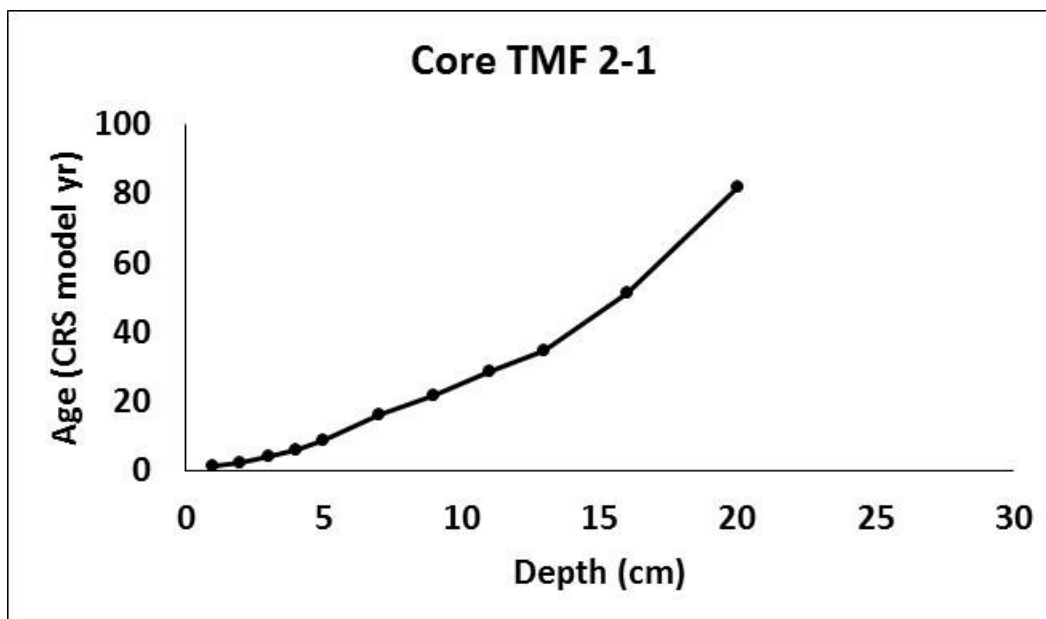| Sample ID	DBD (g cm^{-3})	Upper Depth (cm)	Lower Depth (cm)	Extrapolated Upper Section Depth (cm)	Extrapolated Lower Section Depth (cm)	Age at Bottom of Extrapolated Section (yr)	CRS Sediment Accumulation Rate (g cm^{-2} yr^{-1})
0+1	0.292	0	1	0	1	1.323574	0.220615
2	0.2191	1	2	1	2	2.283357	0.228281
3	0.4043	2	3	2	3	4.031063	0.231332
4	0.485	3	4	3	4	6.17555	0.226765
5	0.6516	4	5	4	5	8.943209	0.235434
7	0.8063	5	7	5	7	16.04905	0.22694
9	0.6366	7	9	7	9	21.85414	0.219325
11	0.748	9	11	9	11	28.87923	0.212951
13	0.5987	11	13	11	13	34.57198	0.210338
16	1.0538	13	16	13	16	51.53309	0.186391
20	1.1437	16	20	16	20	81.90333	0.150634
24	1.3173	20	24	20	24		

Figure 17 Core TMF 2-1 Age (yr) vs Depth (cm)
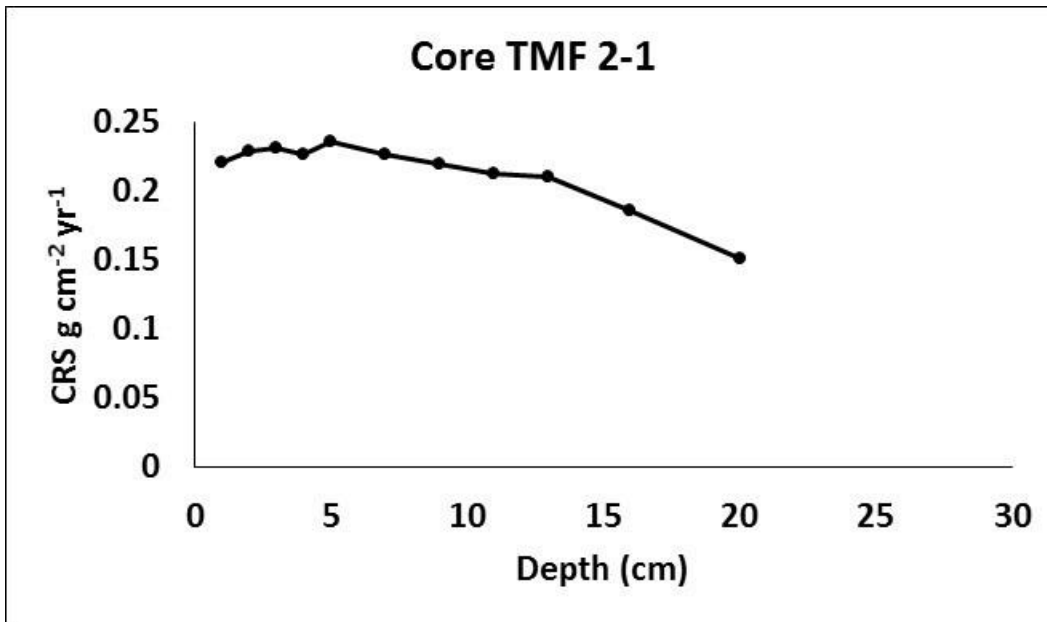
Figure 18 Core TMF 2-1 Sediment Accumulation Rate (CRS g cm^{-2} yr^{-1}) vs Depth (cm)

Appendix C Vegetation Cover Data

Marked Plants Represent those Plants Encountered in Northwest Coast Rhizome Gardens
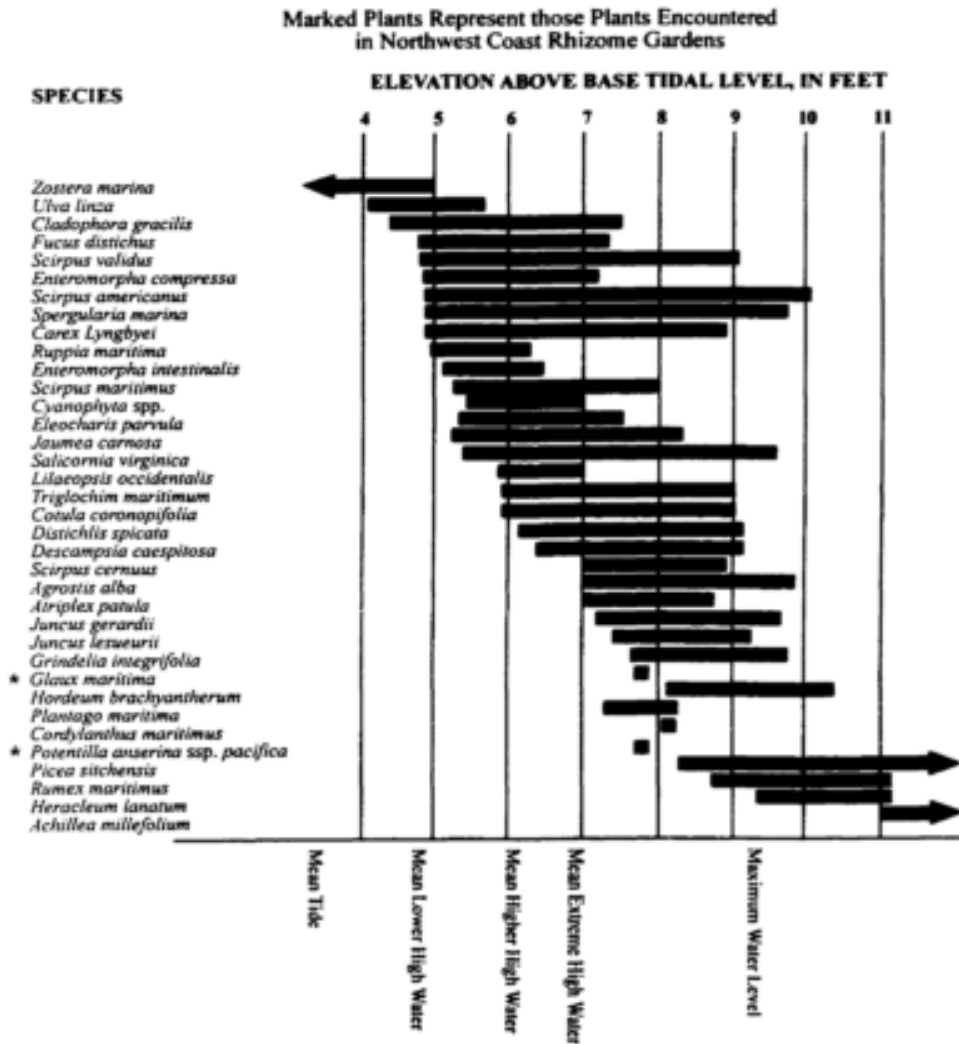
Adapted from Jefferson (1974)

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Figure 19 Reference used for determining marsh stratum based on vegetation

Source: Deur 2000

Table 9 Vegetation survey information

Stratum	Core	Species 1	Species 2	Species 3	Species 4	Species 5
HIGH	GBK 1-1	60% sedges	30% *Potentilla anserina*	10% bare		
HIGH	GBK 1-2	30% rushes	30% sedges	15% *Plantago maritima*	5% *Potentilla anserina*	20% other
HIGH	GBK 1-3	25% *Potentilla anserina*	30% sedges	30% rushes	15% bare	
LOW	GBK 1-4	50% *Lilaeopsis occidentalis*	50% *Salicornia virginica*			
HIGH	CBW 1	60% sedges	30% grasses	10% *Potentilla anserina*		
LOW	CBW 2	80% sedges	20% *Triglochin maritima*	5% *Potentilla anserina*		
LOW	CBW 3	50% rushes	40% *Potentilla anserina*	10% other	5% *Glaux maritima*	
HIGH	CBW 4	50% grasses	30% *Potentilla anserina*	20% *Trifolium ssp.*	10% *Grindelia integrifolia*	
HIGH	KCS 1	60% sedges	20% rushes	10% *Potentilla anserina*	10% bare	
LOW	KCS 2	50% sedges	30% *Potentilla anserina*	20% rushes		
LOW	KCS 3	70% *Potentilla anserina*	30% sedges			
LOW	KCS 4	80% *Potentilla anserina*	20% rushes			
LOW	KCS 5	70% *Distichlis spicata*	30% bare			
HIGH	CBE 1-1	50% *Deschampsia caespitosa*	30% *Grindelia integrifolia*	20% other	5% *Potentilla anserina*	
HIGH	CBE 1-2	60% *Potentilla anserina*	25% rushes	10% other	5% *Grindelia integrifolia*	
HIGH	CBE 1-3	50% *Potentilla anserina*	40% rushes	10% *Plantago maritima*	5% *Glaux maritima*	

LOW	CBE 1-4	50% *Potentilla anserina*	40% *Distichlis spicata*	10% *Trifolium ssp.*		
LOW	CBE 1-5	40% rushes	40% *Potentilla anserina*	20% *Distichlis spicata*		
HIGH	CBE 2-2	20% Potentilla anserina	10% *Equisetum ssp.*	40% rushes	10% *Sagittaria latifolia*	20% other
HIGH	CBE 2-3	30% *Potentilla anserina*	10% sedges	20% *Grindelia integrifolia*	20% *Triglochin maritima*	20% other incl. *Cordylanthis maritimum*
LOW	CBE 2-4	40% sedges	30% bare	20% *Distichlis spicata*	10% rushes	
LOW	CBE 2-5	40% sedges	20% *Fucus ssp.*	20% *Distichlis spicata*	10% *Enteromorpha intestinalis*	10% bare
HIGH	SWC 1-1	50% *Potentilla anserina*	50% *Deschampsia caespitosa*			
HIGH	SWC 2-1	60% *Potentilla anserina*	40% *Deschampsia caespitosa*			
HIGH	TMF 1-1	80% *Potentilla anserina*	20% *Deschampsia caespitosa*			
LOW	TMF 1-2	40% sedges	40% *Distichlis spicata*			
HIGH	TMF 2-1	30% Potentilla anserina	30% *Deschampsia caespitosa*	30% sedges		
LOW	TMF 2-2	40% *Distichlis spicata*	30% sedges	20% *Lilaeopsis occidentalis*	10% rushes	
HIGH	CRF 1-1	60% *Deschampsia caespitosa*	20% sedges	20% bare	10% *Potentilla anserina*	
LOW	CRF 1-2	50% sedges	30% *Triglochin maritima*	25% rushes	5% *Glaux maritima*	
HIGH	CRF 2-1	50% *Potentilla anserina*	25% *Distichlis spicata*	15% sedges	10% *Trifolium ssp.*	
LOW	CRF 2-2	60% *Distichlis spicata*	25% bare	10% *Potentilla anserina*	5% *Glaux maritima*	

HIGH	CRF 3-1	40% rushes	30% *Potentilla anserina*	30% sedges
LOW	CRF 3-2	75% sedges	20% *Distichlis spicata*	5% *Potentilla anserina*