Blue Carbon Storage and Variability in Clayoquot Sound, British Columbia

by

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Abstract

Seagrass habitats store substantial amounts of organic carbon, known as 'blue carbon', We took sediment cores from the intertidal and subtidal zones of three eelgrass (*Zostera marina)* meadows on the Pacific Coast of British Columbia, to assess carbon storage and accumulation rates. Sediment carbon concentrations did not exceed 1.30 $\%C_{org}$, and carbon accumulation rates averaged 10.8 ± 5.2 g C_{org} m^{-2} yr^{-1}. While sediment carbon stocks were generally higher in the eelgrass meadows relative to non-vegetated reference sites, carbon stocks averaged 1343 ± 482 g C_{org} m^{-2}, substantially less than global averages. Our carbon estimates are in line with results from other *Z. marina* meadows; *Z. marina*'s shallow root system may contribute to lower carbon storage. Sandy sediment, nutrient limitation, and low sediment input may also contribute to low carbon values. The larger, more marine influenced meadows with cooler temperatures resulted in larger total carbon stock. By improving the quantification of site-specific carbon dynamics, eelgrass' role in climate change mitigation and conservation can be assessed.

Keywords: blue carbon; eelgrass meadow; carbon stock; carbon accumulation; British Columbia; variability

To my Mom, Dad, and brother, for their unwavering encouragement and love, even from afar.

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Chapter 1. Introduction

Coastal marine ecosystems store significant amounts of carbon, known as ‘blue carbon’, in tropical to subtropical regions, but their potential has largely been overlooked on the Pacific Coast of North America and other temperate regions (McLeod et al. 2011; Fourqurean et al. 2012). These ecosystems, such as mangroves, salt marshes, and seagrass meadows, are estimated to bury carbon at a higher rate per unit area than terrestrial forests (Fourqurean et al. 2012). Specifically, recent estimates suggest that seagrasses are highly efficient carbon sinks, storing a disproportionate amount of carbon for their relatively small area (only approximately 0.2% of the global ocean) (Duarte 2002; Duarte et al. 2013) and the carbon accounts for approximately 10% of the yearly total organic carbon burial in the ocean (Fourqurean et al 2012). The “blue” carbon is stored in the sediment, accumulating mainly from *in situ* production and sedimentation out of the water column (Greiner et al. 2013). Decomposition at depth is inhibited in these ecosystems mainly due to the sediments being predominately anaerobic, slowing microbial carbon oxidation and release (Lavery et al. 2013). Additionally, the sediment can also accrete vertically for a longer period of time than the soils of terrestrial forests, increasing carbon accumulation (Howard et al. 2014).

Seagrass meadows provide multiple additional ecosystem services such as water purification, coastal protection, sediment deposition, substrate stabilization, and habitat for fish and other aquatic species. However, eelgrass ecosystems are among the most threatened ecosystems on Earth (Orth et al. 2006; Waycott 2009). Seagrass meadows are being lost at a rate of 0.4-2.6% yr^{-1}, potentially releasing an average of 0.15 Pg (billion tonnes) carbon dioxide into the atmosphere annually through carbon destabilization and exposure to oxygen (Pendleton et al. 2012). Reasons for meadow health decline include water quality degradation, eutrophication, and development-related destruction. Previous studies show that conserving vegetated ecosystems results in greater storage capacity than restoring degraded habitats (Brisson 2014), and therefore this rapid destruction of seagrass meadows calls for a global conservation and restoration effort to protect these important carbon sinks.

Previous research shows that carbon storage and sequestration in seagrasses varies with different environmental characteristics, so generalizing results from a limited global area is likely not providing reliable data (Lavery et al. 2013). Factors such as depth, irradiance, salinity, exposure, seagrass species, and sediment age, have been shown to influence carbon storage and generate inter-habitat variability (Lavery et al. 2013). Furthermore, uncertainties in the carbon storage capacities of seagrass meadows in different environments have led to major generalizations regarding global blue carbon stocks (Serrano et al. 2014). Most seagrass data are derived from tropical-subtropical regions and used to extrapolate worldwide blue carbon estimates (Miyajima et al. 2015). Finally, this lack of data hinders the incorporation of carbon management into coastal conservation planning and policy development on the Pacific Coast of Canada (Pendleton et al. 2012; Sutton-Grier and Moore 2016). Providing adequate data on regionally specific seagrass meadows could rectify this oversimplification in global blue carbon calculations and help determine eelgrasses' role in mitigating climate change (Howard et al. 2014; Miyajima et al. 2015), and carbon markets (e.g. Hamrick and Goldstein 2015).

In 2016, the Commission for Environmental Cooperation (CEC) identified the Pacific Coast of North America as a high priority area for carbon storage and sequestration research (Chmura et al. 2016). Data are very limited in the Northeast Pacific seagrass bioregion, where the most abundant seagrass species is *Zostera marina* eelgrass (Waycott 2009; Lavery et al 2013). Our study fills this data gap through assessing carbon storage and carbon accumulation rates of three seagrass meadows on the Pacific Coast of Canada. We calculated dry bulk density, percent carbon (% C_{org}), and carbon stocks from sediment cores collected from the intertidal and subtidal zones of each eelgrass meadow. Carbon storage data are extrapolated to the entire meadow using estimated eelgrass meadow areas. We used ^{210}Pb dating to determine sediment age and carbon accumulation rates for each eelgrass meadow. These data are compared among meadows to determine inter-habitat carbon variability and drivers, and among seagrass meadows globally to identify larger spatial trends. Finally, eelgrass' potential role in climate change mitigation and carbon markets is discussed.

Chapter 2. Methods

2.1. Study Area

Our three study sites, Robert Point, Grice Bay, and Kennedy Cove, are located within Tofino Inlet in the southern region of Clayoquot Sound, British Columbia (Figure 1). Grice Bay is also situated within the Long Beach Unit of Pacific Rim National Park Reserve of Canada. Clayoquot Sound's ecology is diverse over its 2600 km^2; it has low human population and a vast expanse of old-growth temperate rainforest, mountainous terrain, fjords, inlets, islands, and species, including threatened or endangered (Government of British Columbia 2017a).

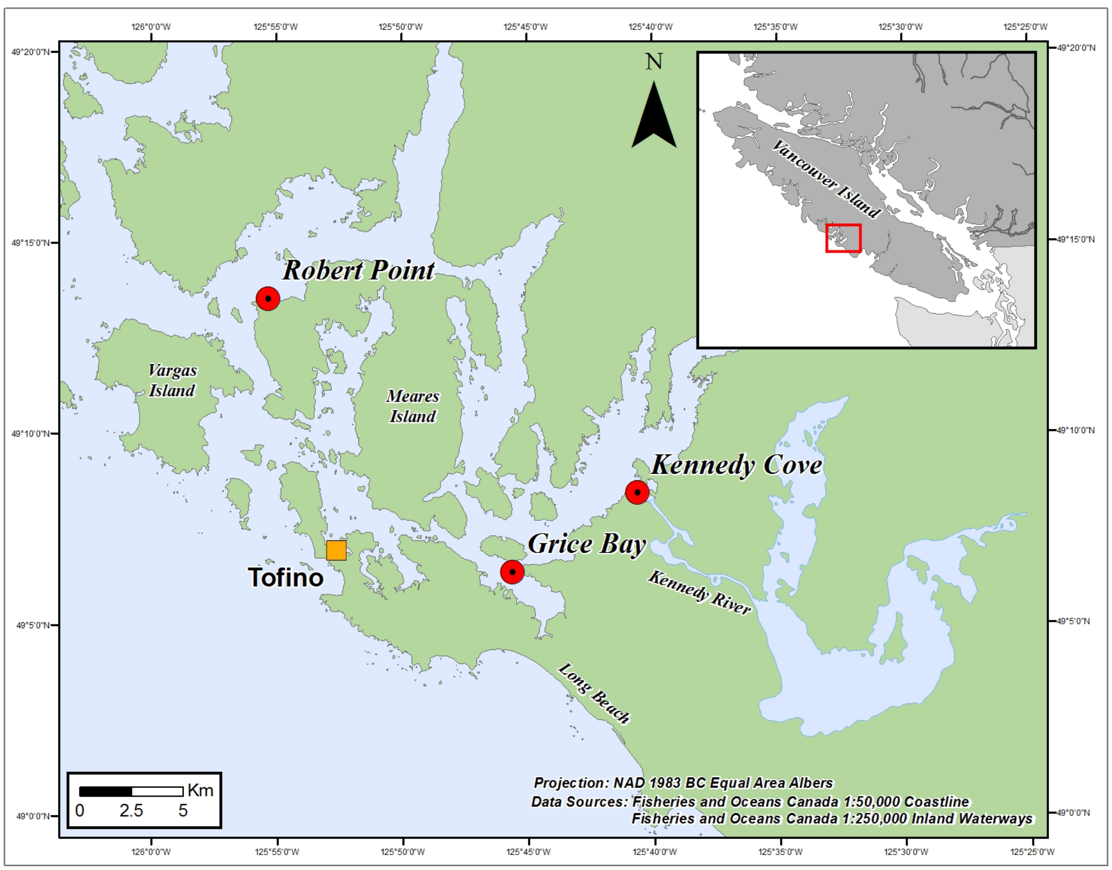

Figure 1. Location of eelgrass meadows sampled in Clayoquot Sound, British Columbia

The three eelgrass meadows were selected for two reasons: first, the meadows are in regions with low human population and thus experience fewer anthropogenic effects. Second, the meadows are distributed along a gradient in water temperature and surface salinity, as a result of freshwater discharge from the lower Kennedy River. Variables such as meadow nutrient regime, sediment trapping, sediment export, and water column irradiance have been shown to influence carbon sequestration (Gacia et al. 2002; Subramaniam et al. 2008; Duarte et al. 2010); the selected study meadows represent a wide range of these variables. Robert Point, our most marine site, furthest from the lower Kennedy River (~22km), had a salinity of 29.3 ± 0.5, and the lowest water temperature and shallowest water irradiance of 12.9 ± 0.1 °C and 4.8 ± 0.1 m, respectively (McGowan et al. 2018). Grice Bay (~8.5 km from the river) had a slightly lower salinity at 24.1 ± 0.1, warmer surface water temperature of 13.9 ± 0.1 °C, and deeper water column irradiance of 6.0 ± 0.5 m (McGowan et al. 2018). Kennedy Cove, adjacent to the lower Kennedy River, has much more freshwater influence, with a salinity of only 6.3 ± 0.4, the warmest temperature of 18.1 ± 0.1 °C, and deepest irradiance of 7.7 ± 0.1 m (McGowan et al. 2018).

2.2. Sediment core collection and carbon analyses

Three sediment cores were collected in late May and early June, 2016, along the upper-intertidal and shallow subtidal zones, which were visually determined through the low tide mark. Cores were placed along the zones using a random number generator, placed along transects running parallel to the sea; this sampling design occurred jointly with McGowan et al. (2018), who sampled above and below-ground biomass at the same locations. One "reference" core was also collected ~250 m from each meadow in three non-vegetated areas. Reference sites were selected to have similar substrate and subject to similar environmental conditions, but with no seagrass present. The large area of the Grice Bay eelgrass meadow made it difficult to find a suitable reference site, and thus the reference core was collected near the meadow (~50 m). Cores were taken using a simple push method, where three-inch polycarbonate tubes were bevelled on one end to help cut through eelgrass shoots and rhizomes in the top layer of sediment, and then pushed into the sediment until depth of refusal. Although recent standard practice for carbon analysis in seagrass recommends sediment cores of 1 m length (Howard et al. 2014), the sediment at these study sites did not allow for extraction of 1 m cores, and therefore ‘depth of refusal’ was used, which varied amongst cores (Table 1). This method resulted in minimal (<2 cm) compaction. Cores were extracted in the field at 1 cm intervals into sterile sample bags and were handled carefully so as not to disturb soil compaction, allowing for accurate dry bulk density (DBD) measurements. The bags were kept in coolers until they were brought back to the laboratory and refrigerated at 4°C.

Table 1. **Sediment core information for three eelgrass meadows in Clayoquot Sound**

Core Number	Latitude	Longitude	Date Collected	Core Length/Depth of Refusal (cm)
Robert Point				
RP 1 IT	49.13064°N	125.55835°W	24-05-2016	51
RP 2 IT	49.13071°N	125.55829°W	24-05-2016	31
RP 3 ST	49.13070°N	125.55836°W	24-05-2016	40
RP 4 ST	49.13063°N	125.55815°W	24-05-2016	35
RP 5 ST	49.21782°N	125.93055°W	26-05-2016	31
RP 6 IT	49.21781°N	125.92999°W	26-05-2016	30
RP Reference	49.11057°N	125.56418°W	27-05-2016	33
Grice Bay				
GB 1 IT	49.06747°N	125.46528°W	25-05-2016	40
GB 2 ST	49.06743°N	125.46535°W	25-05-2016	34
GB 3 ST	49.08368°N	125.43713°W	25-05-2016	43
GB 4 IT	49.06731°N	125.46509°W	25-05-2016	47
GB 5 IT	49.06743°N	125.46516°W	25-05-2016	35
GB 6 ST	49.06731°N	125.46499°W	26-05-2016	40
GB Reference	49.07299°N	125.48171°W	08-06-2016	28
Kennedy Cove				
KC 1 ST	49.08340°N	125.49481°W	07-06-2016	30
KC 2 ST	49.08422°N	125.49481°W	07-06-2016	32
KC 3 ST	49.08337°N	125.49487°W	07-06-2016	39
KC 4 IT	49.08297°N	125.40472°W	06-06-2016	27
KC 5 IT	49.08299°N	125.40475°W	06-06-2016	24
KC 6 IT	49.08309°N	125.40475°W	06-06-2016	20
KC Reference	49.08768°N	125.40156°W	07-06-2016	24

In the laboratory, DBD measurements were taken at each 1 cm interval for each core by sampling a known volume of sediment, drying the sediment at 60°C for no less than 96 hours, and weighing the sediment to obtain g cm^{-3} values (Howard et al. 2014). Loss-on-ignition (LOI) was performed on every 1 cm subsample by removing roots or rhizomes, drying a small amount of sediment (<5g), weighing the dry sample, and then combusting it for 4 hours at 550°C, followed by re-weighing, and obtaining the weight difference from combustion, using the calculation:

$$LOI_{550} = \left(\frac{Pre - Post_{550}}{Pre}\right) \cdot 100 \qquad (1)$$

where LOI_{550} is the weight % LOI, '*Pre*' is the weight of original dry sample before combustion, and '$Post_{550}$'is the weight of the sample after 550°C combustion.

In a small subset of samples, organic carbon content was also determined by measuring the total carbon (%TC) and inorganic carbon (%IC) contents in the same samples, using CHN elemental and coulometric analysis, respectively. Measurements of %IC were subtracted from the %TC measurements to estimate $\%C_{org}$ (Hodgson and Spooner 2016). The values for %IC ranged from 0.0019 to 0.0544 % and did not substantially contribute to the sediment carbon. Gravel particles (>2mm) were not able to be ground, and therefore were removed prior to carbon analyses. The weight percent of gravel, found through grain size analysis and averaged for every 5 cm, was subtracted from uncorrected $\%C_{org}$ values to obtain true $\%C_{org}$ values, using the equation:

$$\%C_{org} = \%C_{org\,uncorrected} - \%C_{org\,uncorrected} \cdot G \qquad (2)$$

where G is the weight % gravel content expressed as a fraction (i.e. 25% gravel = 0.25). The % gravel content was only substantial in the Kennedy Cove cores, where % gravel content ranged from 2 to 43%, and therefore significantly reduced initial $\%C_{org}$ results at this site.

Measurements of $\%C_{org}$ from elemental analysis (EA) were related to measurements of weight %LOI made on the same subset of samples using a simple linear regression (Figure 2). The resulting regression equation was then applied to each weight % LOI value to estimate $\%C_{org(LOI)}$ in all samples where $\%C_{org}$ had not been estimated using elemental analysis.

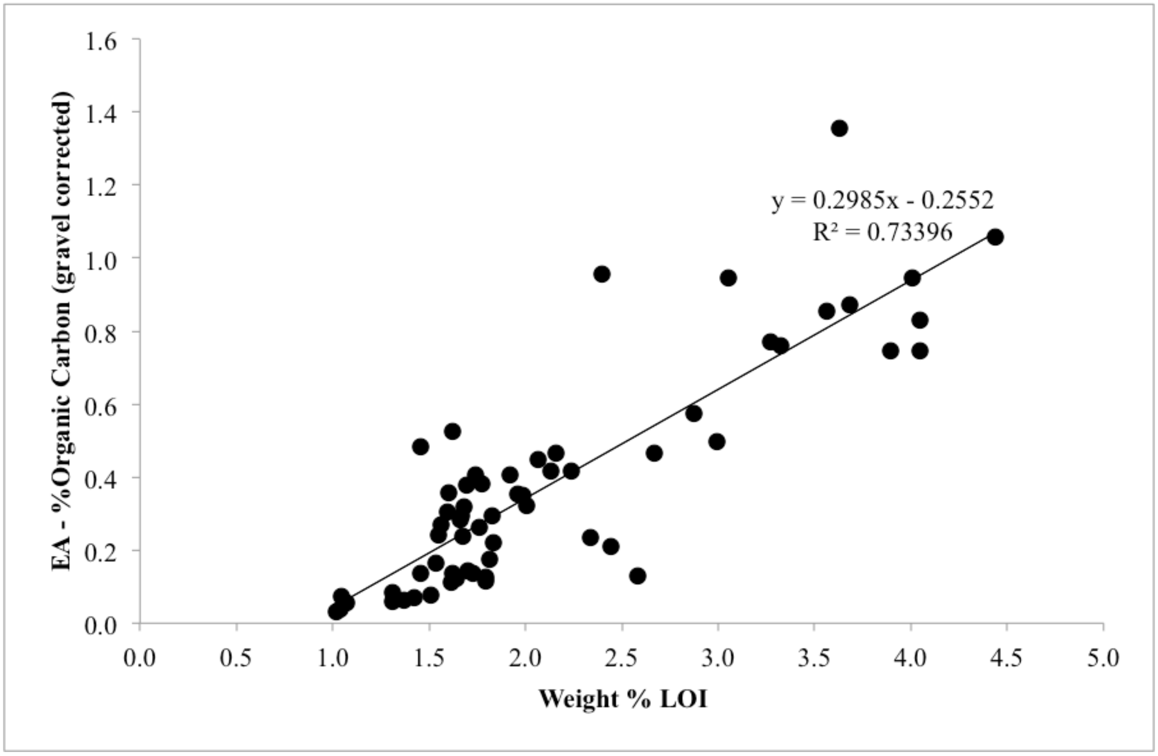

Figure 2. **$\%C_{org}$ vs. weight % LOL regression analysis, with an R^2 value of 0.74**

Carbon density (g C_{org} cm^{-3}) was estimated for each 1-cm sample interval by multiplying the DBD (g cm^{-3}) and $\%C_{org}$ fraction ($\%C_{org}/100$); carbon stocks (g C_{org} cm^{-2}) were then totalled over the length of each core, which ranged from 24 cm (Kennedy Cove intertidal) to a maximum length of 51 cm (Robert Point intertidal). Carbon stocks were scaled up to represent a square metre to allow comparison with other studies.

$$C_{org} = DBD \cdot \left(\frac{\%C_{org}}{100}\right) \cdot depth \qquad (3)$$

Subsamples from nine cores, including the three reference cores, were sent for ^{210}Pb analysis, to obtain radiometric dates for determining mass accretion and carbon accumulation rates. Between 5 and 18 ^{210}Pb measurements were made on each core by Core Scientific International, Winnipeg, Canada, who used a ^{210}Pb constant rate of supply (CRS) model (Rowan et al. 1994) to construct age-depth relationships and determine sediment mass accretion rates (cm yr^{-1}). From mass accretion rates, sediment accumulation rates (SAR) were calculated using dry bulk density, and then carbon accumulation rates (CAR) were determined by multiplying the C_{org} fraction ($\%C_{org}/100$) by SAR.

2.3. Statistical analyses

One-way ANOVAs were used to test the differences carbon stocks and accumulation rates within sites (intertidal v. subtidal) and between the three sites and reference sites. The significance level of these tests was set at $\alpha = 0.05$, and the data were log-transformed to meet the parametric assumptions of an ANOVA when necessary. Assumptions of normality were tested by examining residuals of the data. Statistical analyses were performed in R (RStudio 2016).

Chapter 3. Results

3.1. Sediment Properties

The sediment at Grice Bay and Robert Point was predominantly sand (96% and 84% on average, respectively), with a small proportion of silt and mud (4-5%). The Grice Bay site had <1% gravel content, and the Robert Point site had 15% gravel, skewed high due to gravel below 25cm. A thick shell layer was present at the bottom of each core in these two meadows, as is common in most seagrass sediment (Chmura et al. 2016). Kennedy Cove's sediment had a higher proportion of silt/mud in the top 10cm (8% average) with 2% gravel, followed by increased sand (65% average) and gravel (36%) content below 10cm.

DBD values were not significantly different at Robert Point and Grice Bay, ranging from 1.05 to 1.25 g cm^{-3} (n=213) for Robert Point and from 0.94 to 1.30 g cm^{-3} (n=239) at Grice Bay (Table 2, Appendix A). DBD values for Kennedy Cove were significantly higher ($p<0.001$) than Robert Point and Grice Bay (0.84-1.68 g cm^{-2}, n=173), due to heavy pieces of gravel.

3.2. Carbon Storage and Accumulation

Percent C_{org} was low (<1.30%) and declined with depth at all three sites (Table 2, Appendix B). Percent C_{org} was lowest in Robert Point (n=213) and Grice Bay (n=239), ranging from 0.02-0.82 $\%C_{org}$, and highest at Kennedy Cove where values ranged from 0.15-1.29 $\%C_{org}$ (n=173). All sites were statistically different from each other ($p<0.001$), with Robert Point having the lowest values. The only significant differences between subtidal and intertidal carbon concentrations were found at Grice Bay where percent C_{org} was significantly higher in the subtidal meadow ($p=0.005$). The Robert Point and Kennedy Cove meadows had significantly higher carbon stocks than their associated reference sites, whereas the Grice Bay meadow did not.

Overall, sediment carbon stocks (incorporating depth) averaged 1343 ± 482 g C_{org} m^{-2} for the region, ranging from lowest average values of 820 ± 26 g C_{org} m^{-2} at Robert Point's subtidal meadow (34 cm average depth) to highest average values of

2106 ± 345 g C_{org} m^{-2} at Kennedy Cove's subtidal meadow (34 cm average depth) (Table 2, Figure 3, Appendix C). Carbon stocks were lowest in the more marine-based Robert Point meadow (802-1166 g C_{org} m^{-2}, 30-51cm depth), slightly higher at Grice Bay (947-1924 g C_{org} m^{-2}, 34-47cm depth), and highest near the mouth of the Kennedy River at Kennedy Cove (979- 2519 g C_{org} m^{-2}, 21-39 cm depth). In general, the carbon stocks declined with depth, which is typical of eelgrass carbon stocks due to minimal turnover of the sediment profile and carbon diagenesis (Lavery et al. 2013). Like percent C_{org}, all sites were significantly different from each other, and the Robert Point and Kennedy Cove meadows also had significantly higher carbon stocks than their associated reference sites, whereas the Grice Bay meadow did not. Grice Bay had significantly higher carbon stocks in the subtidal meadow compared to the intertidal ($p<0.001$).

Sediment accumulation rates (SAR) per cm depth averaged 3021 ± 549 g m^{-2} yr^{-1} for all three meadows (Table 2, Appendix D). SARs ranged from 1036-3674 g m^{-2} yr^{-1} at Robert Point, 2553-4908 g m^{-2} yr^{-1} at Grice Bay, and from 841-4314 g m^{-2} yr^{-1} at Kennedy Cove. Carbon accumulation rates (CAR), averaged 10.84 ± 5.20 g C_{org} m^{-2} yr^{-1} for all meadows, with higher rates near the surface and declining with depth (Table 2, Figure 3). CARs ranged from 2.90 to 14.22 g C_{org} m^{-2} yr^{-1} at Robert Point, from 4.71-13.01 g C_{org} m^{-2} yr^{-1} at Grice Bay, and were highest at Kennedy Cove where they ranged from 2.05 to 39.61 g C_{org} m^{-2} yr^{-1}. Additionally, the eelgrass sediments were relatively young. The ^{210}Pb was undetectable past 31cm, and the ages for these depths did not exceed 125 years (Appendix D).

Table 2. **Sediment properties and carbon storage results for the intertidal and subtidal meadows at Robert Point, Grice Bay, Kennedy Cove**

Core ID	Avg Dry Bulk Density ($g\ cm^{-3}$)	Avg $\%C_{org}$	Carbon Stock in Core ($g\ C\ m^{-2}$)	Age at Max ^{210}Pb Depth (year before June 2016)	Avg Sediment Accumulation Rate ($g\ m^{-2}\ yr^{-1}$)	Avg Carbon Accumulation Rate ($g\ C\ m^{-2}\ yr^{-1}$)
				Robert Point		
Intertidal	1.15 ± 0.04	0.24 ± 0.13	955 ± 138	114.5	2633 ± 888	9.12 ± 4.04
Subtidal	1.16 ± 0.02	0.21 ± 0.12	820 ± 26	90.8	2808 ± 711	9.20 ± 3.01
Reference	1.14 ± 0.02	0.13 ± 0.03	503	104.1	3272 ± 646	3.87 ± 1.31
				Grice Bay		
Intertidal	1.14 ± 0.06	0.24 ± 0.04	1074 ± 186	94.3	4291 ± 644	9.92 ± 1.87
Subtidal	1.17 ± 0.05	0.37 ± 0.13	1694 ± 222	94.6	3471 ± 408	11.01 ± 1.73
Reference	1.21 ± 0.03	0.27 ± 0.02	923	103.4	2962 ± 796	7.84 ± 1.89
				Kennedy Cove		
Intertidal	1.22 ± 0.18	0.46 ± 0.25	1280 ± 273	124.9	2554 ± 746	14.86 ± 8.00
Subtidal	1.36 ± 0.17	0.48 ± 0.26	2106 ± 345	113.5	3621 ± 539	22.26 ± 11.35
Reference	1.40 ± 0.06	0.29 ± 0.07	1027	103.7	2764 ± 657	9.54 ± 3.50

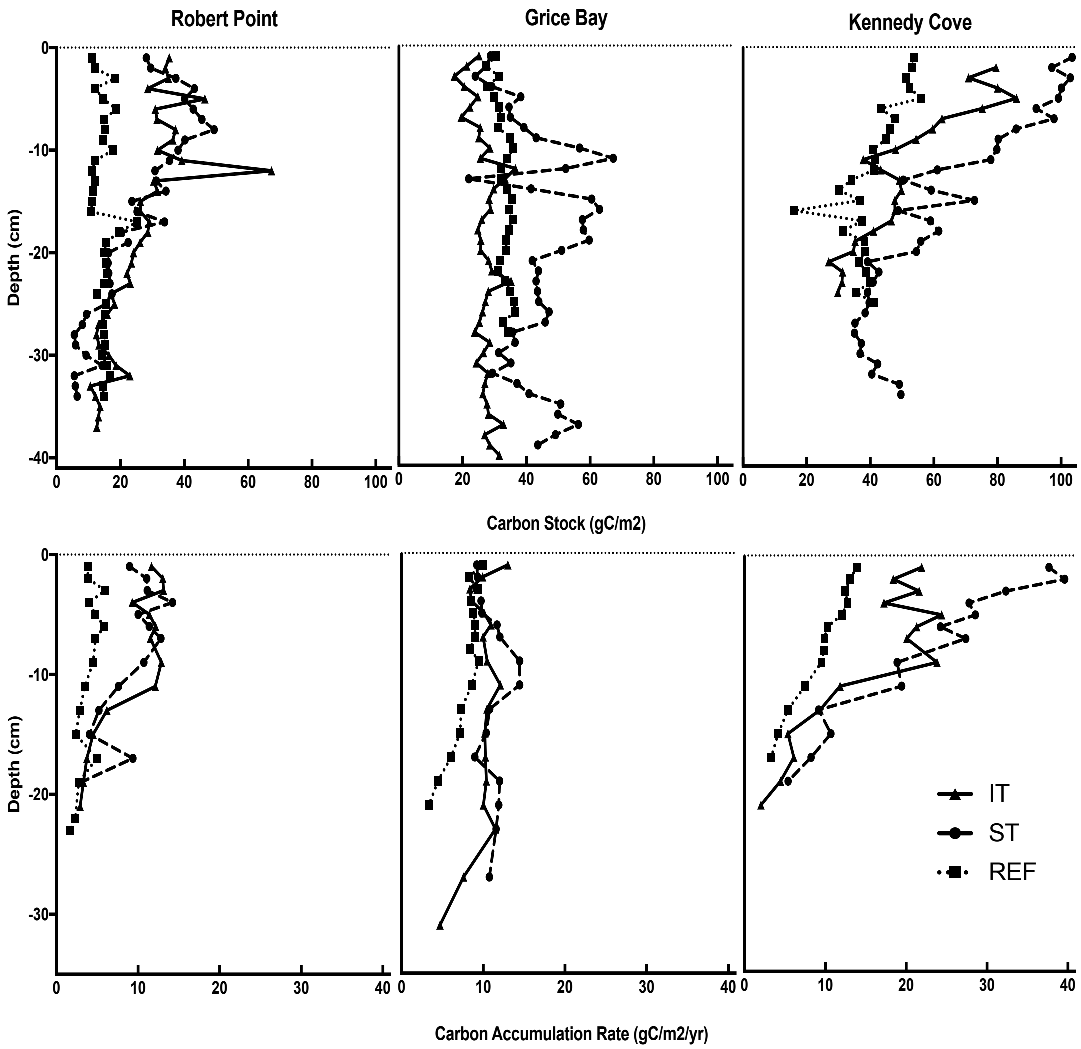

Figure 3. Carbon stock and accumulation rates in Robert Point, Grice Bay, and Kennedy Cove

Triangle symbols: intertidal; circle symbols: subtidal; square symbols: reference

3.3. Meadow Carbon Estimates

While the sediment carbon content per unit area was highest at Kennedy Cove, Grice Bay sediments contained the most carbon after accounting for the size of the meadow, especially in the large intertidal zone (199.8 ± 34.6 Mg C_{org} in the intertidal and 128.7 ± 16.9 Mg C_{org} in the subtidal). Robert Point had the second largest total carbon stock (21.4 ± 3.1 Mg C_{org} in the intertidal and 7.8 ± 0.2 Mg C_{org} in the subtidal). Kennedy Cove had half as much as Robert Point, with 1.3 ± 0.3 Mg C_{org} in the intertidal and 9.1 ± 1.5 Mg C_{org} in the subtidal (Figure 4). McGowan et al. (2018) assessed eelgrass meadow extent in Clayoquot Sound and determined that the Grice Bay was substantially larger than the other sites (262,000 m^2, as compared to 31,900 m^2 at Robert Point and 5,340 m^2 at Kennedy Cove). The intertidal zone of Grice Bay was 186,000 m^2 compared to the smaller subtidal zone of 76,000 m^2 (McGowan et al. 2018). These results allowed for extrapolation of carbon stock to the full meadow area. Total meadow sediment content was calculated by determining the average depth of refusal for each meadow and zone, and calculating carbon content to that depth.

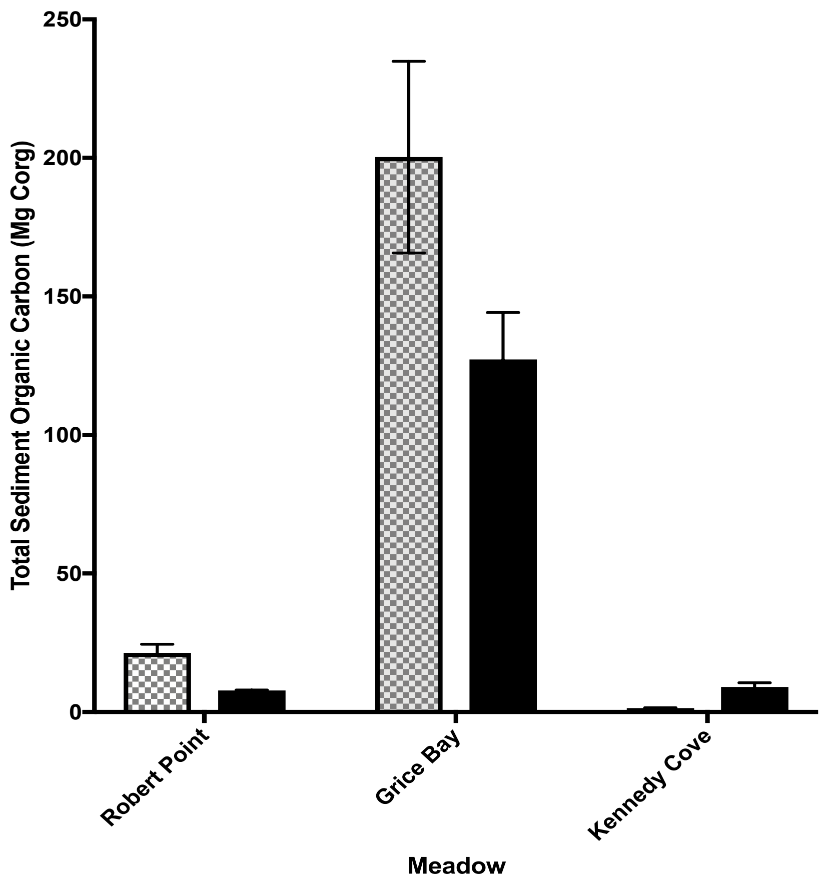

Figure 4. Total sediment carbon per meadow area in the intertidal and subtidal zones of Robert Point, Grice Bay, and Kennedy Cove
Hashed pattern bars: intertidal meadow; solid bars: subtidal.

CARs per meadow area were also highest in Grice Bay, with an average rate of 1.85 ± 0.35 Mg C_{org} in the intertidal zone and 0.84 ± 0.13 Mg C_{org} in the subtidal zone. In Robert Point, the intertidal zone had a much lower average CAR of 0.20 ± 0.09 Mg C_{org} and the subtidal zone had less, at 0.09 ± 0.03 Mg C_{org} Finally, Kennedy Cove had the lowest CAR with an average rate of 0.02 ± 0.01 Mg C_{org} in the intertidal and 0.10 ± 0.05 Mg C_{org} in the subtidal.

Chapter 4. Discussion

4.1. Sediment

Dry bulk density values were consistent with values found in the literature, which can range from 0.24-1.61 g cm^{-3}, depending on the sediment type and location (Fourqurean et al. 2012; Greiner et al. 2013). Values in this study averaged at 1.15 ± 0.06 g cm^{-3} for Robert Point and Grice Bay, but were much higher and more variable in Kennedy Cove, averaging at 1.30 ± 0.19 g cm^{-3}, due to the presence of gravel. It is important to correct for gravel in carbon estimates to prevent over-estimation from high bulk density values and because gravel cannot be included in common carbon storage methods, such as elemental analysis (Gerzabek et al. 2005).

4.2. Carbon Stocks and Accumulation Rates

Carbon concentrations, stocks, and accumulation rates in Clayoquot Sound were lower than global estimates, but in line with other *Z. marina* carbon estimates. While carbon stocks ranged from 802 to 2519 g C_{org} m^{-2} in Clayoquot Sound eelgrass meadows, recent global estimates average 19,420 ± 2020 g C_{org} m^{-2} (Fourqurean et al. 2012). For *Z. marina,* estimates from the Baltic Sea and Northern Europe, range from 500-4324 for the top 25cm (Dahl et al. 2016; Röhr et al. 2016), placing our findings within the range of carbon stocks for *Z. marina* but much lower than global averages. Similarly, the sediment carbon contents (% C_{org}) estimated in this study are much lower than those found in the literature. Values from Australia, the Mediterranean, and Florida, range from 0 to 48 % C_{org}, with an average value of 2.5 ± 0.1 % C_{org} (Fourqurean et al. 2012; Pendleton et al. 2012). Carbon values in this study did not exceed 1.30 % C_{org}. Finally, carbon accumulation (sequestration) rates in this study were low as compared to previously published estimates. While CAR ranged from 2.05-39.61 g C_{org} m^{-2} yr^{-1} and averaged 10.84 g C_{org} m^{-2} yr^{-1} in Clayoquot Sound, global estimates range from 45-190 g C_{org} m^{-2} yr^{-1} and average 138 g C_{org} m^{-2} yr^{-1} (McLeod et al. 2011). *Z. marina* estimates of CAR range from 0.84-36.68 (Greiner et al. 2013; Miyajima et al. 2015; Hodgson and Spooner 2016; Jankowska et al. 2016; Prentice 2018), indicating our values are in line with other estimates for *Z. marina* but much lower than global averages. Three main factors may contribute to the low carbon stocks in this study, including (1) *Z. marina*'s shallow root system and the ecosystem's nitrogen limitation, (b) sediment type, and (c) low sediment discharge.

A contributor to low carbon stocks in this study may be the presence of *Z. marina* as the dominant seagrass species. The species *Z. marina* tends to have much shallower roots than *P. oceanica* and other Mediterranean species (Lavery et al. 2013), which produce thick root mats that promote sediment carbon storage (Armitage and Fourqurean 2016; Johannessen and Macdonald 2016). The shallow root system of *Z. marina* in the Clayoquot Sound meadows are not sufficient to trap carbon through sedimentation processes, resulting in low carbon storage (Johannessen and Macdonald 2016). This shallow root system may be influenced by nitrogen limitation, as seagrasses require a high volume of inorganic nutrients due to their high rates of primary productivity, meaning that they can often be nutrient limited (Lee et al. 2007). Seagrass tissue nitrogen content is highly variable, and tends to be highest in winter and lowest in summer (Duarte and Kirkman 2002). A median N content of 1.8% (of dry weight) has been used to discriminate between nutrient limited and nutrient sufficient ecosystems (Duarte and Kirkman 2002). The median nitrogen concentration of the sediment in our eelgrass meadows was only 0.041% (Appendix E), indicating nitrogen limitation in the summer months. Biomass responses to nitrogen enhancement or limitation are species specific (Udy and Dennison 1997); *Z. marina* shows minor productivity increases in the roots and rhizomes (Murray et al. 1992). Nitrogen limitation may therefore be one of the causes of *Z. marina*'s shallow root system but further work should be done to determine if this nutrient limitation is a trend in the growing season for other *Z. marina* meadows.

A second contributor to the low carbon stocks may be sediment type. Fine grained particles, such as silt/mud, tend to promote more carbon adsorption (Kennedy et al. 2010). The meadows contained a large proportion of sand (65-96%); previous studies found the lowest carbon stocks for *Z. marina* at sandy, exposed sites in the Baltic Sea (Röhr et al. 2016), suggesting that sediment type coupled with the presence of *Z. marina*, may be limiting carbon stock. The influence of sediment size may also be the reason for higher carbon stock per unit area in the Kennedy Cove cores, as Kennedy Cove had a higher proportion of mud (in the top 10cm) than the other two sites. Sandy sediment may also inhibit root growth, potentially leading to the shallow root system as noted above.

Finally, low sediment discharge may be contributing to the low sediment accumulation and allocthonous contribution to the carbon stock. This low sediment discharge can be seen through relatively high secchi disc measurements (4.8-8.8 m) (McGowan et al. 2018) and C:N ratios indicative of predominantly marine influence (Tue et al. 2011). Tue et al. (2011) estimates that C:N ratios of <12 indicate marine sources, and we found a mean C:N ratio of 9.54 ± 2.19. Limited terrestrial sources of sediment may indicate low sediment discharge into the meadows, possibly resulting in low sediment accumulation and, when combined with low autochthonous carbon input, low carbon accumulation. The sites, like the majority of eelgrass meadows, including those with *Z. marina* (Bekkby et al. 2008), also exist in relatively sheltered areas, which may influence the low carbon accumulation rates. Further isotopic data are needed to confirm marine and terrestrial inputs into the meadows.

We note that we did not follow previous recommendations to extrapolate cores down to 1 m when estimating carbon stocks and accumulation rates (Fourqurean et al. 2012; Chmura et al. 2016). The thick shell hash layer at depth of refusal in our sediment cores coupled with declining CARs indicated that assuming carbon accumulation to 1 m would have grossly over-estimated carbon stocks for our sites. Using a 1 m standard has received some criticism in the literature recently (Johannessen and Macdonald 2016) because of the likelihood of overestimating carbon stocks in some systems. However, other studies have noted that extrapolating the carbon stocks in short cores to 1 m actually underestimated the total carbon stocks found in associated, deeper cores (Fourqurean et al. 2012). Overall, this suggests depth of carbon accumulation has high geographic variability.

Comparisons of carbon stock and accumulation rate estimates between studies is difficult and time consuming due to variability in data collection and reporting, including, but not limited to, the depth of the core. Howard et al. (2014) attempted to standardize blue carbon methodology to address much of this variability; however, as methods have progressed further since 2014, a new method paper would be useful to further refine blue carbon work. Suggestions to include in a method/review paper are: (1) a rationale for the depth of the cores; (2) an indication of whether a carbon stock or accumulation rate value incorporates depth; (3) a standardization of units; (4) an updated “global” estimate that includes recent work from temperate ecosystems, such as this study and others (Greiner et al. 2013; Miyajima et al. 2015; Dahl et al. 2016; Hodgson and Spooner 2016; Jankowska et al. 2016; Röhr et al. 2016; Prentice 2018) and; (5) a representative sample of estimates from a variety of ecosystem types and species.

4.3. Inter-Meadow Carbon Storage Variability

Our results suggest very few significant differences between the intertidal and subtidal meadows, where the only difference was that the Grice Bay meadow had significantly higher carbon concentrations and stocks than the intertidal. This may be due to erosion by wave action disrupting carbon storage for the intertidal meadow, whereas in the fully inundated areas of the meadow (ie. subtidal), decay rates are likely slower, increasing the carbon storage (Fourqurean et al. 2012), however this trend was not seen in the other meadows. Serrano et al. (2014) found a negative relationship with increased water depth to carbon storage, which this study did not find, however we only sampled the shallow subtidal, and more substantial differences in C_{org} storage may be seen if deep subtidal meadows had been sampled. Lavery et al. (2013) did not find a significant difference between intertidal and subtidal meadows for Australian meadows of *Posidonia sinuosa* and *P. australis*. While eelgrass in the Clayoquot Sound appears to have low C_{org} values, carbon stocks were significantly higher in the majority of eelgrass meadows as compared to the non-vegetated reference sites, which has been seen in previous studies (Kennedy et al. 2010). This confirms that eelgrass does contribute to carbon storage in Clayoquot Sound but not at rates identified for more tropical seagrasses.

We did not find a significant difference between the Grice Bay meadow and reference site. However, as noted in the results section, a reference site outside of the meadow, with similar substrate and subject to similar environmental conditions, was not found at this site, and therefore the reference core was taken from bare sediment, but had eelgrass surrounding it. Thus, underground carbon transport may be responsible for the carbon stock of the Grice Bay reference site. Evidence of the close proximity to the meadow was noted with the presence of roots and rhizomes in the reference core sediment.

While differences between the intertidal and subtidal meadows were limited, our results suggest strong spatial patterns. While per unit area, Kennedy Cove had the highest sediment carbon, overall, the highest sediment carbon was found in the two meadows with high salinity and cooler water; Grice Bay had a total sediment carbon stock of 329.5 Mg C_{org}, followed by Robert Point with 29.2 Mg C_{org}. Kennedy Cove, with the warmest temperatures and lowest salinity, had the least with only 10.4 C_{org}. A similar pattern was observed with the CAR per meadow, with Grice Bay having the largest carbon accumulation rates and Kennedy Cove experiencing the smallest. These differences in carbon stocks are likely related both to meadow size and the meadow's environmental characteristics. First, on an aerial basis, Grice Bay's large intertidal meadow had 10-20 times the carbon storage capacity compared to Kennedy Cove or Robert Point because of the size of the meadow (McGowan et al. 2018). Eelgrass is known to increase sedimentation (Howard et al. 2014), so the higher carbon storage in the large eelgrass flats of Grice Bay may be due to their increased capacity for particle sedimentation. Fringe meadows like Kennedy Cove are narrow and are less able to capture sediment.

Secondly, the differences in environmental characteristics, such as salinity and temperature, play an important role. *Z. marina* occurs throughout the northern hemisphere in a wide range of salinity levels between 3 and 30 ppt (Kaldy 2014). Physiological stress symptoms, including reduced photosynthetic capacity, have been seen at salinities <9 (Thom et al. 2003), which may have led to decreased eelgrass health at Kennedy Cove (6.3 ppt). Different eelgrass populations, however, show marked adaptability to salinity levels, and so there are likely additional factors affecting the Clayoquot Sound eelgrass meadows, such as temperature. *Z. marina* in the Pacific Northwest are healthiest at 5-8°C, and exhibit physiological stress at temperatures above 15°C (Thom et al. 2003). Therefore, Kennedy Cove with a surface water temperature of 18.1°C (and likely warmer later in the summer), is likely too warm in the growing season for the eelgrass to thrive. This is seen in the low shoot densities found by McGowan et al. (2018), compared to the two other, cooler meadows, which experienced surface water temperatures of <15°C. It is worth noting that temperature and salinity measurements were only taken on the day of sampling (late May and early June); additional measurements throughout the growing season would have been useful to confirm this hypothesis.

Additional variables that influence seagrass growth are light availability and nutrient loading (Thom et al. 2003). Kennedy Cove showed the deepest secchi disc measurement (albeit sightly) (McGowan et al. 2018), suggesting highest light availability, but that does not appear to have been enough to promote eelgrass carbon storage. Addtionally, Kennedy Cove had the highest average nitrogen content (0.08% in the intertidal and 0.09% in the subtidal), suggesting less severe nutrient limitation, but again this does not appear to have been sufficient to promote eelgrass growth. Spatial variability clearly plays an important role in eelgrass carbon storage, and temporal variability is likely another driver of variability in these ecosystems. Further investigation into the factors influencing variability in eelgrass meadows is needed.

4.4. Valuing Blue Carbon

The monetary value of blue carbon ecosystems, like with forest carbon, can be estimated by (1) determining the quantity of CO_2 released upon ecosystem degradation or destruction, and (2) assigning a monetary value to each unit of CO_2. Using the C to CO_2 atomic mass conversion of 3.67, Grice Bay, the largest and most significant contributor to carbon storage in this study, has the potential to release 1105.5 Mg CO_2 into the atmosphere based on its current (2016) carbon stock. Additionally, the annual carbon accumulation rates would increase this amount by 9.8 Mg CO_2 each year. This calculation assumes that, if the meadow was degraded, all the stored carbon would be released as CO_2, and that the carbon accumulated each year remains in the sediment over the long term. Further studies could estimate carbon transport upon meadow degradation to determine a more accurate carbon release figure. Using British Columbia's current carbon price of $30/tonne (Government of British Columbia 2014), I estimate that Grice Bay is valued at approximately $36,033 based on its current (2016) carbon stock. When annual carbon sequestration is taken into account, the value of Grice Bay increases by $295 per year. Robert Point and Kennedy Cove would be valued at less due to their smaller size, at approximately $3214.9 and $1145.0, respectively, with an additional $32 and $12 per year, respectively, when annual carbon accumulation is accounted for. The BC Government website states that the existing price of carbon will rise to $50/tonne by 2022 (2014), further increasing the value of the carbon storage service these ecosystems provide.

Carbon storage and release can also be valued using the Social Cost of Carbon (SCC), which takes into account the monetary value of economic damages associated with CO_2 emissions, as well as the value of damages avoided by an emission reduction (Cole and Moksnes 2016; Environment and Climate Change Canada 2016). Cole and Moksnes (2016) valued eelgrass carbon storage using the Social Cost of Carbon (SCC) amount of $127 USD ($161 CAD as of February 24, 2018), taken as an average of several estimates. Using that estimate, and again assuming that upon degradation the entire carbon store would be lost and converted to CO_2, the Grice Bay meadow could be valued at CAD $177,982 (in 2016), gaining $1584 per year. In addition to the carbon storage benefits, eelgrass meadows provide a range of other ecosystem services, including fish habitat, erosion control, and water filtering, and so the total value of the eelgrass meadows is significantly greater than the value of the carbon storage alone.

4.5. Eelgrass' Role in Climate Change Mitigation

This study emphasizes the need for regionally specific data to ground-truth global estimates. Coastal ecosystems, including eelgrass meadows, are highly variable and their structure is dependent on a variety of environmental factors, including climate, exposure, and salinity, meaning that extrapolation from global averages has led to overestimation of blue carbon in some areas. The improved quantification of site-specific carbon dynamics helps to determine eelgrass' role in climate change mitigation and potentially their use in carbon markets around the world. While our study shows that eelgrass meadow carbon storage in Clayoquot Sound, and potentially in the Pacific Northwest, is substantially less than global estimates, the valuation of blue carbon demonstrates that they can still play an important role in climate change mitigation.

Eelgrass meadows, and other blue carbon habitats, could play a role in carbon markets and carbon offsets (Emmer et al. 2015). The VCS Methodology for Tidal Wetland and Seagrass Restoration (Emmer et al. 2015) identifies the methodology for using wetland restoration for carbon credits. This study explains that voluntary carbon markets allow for the buying and selling of carbon offsets, outside of a regulatory system, where an industry, for example, could purchase a carbon credit to offset their emissions (Emmer et al. 2015). A mandatory carbon market system can also be referred to as a cap-and-trade system, and refers to industrial polluters buying unused quota from other companies that were able to meet their emissions (David Suzuki Foundation 2015). The carbon market methodology report (Emmer et al. 2015) notes that vegetated coastal ecosystems could be used in carbon markets through restoration projects that increase sequestration, resulting in the earning of carbon credits.

In Canada, Quebec and Ontario have implemented a cap-and-trade system that could be used as a vehicle for carbon offsets from wetland restoration. In 2013, Quebec introduced a cap-and-trade system in their province, and has since linked it with that of California (Center for Climate and Energy Solutions 2014). Businesses that emit 25,000 tonnes or more of CO_2 or an equivalent per year are subject to this system, and the cap will be reduced 1-2% per year, to encourage further emissions reductions (Government of Quebec 2017). Revenue generated from this 'carbon market' is reinvested towards implementation of the Climate Change Action Plan (Government of Quebec 2017). Ontario's cap-and-trade system was recently signed and came into effect on January 1, 2018, which will be linked with Quebec and California (Government of Ontario 2018). This system could incorporate blue carbon ecosystems into the market. Additionally, Alberta is developing a Wetland Restoration Offset Program that will allow for a restoration carbon market, although this program is still in early stages (Government of Alberta 2015).

Another, potentially more politically challenging, method of including blue carbon in climate change mitigation is a carbon tax. A carbon tax is similar to cap-and-trade where emitters are financially penalized for emitting, however a carbon tax puts a direct monetary price on greenhouse gas pollution, mainly from the burning of fossil fuels, rather than creating a market for it (David Suzuki Foundation 2015). This is done by placing a surcharge on carbon-based fuels (natural gas, oil, coal) and other sources of pollution, as a way of discouraging fossil fuel emissions, and as an incentive to move towards clean energy (David Suzuki Foundation 2015). British Columbia established the Carbon Tax Act in 2008 under the Liberal party. It started low ($10/tonne of CO_2), and was increased on an annual basis until 2012, to the current $30/tonne, aiming to rise to $50/tonne by 2022 (Government of British Columbia 2014). A carbon tax could incorporate blue carbon by taxing emissions associated with the degradation of coastal ecosystems, such as from a development.

The Intergovernmental Panel on Climate Change (IPCC) sets standards for carbon accounting, which should be adhered to should blue carbon be incorporated into carbon accunting. The IPCC notes that a well-designed carbon accounting system should provide recording and reporting that is transparent, consistent, comparable, complete, and accurate (2014), so reporting standards for blue carbon should be revised and followed. Changes in the carbon stocks must be monitored, so repeat annual sampling may be required. The carbon stock and emission estimates can be either land-based (measuring the change in carbon stocks from an activity in a specific “land unit”) or activity-based (where emissions are calculated based on changes per activity or time period) (IPCC 2014).

Finally, while carbon pricing/markets is a potential method to include blue carbon ecosystems in climate change mitigation strategies, protecting these vital ecosystems through law is also an important step. In total, only 211km^2 of seagrass meadows in Canada are protected, out of a possible ~645km^2 existing today (Richardson 2016). Therefore, further protection of these areas through Marine Protected Areas (MPAs) is required. Canada has a target of protecting 10% of marine and coastal areas by 2020 and has already passed its interim target (Fisheries and Oceans Canada 2018). The carbon storage potential and resultant monetary value of blue carbon ecosystems could be used as an additional reason to incorporate protection into marine conservation planning.

Chapter 5. Conclusion

This research quantified sediment carbon storage and accumulation rates in the intertidal and subtidal zones of three eelgrass meadows on the Pacific coast of Canada, addressing the knowledge gap identified by the Commission for Environmental Cooperation in 2016. Carbon stocks and accumulation rates in Clayoquot Sound are lower than previous estimates from global studies, ranging from 802–2519 g C_{org} m^{-2}. Carbon accumulation rates were also substantially lower than global estimates, however carbon data were in line with estimates from other *Z. marina* studies. The low carbon stock and accumulation rates are likely due to the shallow root system of *Z. marina*, the nitrogen limitation of the meadows, sediment type, especially the high proportion of sand, low sediment input into the meadows.

Our results suggest very few significant differences between the intertidal and subtidal meadows; however, our eelgrass meadows had significantly higher carbon storage compared to the non-vegetated reference sites, confirming that eelgrass does contribute to carbon storage in Clayoquot Sound but not at rates identified for more tropical seagrasses. The environmental characteristics of the meadow, such as temperature and salinity, play an important role in inter-habitat variability; we found that the high salinity, cooler temperature meadows stored more carbon than the low salinity, warmer temperature meadow when extrapolated to the entire meadow area.

The carbon storage of eelgrass meadows in Clayoquot Sound, and potentially in the Pacific Northwest, can play a vital role in climate change mitigation strategies. Blue carbon could be incorporated into climate change mitigation through carbon markets and accounting, and it is crucial to protect these ecosystems to prevent potential carbon release and to preserve the ancillary ecosystem services eelgrass meadows provide.

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Appendix A. Dry Bulk Density

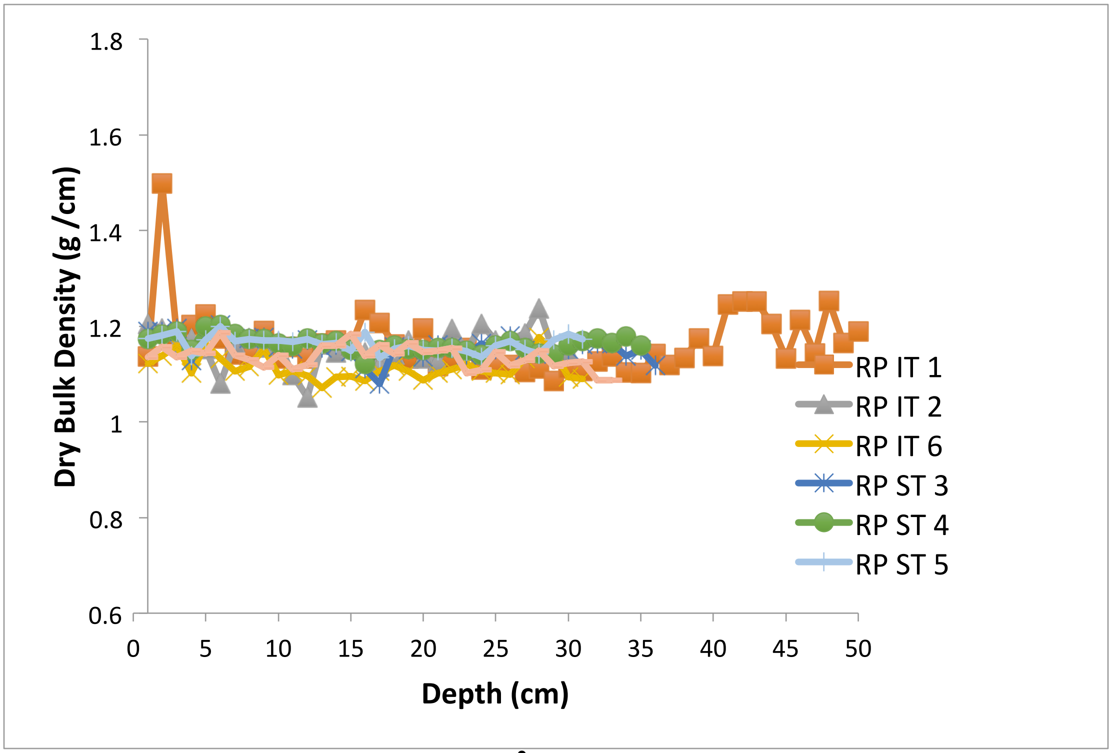

Figure A1. **Dry bulk density (g cm^{-3}) in the intertidal (IT), subtidal (ST) and reference (REF) cores from Robert Point meadow**

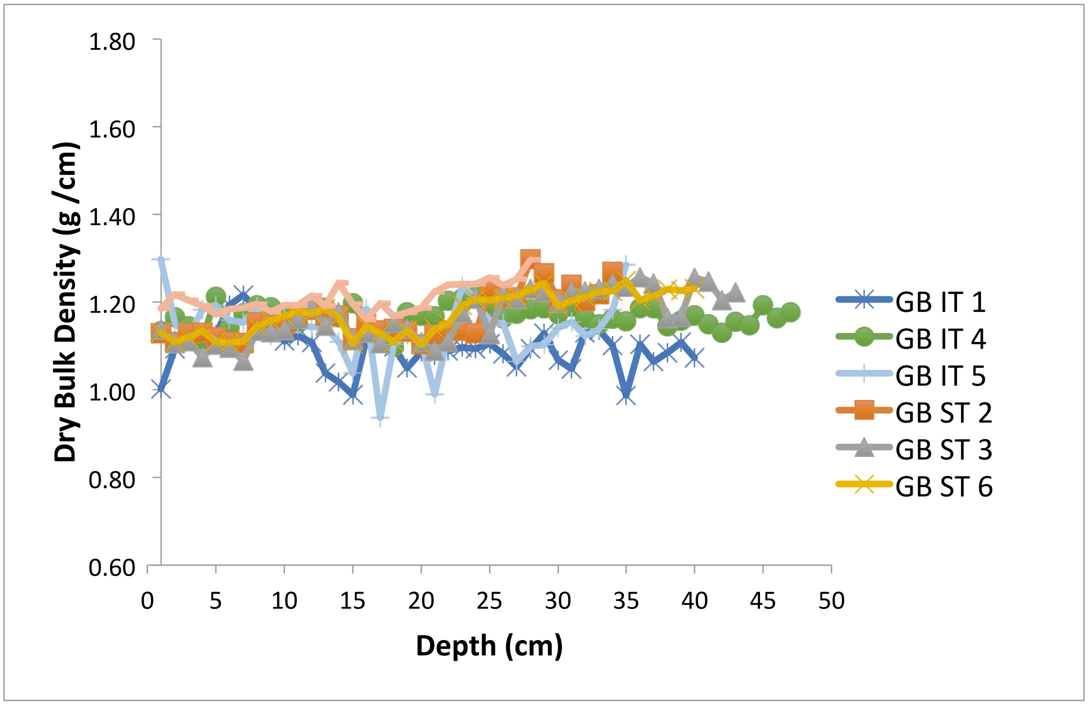

Figure A2. **Dry bulk density (g cm^{-3}) in the intertidal (IT), subtidal (ST) and reference (REF) cores from Grice Bay meadow**

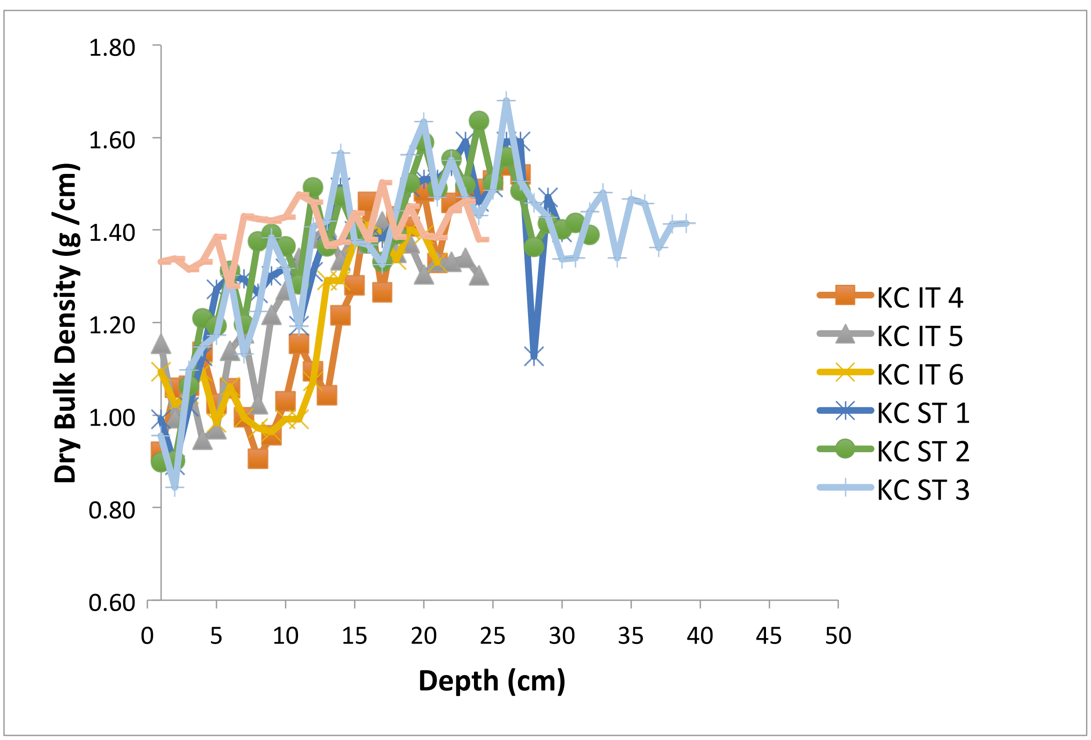

Figure A3. **Dry bulk density (g cm^{-3}) in the intertidal (IT), subtidal (ST) and reference (REF) cores from Kennedy Cove meadow**

Appendix B. Carbon Concentration

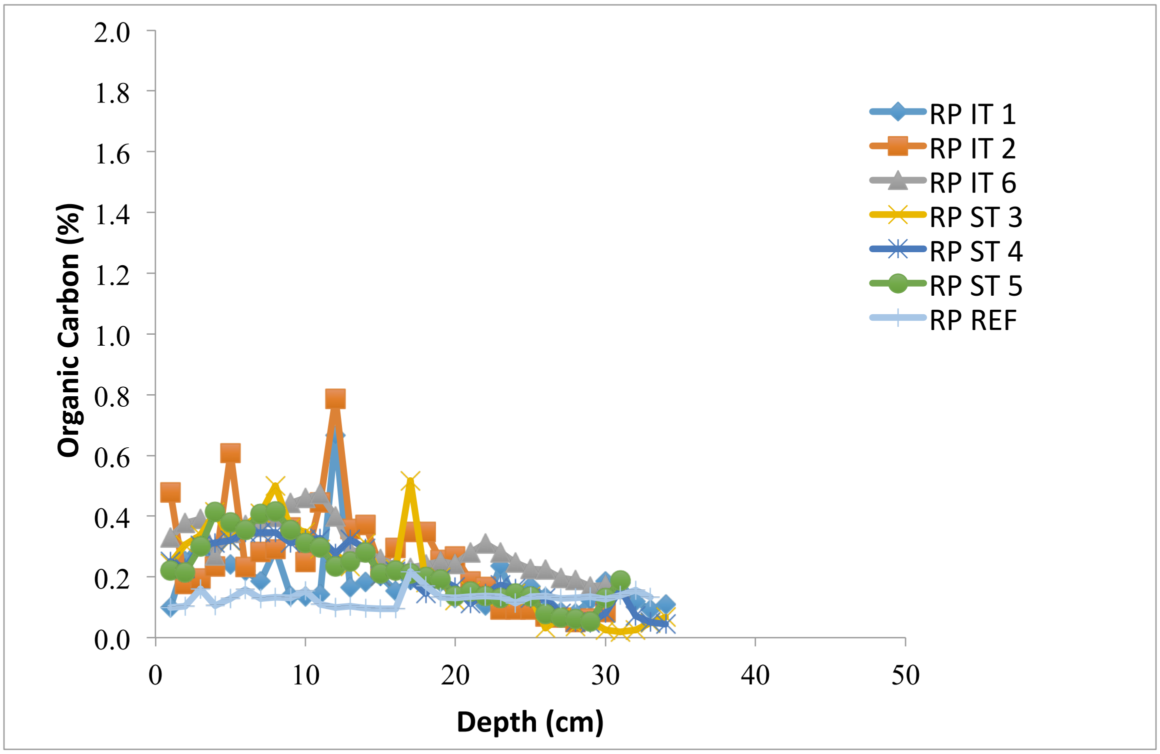

Figure B1. **Percent organic carbon in the intertidal (IT), subtidal (ST) and reference (REF) cores from Robert Point meadow**

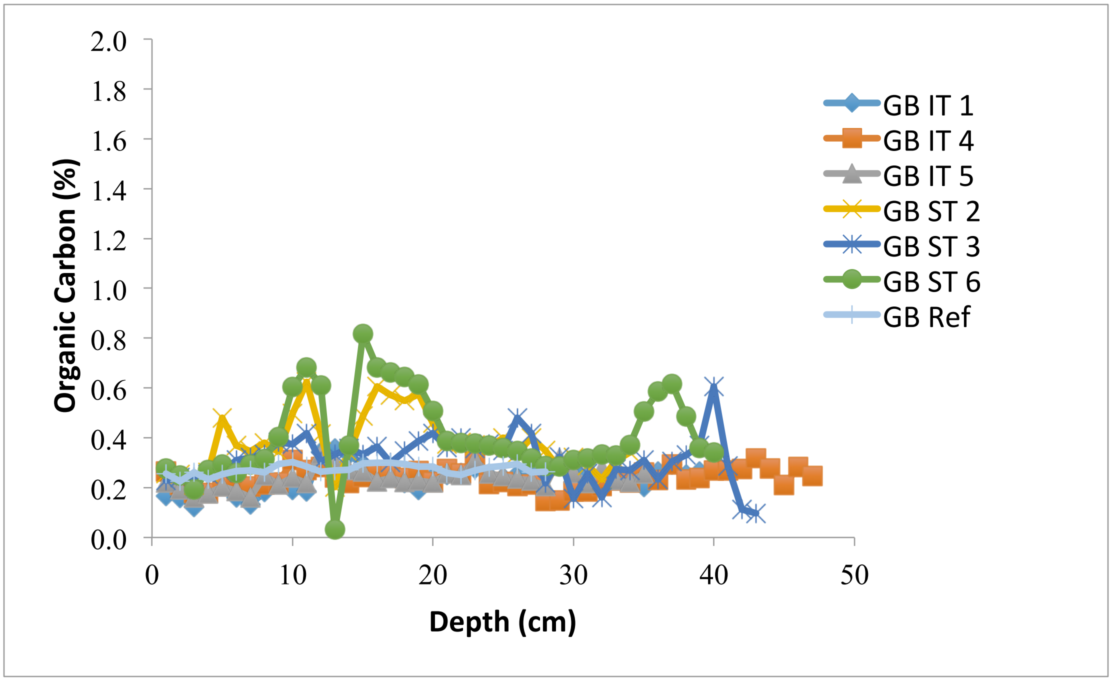

Figure B2. Percent organic carbon in the intertidal (IT), subtidal (ST) and reference (REF) cores from Grice Bay meadow

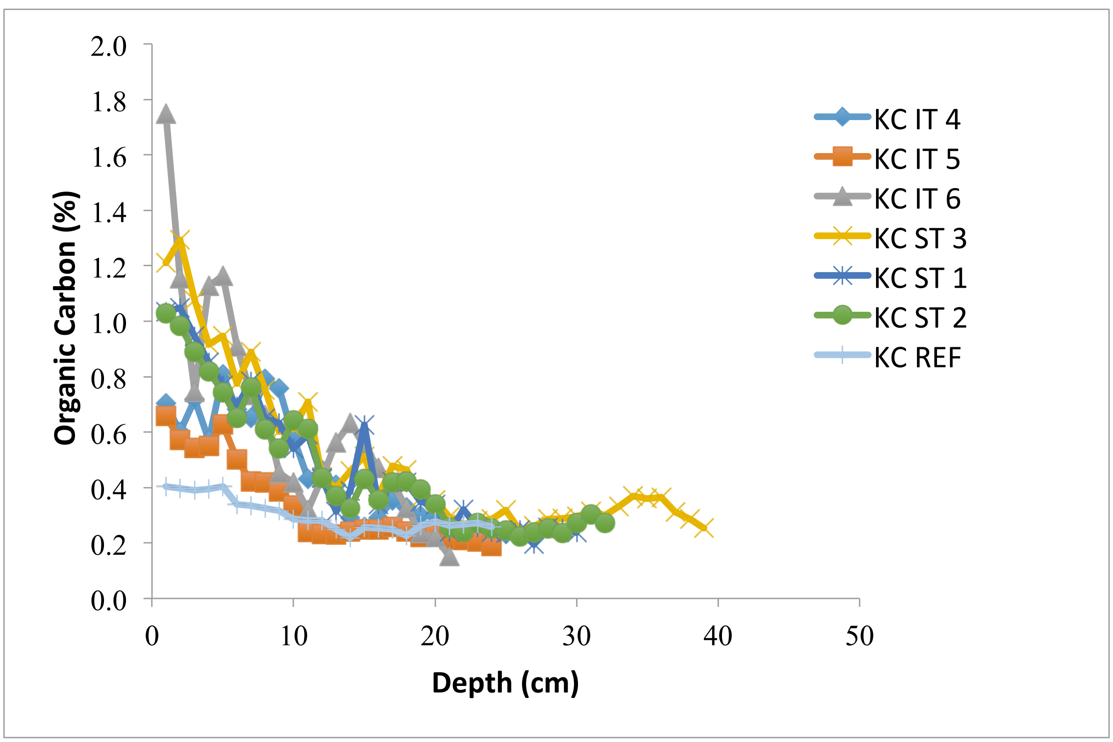

Figure B3. Percent organic carbon in the intertidal (IT), subtidal (ST) and reference (REF) cores from Kennedy Cove meadow

Appendix C. Carbon Stocks

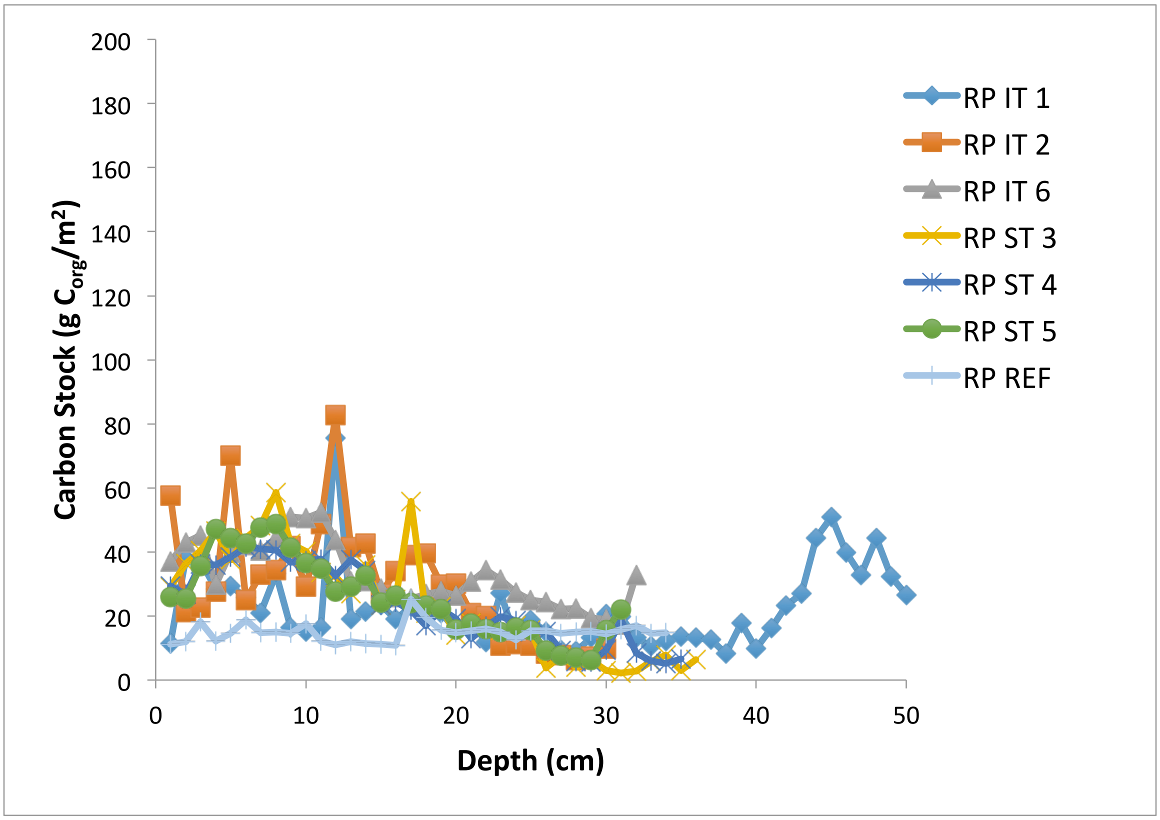

Figure C1. **Carbon stocks (g Corg m^{-2}) in the intertidal (IT), subtidal (ST), and reference (REF) cores from the Robert Point meadow**

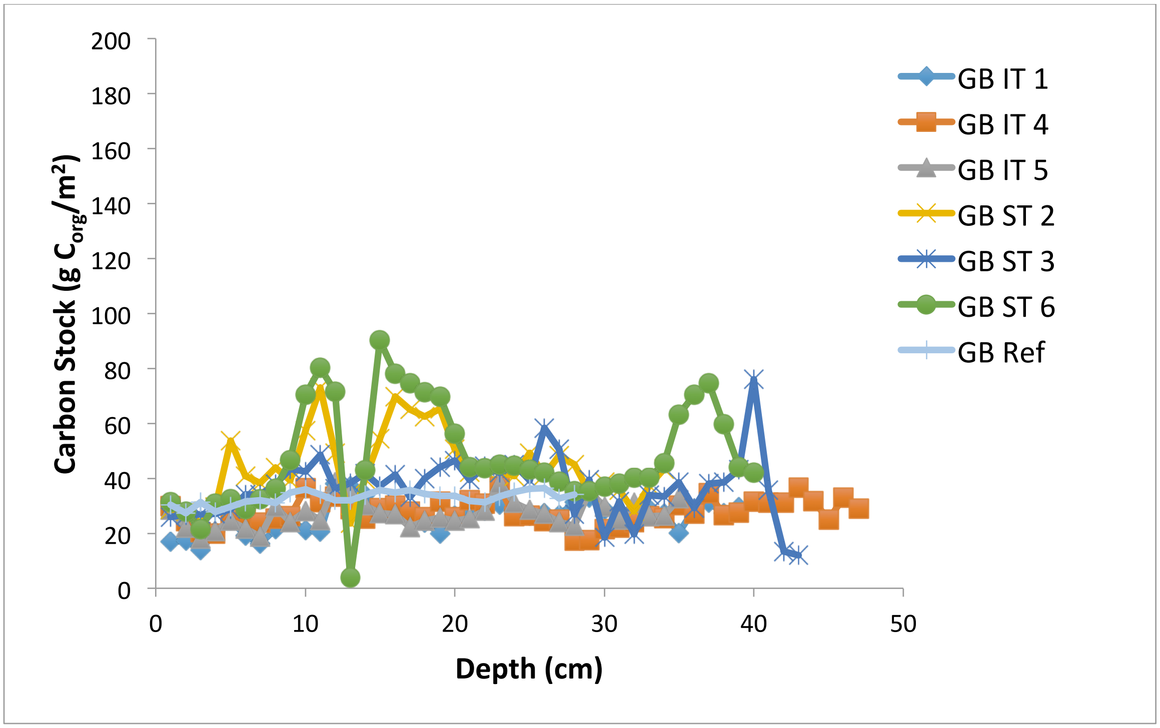

Figure C2. **Carbon stocks (g Corg m-2) in the intertidal (IT), subtidal (ST), and reference (REF) cores from the Grice Bay meadow**

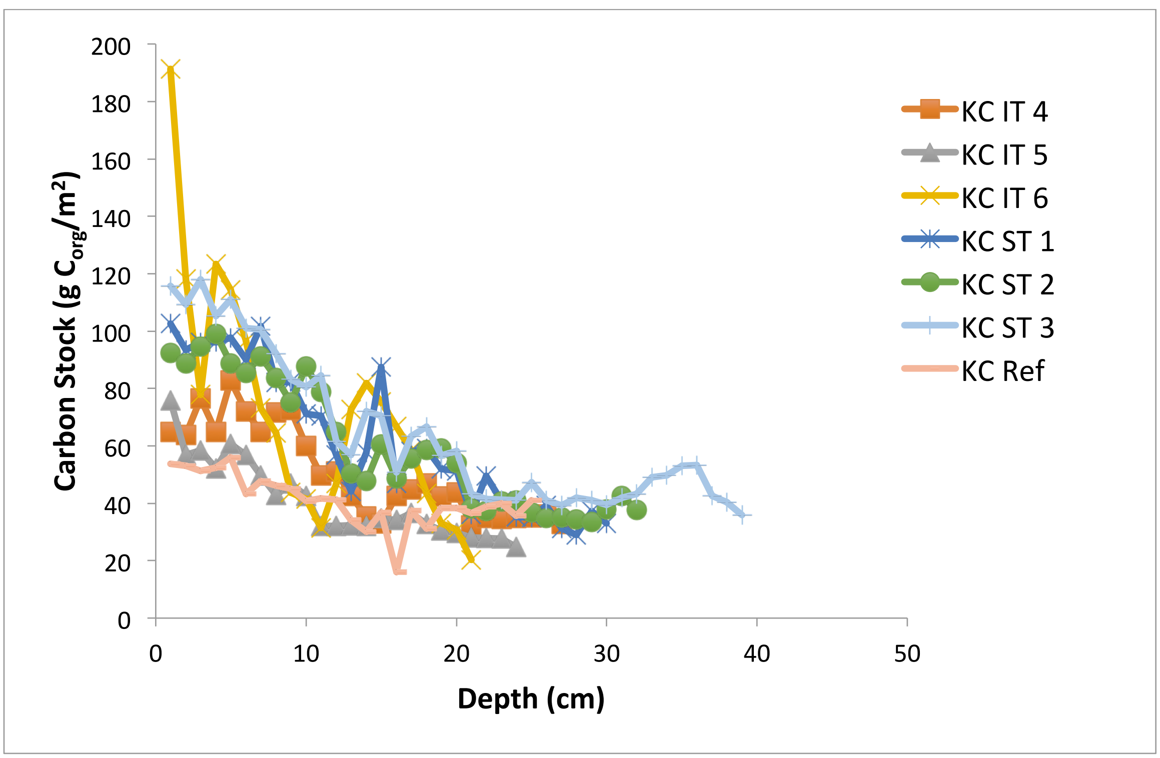

Figure C3. **Carbon stocks (g C_{org} m^{-2}) in the intertidal (IT), subtidal (ST), and reference (REF) cores from the Kennedy Cove meadow**

Appendix D. Pb-210 Dating Data and Age Profiles

Table D1. Pb-210 data for Robert Point intertidal core (RP IT 6)

Upper Section Depth (cm)	Lower Section Depth (cm)	DBD (g cm^{-3})	Po^{210} Total Activity (DPM/g)	Age at Bottom of Extrapolated Section (yr)	CRS Sediment Accumulation Rate (g cm^{-2} yr^{-1})
0.00	1.00	1.1225	12.26	3.17	0.3542
1.00	2.00	1.1386	11.48	6.5	0.3446
2.00	3.00	1.1589	10.68	9.9	0.3369
3.00	4.00	1.1025	9.70	13.2	0.3435
4.00	5.00	1.1616	9.01	16.7	0.3321
5.00	6.00	1.1326	8.33	20.1	0.3270
6.00	7.00	1.1058	7.84	23.6	0.3151
7.00	9.00	1.1523	7.24	31.6	0.2908
9.00	11.00	1.1064	6.52	40.2	0.2561
11.00	13.00	1.0711	5.95	50.1	0.2155
13.00	15.00	1.0955	5.38	62.8	0.1729
15.00	17.00	1.1060	4.17	76.4	0.1631
17.00	19.00	1.1060	3.52	93.2	0.1315
19.00	21.00	1.1021	2.86	114.5	0.1036
21.00	23.00	1.1205	2.16		
23.00	27.00	1.1330	1.65		
27.00	31.00	1.0902	1.27		

Table D2. Pb-210 data for Robert Point subtidal core (RP ST 3)

Upper Section Depth (cm)	Lower Section Depth (cm)	DBD (g cm^{-3})	Po^{210} Total Activity (DPM/g)	Age at Bottom of Extrapolated Section (yr)	CRS Sediment Accumulation Rate (g cm^{-2} yr^{-1})
0.0	1.0	1.1891	12.14	3.24	0.3674
1.0	2.0	1.1887	11.27	6.5	0.3613
2.0	3.0	1.1957	11.14	10.2	0.3290
3.0	4.0	1.1280	10.28	13.6	0.3445
4.0	5.0	1.1829	9.55	17.4	0.3153
5.0	6.0	1.2028	8.79	21.3	0.3090
6.0	7.0	1.1738	7.91	25.0	0.3124
7.0	9.0	1.1770	7.14	33.0	0.2964
9.0	11.0	1.1525	6.45	41.8	0.2607
11.0	13.0	1.1535	5.81	52.2	0.2220
13.0	15.0	1.1469	4.92	63.7	0.2000
15.0	17.0	1.0796	4.12	75.6	0.1814
17.0	19.0	1.1510	3.58	90.8	0.1510
19.0	21.0	1.1608	3.03		
21.0	23.0	1.1398	2.58		
23.0	27.0	1.1480	2.06		
27.0	31.0	1.1617	1.58		
31.0	35.0	1.1506	1.51		
35.0		1.1176	1.07		

Table D3. Pb-210 data for Robert Point reference core (RP REF)

Upper Section Depth (cm)	Lower Section Depth (cm)	DBD (g cm^{-3})	Po^{210} Total Activity (DPM/g)	Age at Bottom of Extrapolated Section (yr)	CRS Sediment Accumulation Rate (g cm^{-2} yr^{-1})
0.0	1.0	1.1346	12.03	2.9	0.3890
1.0	2.0	1.1566	11.40	6.0	0.3763
2.0	3.0	1.1350	10.54	9.0	0.3734
3.0	4.0	1.1481	9.90	12.2	0.3754
4.0	5.0	1.1432	8.90	15.2	0.3732
5.0	6.0	1.1862	8.19	18.4	0.3729
6.0	7.0	1.1391	7.61	21.5	0.3687
7.0	9.0	1.1134	7.11	28.0	0.3451
9.0	11.0	1.1093	6.42	35.0	0.3173
11.0	13.0	1.1594	5.88	43.3	0.2786
13.0	15.0	1.1840	5.15	52.7	0.2503
15.0	17.0	1.1606	4.40	63.0	0.2271
17.0	19.0	1.1650	3.73	74.3	0.2057
19.0	22.0	1.1544	3.10	95.0	0.1674
22.0	23.0	1.1016	2.84	104.1	0.1204
23.0	27.0	1.1285	2.12		
27.0	30.0	1.1227	1.54		
30.0	33.0	1.0866	1.18		

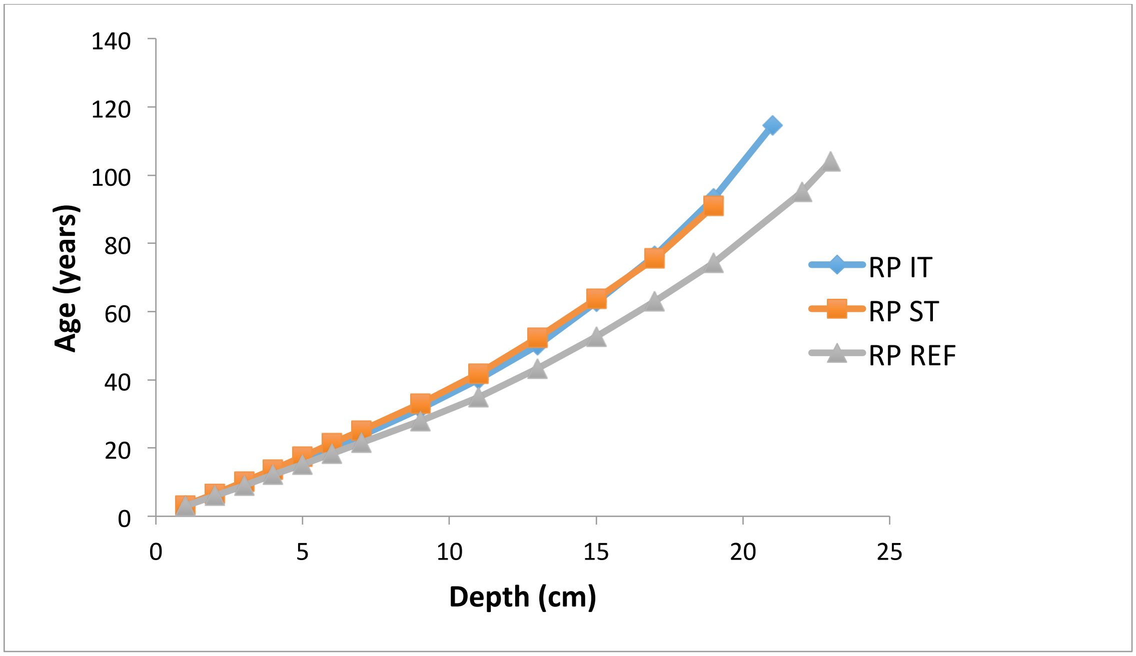

Figure D1. Age (year) vs. depth (cm) in the intertidal (IT), subtidal (ST), and reference (REF) sites of the Robert Point meadow

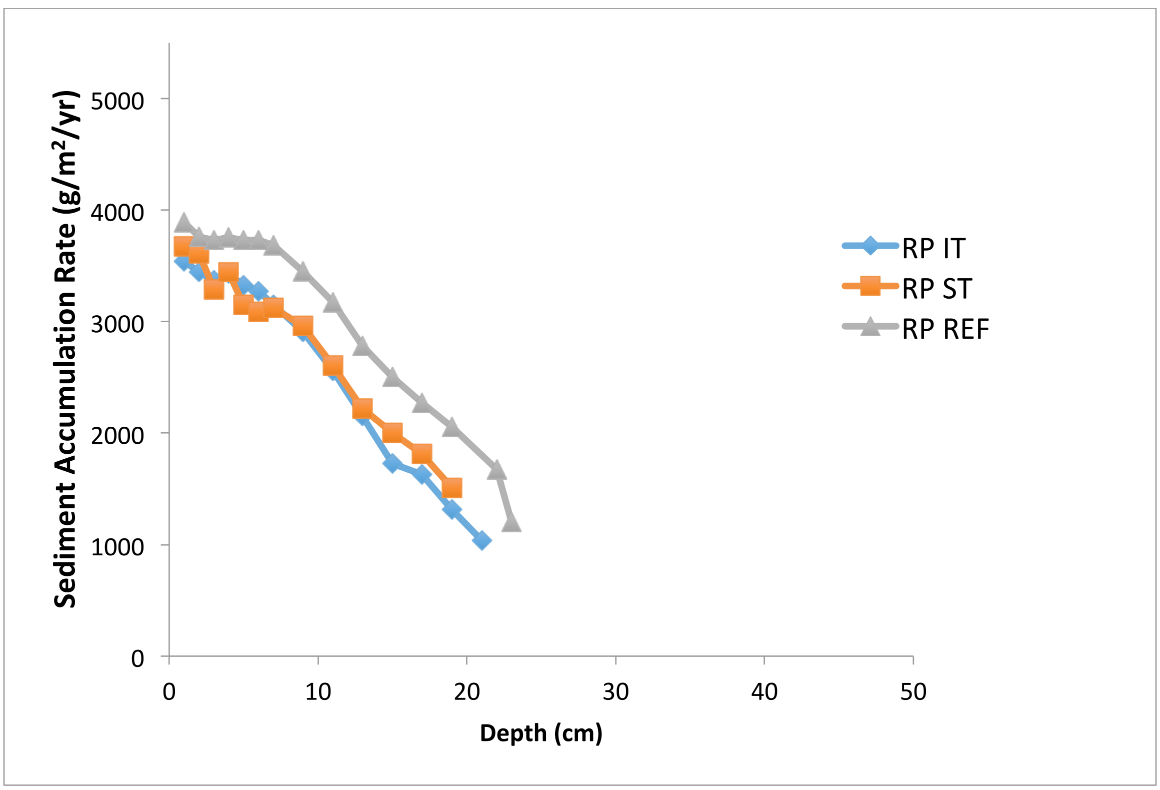

Figure D2. Sediment accumulation rates in the intertidal (IT), subtidal (ST), and reference (REF) sites of the Robert Point meadow

Table D4. Pb-210 data for Grice Bay intertidal core (GB IT 4)

Upper Section Depth (cm)	Lower Section Depth (cm)	DBD (g cm^{-3})	Po^{210} Total Activity (DPM/g)	Age at Bottom of Extrapolated Section (yr)	CRS Sediment Accumulation Rate (g cm^{-2} yr^{-1})
0.0	1.0	1.1326	12.45	2.31	0.4908
1.0	2.0	1.1648	12.03	4.8	0.4734
2.0	3.0	1.1454	11.34	7.2	0.4686
3.0	4.0	1.1145	10.43	9.5	0.4776
4.0	5.0	1.2114	9.63	12.0	0.4862
5.0	6.0	1.1418	9.08	14.4	0.4825
6.0	7.0	1.1738	8.42	16.8	0.4888
7.0	9.0	1.1888	7.83	21.8	0.4753
9.0	11.0	1.1555	7.22	27.0	0.4473
11.0	13.0	1.1864	6.46	32.4	0.4338
13.0	15.0	1.1967	5.79	38.2	0.4185
15.0	17.0	1.1088	5.14	43.6	0.4102
17.0	19.0	1.1773	4.69	49.6	0.3884
19.0	21.0	1.1683	4.26	56.0	0.3651
21.0	23.0	1.2088	3.64	62.5	0.3766
23.0	27.0	1.1736	3.12	75.6	0.3565
27.0	31.0	1.1906	2.85	94.3	0.2553
31.0	35.0	1.1557	2.58		
35.0	39.0	1.1576	1.81		
39.0	43.0	1.1550	1.42		
43.0	47.0	1.1762	1.23		

Table D5. Pb-210 data for Grice Bay subtidal core (GB ST 3)

Upper Section Depth (cm)	Lower Section Depth (cm)	DBD (g cm^{-3})	Po^{210} Total Activity (DPM/g)	Age at Bottom of Extrapolated Section (yr)	CRS Sediment Accumulation Rate (g cm^{-2} yr^{-1})
0.0	1.0	1.1370	12.36	2.82	0.4034
1.0	2.0	1.1062	11.92	5.7	0.3841
2.0	3.0	1.1118	11.16	8.6	0.3770
3.0	4.0	1.0752	10.30	11.5	0.3851
4.0	5.0	1.1024	9.51	14.4	0.3766
5.0	6.0	1.0967	8.78	17.3	0.3767
6.0	7.0	1.0655	8.15	20.2	0.3750
7.0	9.0	1.1314	7.21	26.2	0.3777
9.0	11.0	1.1616	6.57	32.9	0.3461
11.0	13.0	1.1468	5.82	40.0	0.3238
13.0	15.0	1.1127	5.03	47.1	0.3110
15.0	17.0	1.1063	4.36	54.5	0.2994
17.0	19.0	1.1386	3.60	61.9	0.3092
19.0	21.0	1.0893	2.99	68.5	0.3285
21.0	23.0	1.1747	2.64	75.8	0.3239
23.0	27.0	1.2078	2.41	94.6	0.2566
27.0	31.0	1.2247	1.95		
31.0	35.0	1.2356	1.54		
35.0	39.0	1.1665	1.40		
39.0	43.0	1.2226	1.08		

Table D6. Pb-210 data for Grice Bay reference core (GB REF)

Upper Section Depth (cm)	Lower Section Depth (cm)	DBD (g cm^{-3})	Po^{210} Total Activity (DPM/g)	Age at Bottom of Extrapolated Section (yr)	CRS Sediment Accumulation Rate (g cm^{-2} yr^{-1})
0.0	1.0	1.1856	12.19	3.05	0.3884
1.0	2.0	1.2181	11.77	6.4	0.3666
2.0	3.0	1.2039	10.99	9.7	0.3590
3.0	4.0	1.1913	10.41	13.2	0.3640
4.0	5.0	1.1727	9.50	16.6	0.3468
5.0	6.0	1.1835	8.91	20.1	0.3381
6.0	7.0	1.1875	8.24	23.6	0.3346
7.0	8.0	1.1956	7.80	27.3	0.3214
8.0	9.0	1.1788	7.17	31.0	0.3200
9.0	11.0	1.1933	6.58	38.9	0.3019
11.0	13.0	1.1917	5.89	47.7	0.2728
13.0	15.0	1.1959	5.29	57.6	0.2402
15.0	17.0	1.1979	4.76	69.4	0.2031
17.0	19.0	1.1764	4.35	84.4	0.1566
19.0	21.0	1.2237	3.65	103.4	0.1292
21.0	23.0	1.2411	3.20		
23.0	25.0	1.2557	2.72		
25.0	28.0	1.2968	1.87		

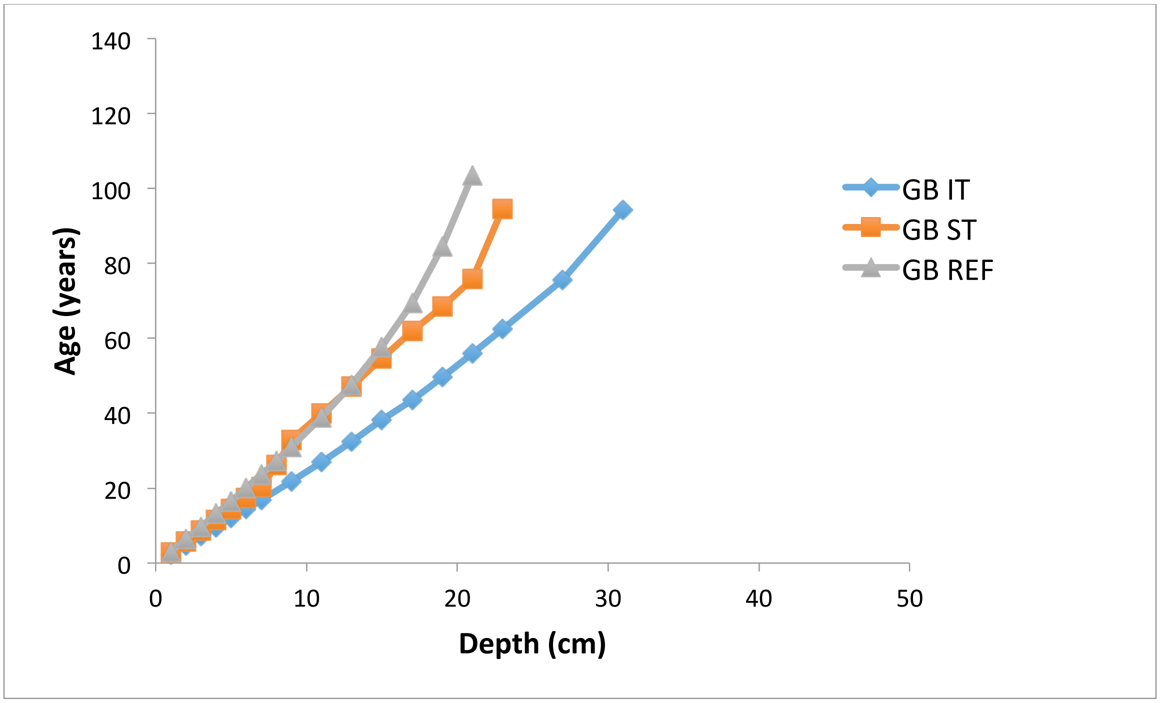

Figure D3. Age (year) vs. depth (cm) in the intertidal (IT), subtidal (ST), and reference (REF) sites of the Grice Bay meadow

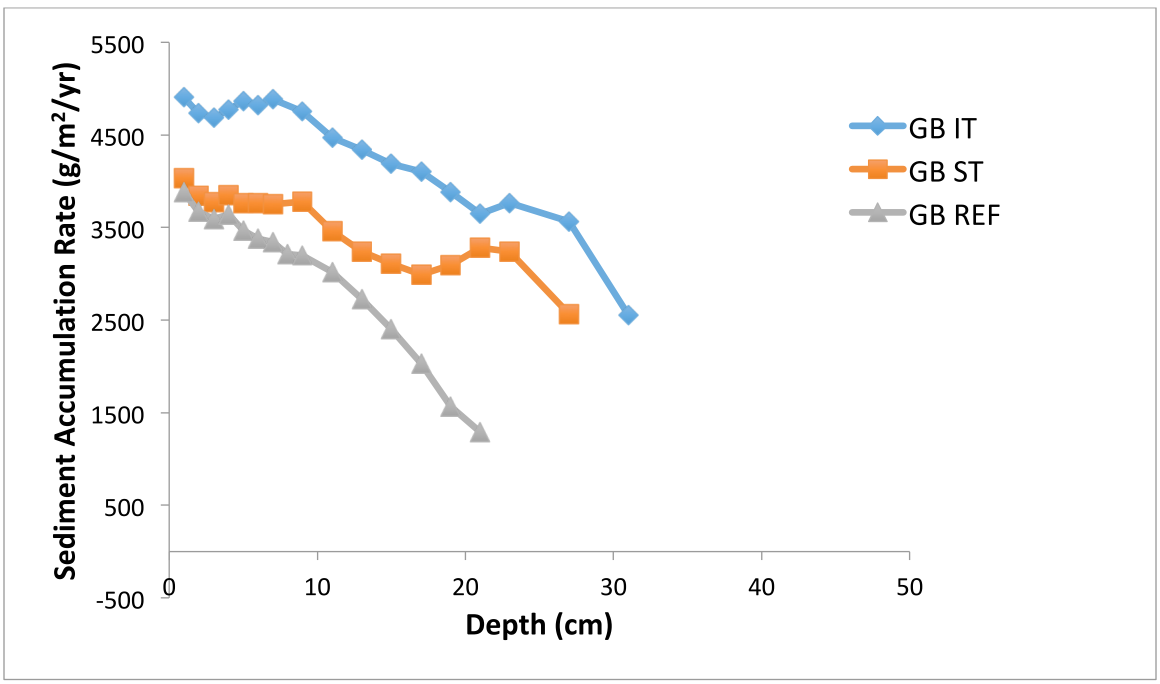

Figure D4. Sediment accumulation rates in the intertidal (IT), subtidal (ST), and reference (REF) sites of the Grice Bay meadow

Table D7. Pb-210 Data for Kennedy Cove intertidal core (KC IT 4)

Upper Section Depth (cm)	Lower Section Depth (cm)	DBD (g cm^{-3})	Po^{210} Total Activity (DPM/g)	Age at Bottom of Extrapolated Section (yr)	CRS Sediment Accumulation Rate (g cm^{-2} yr^{-1})
0.0	1.0	0.9206	12.13	3.0	0.3112
1.0	2.0	1.0595	11.28	6.4	0.3061
2.0	3.0	1.0639	10.43	10.0	0.3007
3.0	4.0	1.1370	9.61	13.8	0.3028
4.0	5.0	1.0243	8.60	17.2	0.3017
5.0	6.0	1.0584	7.67	20.6	0.3128
6.0	7.0	0.9957	7.15	23.8	0.3081
7.0	9.0	0.9564	6.31	29.9	0.3140
9.0	11.0	1.1543	5.90	38.3	0.2741
11.0	13.0	1.0421	5.51	47.4	0.2293
13.0	15.0	1.2803	4.68	59.7	0.2087
15.0	17.0	1.2656	4.04	74.4	0.1726
17.0	19.0	1.4082	3.27	93.3	0.1487
19.0	21.0	1.3281	2.97	124.9	0.0841
21.0	25.0	1.5064	1.90		
25.0	27.0	1.5215	1.54		

Table D8. Pb-210 Data for Kennedy Cove subtidal core (KC IT 4)

Upper Section Depth (cm)	Lower Section Depth (cm)	DBD (g cm^{-3})	Po^{210} Total Activity (DPM/g)	Age at Bottom of Extrapolated Section (yr)	CRS Sediment Accumulation Rate (g cm^{-2} yr^{-1})
0.0	1.0	0.9553	12.27	2.35	0.4074
1.0	2.0	0.8439	11.86	4.5	0.3949
2.0	3.0	1.0979	10.99	7.2	0.3994
3.0	4.0	1.1470	10.43	10.2	0.3970
4.0	5.0	1.1732	9.42	13.1	0.3992
5.0	6.0	1.3025	8.71	16.4	0.3979
6.0	7.0	1.1329	7.97	19.2	0.4029
7.0	9.0	1.3844	7.06	26.1	0.4039
9.0	11.0	1.1919	6.54	32.7	0.3606
11.0	13.0	1.4194	5.67	40.9	0.3461
13.0	15.0	1.3753	4.88	49.2	0.3289
15.0	17.0	1.3260	4.21	57.6	0.3159
17.0	19.0	1.5620	3.43	67.0	0.3333
19.0	23.0	1.4713	2.75	84.5	0.3367
23.0	27.0	1.5063	2.50	113.5	0.2075
27.0	31.0	1.3396	2.02		
31.0	35.0	1.4666	1.67		
35.0	39.0	1.4139	1.45		

Table D9. Pb-210 Data for Kennedy Cove reference core (KC REF)

Upper Section Depth (cm)	Lower Section Depth (cm)	DBD (g cm^{-3})	Po^{210} Total Activity (DPM/g)	Age at Bottom of Extrapolated Section (yr)	CRS Sediment Accumulation Rate (g cm^{-2} yr^{-1})
0.0	1.0	1.3314	12.26	3.9	0.3441
1.0	2.0	1.3379	11.46	7.9	0.3287
2.0	3.0	1.3149	10.50	12.0	0.3201
3.0	4.0	1.3317	9.73	16.4	0.3244
4.0	5.0	1.3849	8.89	21.0	0.2975
5.0	6.0	1.2790	7.81	25.3	0.3033
6.0	7.0	1.4300	7.12	30.1	0.2961
7.0	8.0	1.4248	6.24	34.8	0.3028
8.0	9.0	1.4198	5.63	39.5	0.3002
9.0	11.0	1.4765	5.17	50.7	0.2652
11.0	13.0	1.3664	4.62	63.3	0.2154
13.0	15.0	1.4370	4.10	81.0	0.1626
15.0	17.0	1.5031	3.21	103.7	0.1327
17.0	19.0	1.4515	2.68		
19.0	21.0	1.3837	2.09		
21.0	24.0	1.3793	1.50		

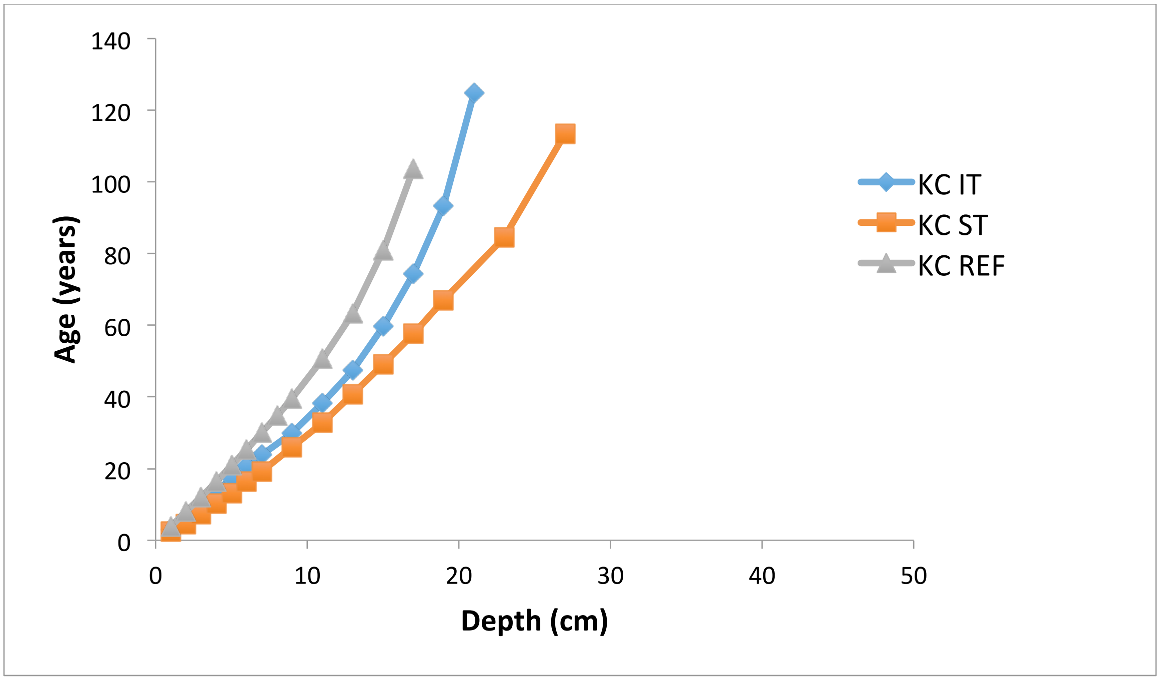

Figure D5. **Age (year) vs. depth (cm) in the intertidal (IT), subtidal (ST), and reference (REF) sites of the Kennedy Cove meadow**

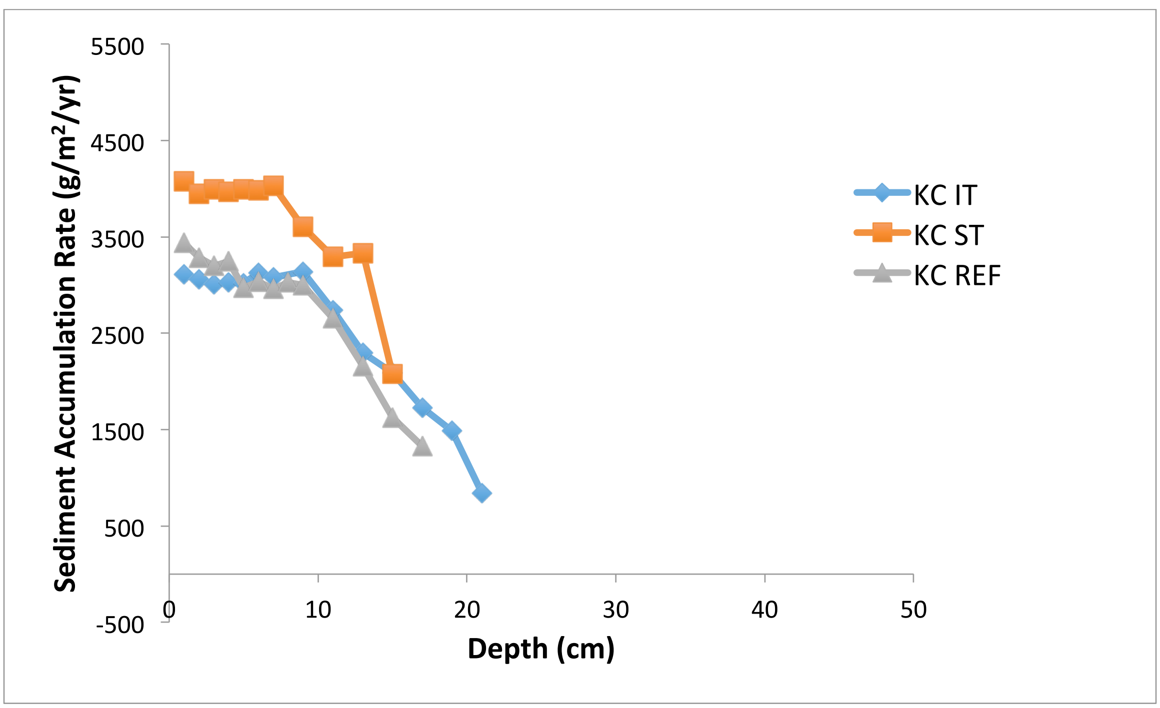

Figure D6. **Sediment accumulation rates in the intertidal (IT), subtidal (ST), and reference (REF) sites of the Kennedy Cove meadow**

Appendix E. Nitrogen Data

Table E1. Average nitrogen (%N) and carbon:nitrogen ratios (C:N) of sediment at Robert Point, Grice Bay, and Kennedy Cove

	Nitrogen (% DW)		C:N ratio	
Zone	**Average**	**SD**	**Average**	**SD**
		Robert Point		
Intertidal	0.024	0.15	10.29	2.04
Subtidal	0.027	0.021	8.62	2.14
		Grice Bay		
Intertidal	0.042	0.008	8.30	1.65
Subtidal	0.043	0.007	8.27	0.61
		Kennedy Cove		
Intertidal	0.077	0.016	12.01	2.23
Subtidal	0.090	0.010	11.07	0.21