



# Blue Carbon in Tidal Wetlands of the Pacific Coast of Canada



## Examples from Pacific Rim National Park Reserve and the Clayoquot Biosphere Reserve

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Recent research has focused on the high carbon accumulation rates of coastal ecosystems, such as those of mangroves, seagrasses, and salt marshes, as a means of sequestering (blue) carbon for climate mitigation purposes. Material from dead plants and animals in salt marshes accumulates over time in low-oxygen conditions, limiting the CO<sub>2</sub> emissions from the normal process of aerobic decomposition (McLeod et al. 2011; Chmura et al. 2003; Duarte et al. 2013). This accumulation of organic matter can lead to a significant buildup of carbon stored in the soils and sediments of these ecosystems. Including carbon from these ecosystems in carbon accounting mechanisms requires thorough quantification of carbon stored in the relevant carbon sinks (Coverdale et al. 2014; Macreadie et al. 2012; McLeod et al. 2011; Mitsch et al. 2012). Although coastal salt marshes constitute only a small portion of the global land area, they are capable of storing a relatively large amount of carbon relative to their area due to their high productivity (McLeod et al. 2011). This carbon storage potential is increasingly recognized as a valuable ecosystem service of coastal salt marshes (Coverdale et al. 2014; Fourqurean et al. 2012; McLeod et



Kennedy Cove South, British Columbia.

Photo: Courtesy of Stephen Chastain

al. 2011). However, the world has lost between one-quarter and one-half of all coastal vegetated ecosystems in the past 50 to 100 years, (McLeod et al. 2011) and estimates have placed the total carbon emissions from these losses at up to 19% of the total carbon emitted by deforestation (Pendleton et al. 2012). One case study estimates that salt marshes in England store 70,000 fewer tons of carbon per year than they did in 1950 (Beaumont et al. 2014).

This study is part of an effort to quantify the soil carbon stocks and carbon accumulation rates in salt marsh ecosystems along the Pacific coast of Canada. Estimates of carbon accumulation in salt marshes from the Northeastern Pacific region are much less complete than for other areas of the globe, such as the Mediterranean Sea, Mexico, and Australia. Salt marshes in Eastern Canada at a similar latitude have been studied, but a survey of available worldwide salt marsh carbon accumulation data included only a single data point from Western Canada (Chmura et al. 2003). Thus, more data are needed to produce a regional estimate that better represents the different environmental and anthropogenic influences experienced in the Pacific Coast region of Canada (Chmura et al. 2003; Ouyang and Lee 2014).

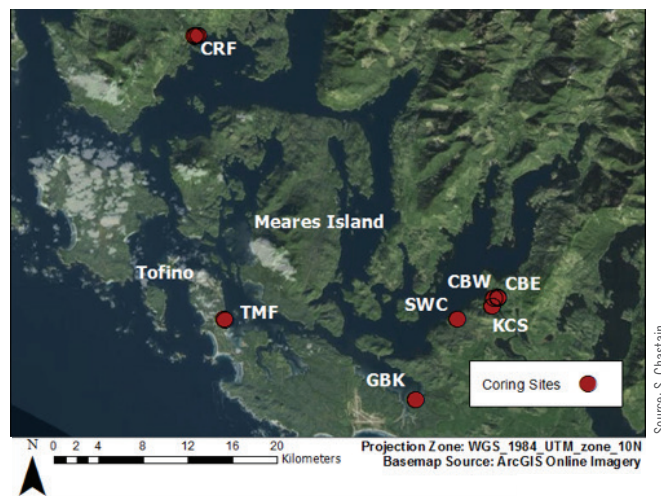
This study also examined the potential impact of eco-cultural modification of salt marsh systems on carbon storage. In some locations along the Pacific Coast of Canada, salt marsh areas were used for intensive gathering and cultivation of rhizome vegetables by First Nations people prior to European contact (Deur 2002). Raised terraces were constructed in the high marsh zone of salt marshes to increase the area in which the desired plants could grow. Extensive tilling and plowing ensured that the soils were well mixed and fertile; the indigenous word for these terraces translates as “the place of human-made soil” (Deur 2002). These gardens and rockworks have been abandoned for nearly a century, but evidence of their existence remains detectable as highly mixed topsoils (Deur 2000).

## Research Summary

Several sites were selected in Clayoquot Sound, an inlet of the Pacific Ocean on the West Coast of Vancouver Island, British Columbia, Canada. The Sound includes land under several different types of protected area designation. The largest is the UNESCO Clayoquot Sound Biosphere Reserve, encompassing 350,000 hectares and Pacific Rim National Park Reserve and Meares Island, a Tla-o-qui-aht tribal park (Figure 1). Seven salt marshes sites were sampled in the Sound: Cannery Bay East

(CBE), Cannery Bay West (CBW), Cypress River Flats (CRF), Grice Bay- Kootowis Creek (GBK), Kennedy Cove South (KCS), Shipwreck Cove (SWC), and Tofino Mud Flats (TMF) (Figure 1).

Figure 1. Overview of marsh areas sampled in Clayoquot Sound



These sites were selected for two reasons:

- The sites are relatively undisturbed and lie within protected areas, allowing the quantification of carbon accumulation rates in a close analogue to natural conditions.
- The region contains sites where the cultivation practices of Aboriginal peoples have altered salt marshes, allowing the examination of the effects of past eco-cultural modification on salt marsh carbon accumulation.

At each site, core locations were selected to represent a range of salinities that occurred as a result of inundation across high, middle, and low tide exposures because of the potential impact on carbon burial (Chmura et al. 2011; IPCC 2013) (Figure 2). Linear transects were set up perpendicular to the shoreline, and cores were collected across the range of strata represented by different elevations and vegetation types (Fourqurean et al. 2014a).

Thirty-six sediment cores were collected from the low and high marsh zones of seven salt marshes located along transects meant to sample the full range of marsh vegetation from the seaward edge to the zone of highest inundation (Figure 3). Sediment characteristics and carbon content on 34 cores were measured and <sup>210</sup>Pb chronologies for four

of these cores were developed. This information was then used to estimate carbon storage and carbon accumulation rates (Howard et al. 2014). Soil texture and color of each core were also described and cores were sampled at 1-cm resolution to measure dry bulk density and loss-on-ignition (LOI) to measure organic material. Carbon stock estimates were made using two different methods to scale up the carbon content estimates from individual cores to megagrams per hectare (Mg-C ha<sup>-1</sup>). Lastly, one deep core each from four of the seven sites was dated using <sup>210</sup>Pb radioisotopic dating to establish sediment accumulation rates and calculate carbon accumulation rates.

Measurements of carbon stocks and accumulation rates from six high marsh cores were also taken from an historically documented garden site. These cores were compared with estimates collected from the other 29 cores from salt marsh systems in the study area to examine how soil modification in the high marsh zone may have impacted carbon storage and accumulation rates.

Soil carbon density (SCD) and carbon stocks were estimated for each core, and carbon accumulation rates (CAR) were estimated for each core with <sup>210</sup>Pb dates.

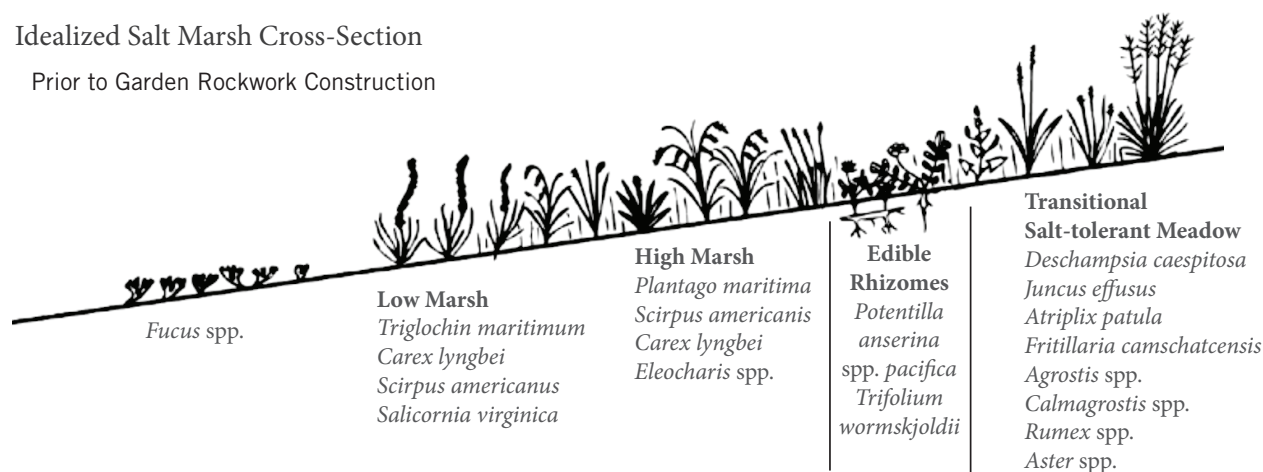
First, for SCD, the mass of carbon found in a cubic centimeter of soil at the given depth, was estimated as the product of the organic carbon content % C<sub>org</sub> and the dry bulk density (DBD):

$$SCD \left( \frac{gC_{org}}{cm^3} \right) = \left( \frac{\%C_{org}}{100} \right) \times DBD$$

Figure 2. Cross-section of idealized British Columbia salt marsh

### Idealized Salt Marsh Cross-Section

Prior to Garden Rockwork Construction



Note: The characteristic vegetation strata in this figure are used to separate high from low marsh core locations.

Figure 3. Overhead view of a transect

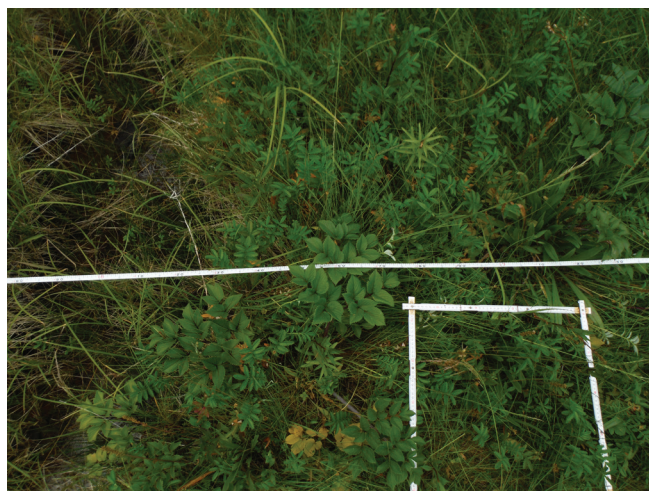


Photo: Stephen Chastain

Note: The core was taken from a corner within the 50 x 50 cm quadrat and the vegetation is typical of the high marsh stratum.

Second, carbon stocks (g-C cm<sup>-2</sup>) were estimated by two methods: (1) summing the carbon stocks for each 1-cm thick sample interval for which SCD had been estimated, over the entire length of the core, assuming the depth of refusal (which ranged from 5 to 100 cm) represented the depth below which carbon was no longer accumulating (Fourqurean et al. 2014b); and (2) estimating the average SCD for each core (average DBD, average % C<sub>org</sub>) and multiplying by the depth of refusal. Carbon stock estimates (g-C cm<sup>-2</sup>) made using both methods were then converted to Mg-C ha<sup>-1</sup> for each core. A site-wide average was estimated using all cores at each site, and a regional average was calculated from the site-wide averages.





Extracting a core, Cannery Bay East.

Finally, the carbon accumulation rate (CAR) was estimated using the bulk sediment accumulation rate (SAR) and the average soil carbon densities (SCD) estimated for the four cores with <sup>210</sup>Pb dates and expressed in terms of g-C m<sup>-2</sup>•yr<sup>-1</sup> (Crooks et al. 2014):

$$CAR \left( \frac{g\ C}{m^2\ yr} \right) = SAR \left( \frac{cm}{yr} \right) \times SCD \left( \frac{g\ C}{cm^3} \right) * 10,000 \left( \frac{cm^2}{m^2} \right)$$

Sediment accumulation rates (SAR) were estimated using <sup>210</sup>Pb ages for each cores. However, since many of the cores from this study experienced compaction during collection, a compaction correction factor was calculated (Fourqurean et al. 2014b):

$$Compaction\ correction\ factor = \frac{length\ of\ sample\ (cm)}{length\ of\ core\ penetration\ (cm)}$$

The compaction correction factor was then applied to each 1-cm increment to estimate the uncompacted depth below the surface (Fourqurean et al. 2014b):

The bulk sediment accumulation rate (SAR) was then calculated for the entire core, using the uncompacted core depth divided by the age of the deepest portion of the core containing <sup>210</sup>Pb activity:

$$SAR \left( \frac{cm}{yr} \right) = \frac{uncompacted\ core\ depth\ (cm)}{^{210}Pb\ age\ of\ core\ deepest\ point\ (yr)}$$

Results showed that the zone of carbon accumulation, defined in this study as the depth of soil described as top-soil or peat through which the percussion corer could be driven (Fourqurean et al. 2014b), ranged from less than five cm to 60 cm.

Average carbon stocks in Clayoquot Sound marsh soils range between 35 and 113 Mg-C ha<sup>-1</sup>, as estimated by method one, and between 56.4 and 173 Mg-C ha<sup>-1</sup> by method two (Figure 4). The regional average calculated by method one is 80.6 ± 43.8 Mg-C ha<sup>-1</sup> and 126 ± 71.2 Mg-C ha<sup>-1</sup> for method two. The carbon stock calculations made using method one are comparable to those from Everett (WA), USA (78.1 Mg-C ha<sup>-1</sup>, Crooks et al. 2014) which were calculated using a similar methodology. Method two estimates of carbon stocks are consistently higher than those for method one and are closer to carbon stock estimates made for Florida salt marshes (201.5 Mg-C ha<sup>-1</sup>, R.A.E. 2016).

Figure 4. Carbon stock estimates from Clayoquot Sound sites

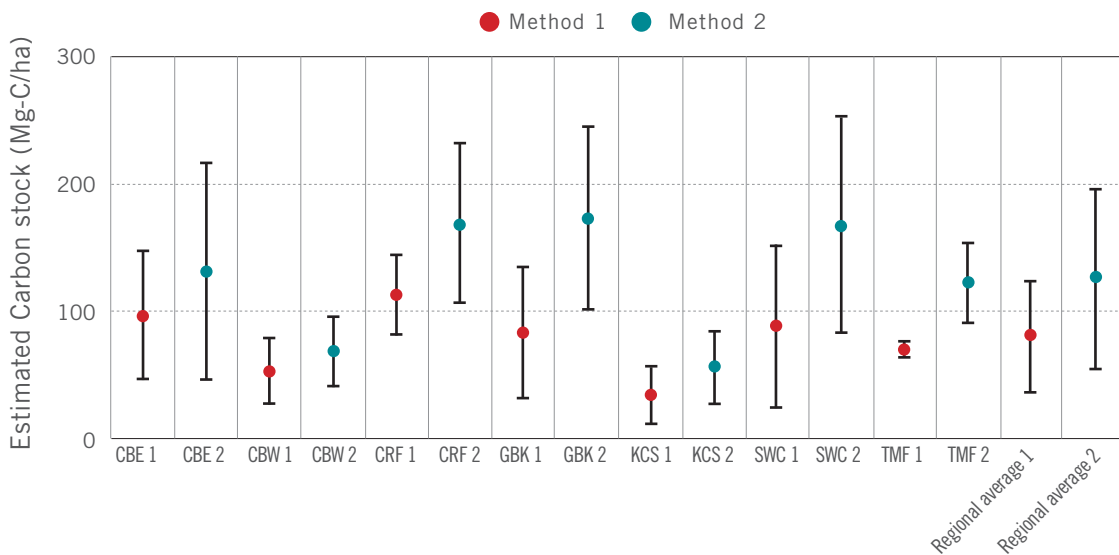




Photo: Courtesy of Stephen Chastain

Coring team, Clayoquot Sound.

The average carbon density was  $0.033 \text{ g-C cm}^{-3}$ , which is higher than published carbon densities of marshes in nearby sites of Ucluelet, Canada ( $0.017 \text{ g-C cm}^{-3}$ ) (Chmura et al. 2003) and Everett, WA, USA ( $0.027 \text{ g-C cm}^{-3}$ ) (Crooks et al. 2014).

The carbon accumulation rates (CARs) in Clayoquot Sound range from  $75$  to  $264 \text{ g-C m}^{-2}\cdot\text{yr}^{-1}$ . The Clayoquot Sound regional average CAR of  $173 \text{ g-C m}^{-2}\cdot\text{yr}^{-1}$  is below the global average of  $245 \text{ g-C m}^{-2}\cdot\text{yr}^{-1}$  and the regional estimate of  $315 \text{ g-C m}^{-2}\cdot\text{yr}^{-1}$  calculated for the latitude range  $48.4\text{-}58.4^\circ\text{N}$  (Ouyang and Lee 2014). At the same time, the average Clayoquot Sound carbon accumulation rate is very close to the North Pacific average of  $174 \text{ g-C m}^{-2}\cdot\text{yr}^{-1}$  estimated for  $28.4\text{-}38.4^\circ\text{N}$ , using eight studies from the coast of California (Chmura et al. 2003).

Several factors can influence our estimates of soil carbon density, carbon stocks, and carbon accumulation rates, including (1) the representativeness of coring in each marsh; (2) effects of compaction during coring process; and (3) estimation of the deepest depth of carbon accumulation.

Overall, the sampling strategy was designed to obtain roughly an equal number of high and low marsh cores from the region as a whole. The average carbon stocks of high marsh cores were  $105 \pm 40.1 \text{ Mg-C ha}^{-1}$  and the average carbon stocks of low marsh cores were  $53.6 \pm 30.8 \text{ Mg-C ha}^{-1}$  using method one. These data suggest that the

high marsh areas contain twice as much carbon as the low marsh areas. This significant difference emphasizes the small-scale variation in carbon stocks across a marsh.

Results here also support the observations of previous studies that the coring method used affects both the degree of compaction and the estimated depth of refusal. Of our 36 cores, 11 experienced compaction of 30% or more. For calculating carbon accumulation rates, it was assumed compaction was uniform over the core for simplicity, but compaction likely affects upper levels of soil more than lower levels where density is naturally higher.

The zone of carbon accumulation, defined in this study as the depth of soil described as topsoil or peat through which the percussion corer could be driven (Fourqurean et al. 2014b), ranged from less than 5 to 60 cm. The greatest variation of depth of refusal within a single site is from 14 to 59 cm. These depths of carbon accumulation are shallower than many of those commonly encountered in salt marshes, which can range up to 3 m deep or more (Fourqurean et al. 2014b). Previous studies have assumed average depths of carbon accumulation ranging from 30 cm (Crooks et al. 2014) to 1 m (IPCC 2013). Extrapolating carbon stock estimates to an assumed depth of accumulation increases the uncertainty in these carbon stock estimates, and even the assumption of 30 cm accumulation results in up to five-fold higher estimate in carbon stocks.

## Factors affecting Carbon Stocks in Clayoquot Sound

This study provides an estimate of carbon stocks and accumulation rates that are comparable with other regional estimates but somewhat smaller than global estimates for this latitudinal band. While some of the factors controlling carbon accumulation rates and stocks in this area are common to all areas, some are specific to the region.

Sea level rise and tectonic activity – Accelerated rates of sea-level rise are currently thought to be reducing the areal extent of salt marshes worldwide but the rate of loss is not well quantified (Howard et al. 2014; McLeod et al. 2011; Craft et al. 2009). Sea-level rise may not be a significant factor in Clayoquot Sound because of regional tectonic activity: in nearby Tofino, mean sea level is estimated to have been decreasing by 1.7 mm per year over the last century (NOAA 2013).

Rate of sediment flow – The rate of sediment flow from upstream seldom matches the rate of erosion at the seaward edge of a marsh, and the lateral extent of a marsh is a dynamic factor affecting its carbon storage capacity (Fagherazzi et al. 2013). The contemporary extent of marshes in Clayoquot Sound could be a product of a pulse of sediment eroded from upstream, specifically in response to clearcutting of forested areas during logging earlier in the 20<sup>th</sup> century.

First Nations land use – Cypress River Flats is historically documented as a place where Pacific silverweed was cultivated by First Nations people. While one might expect that cultivation practices would enhance carbon stocks and carbon accumulation rates, this study suggests that carbon stocks were not statistically different from five other sites, and accumulation rates were actually lower (161 versus 212–280 g-C m<sup>-2</sup>•yr<sup>-1</sup>) than rates at two of the three other sites. One explanation is that the culturally modified salt marsh at Cypress River Flats did not contain a raised stone terrace at the base of the high marsh zone. Such stone walls are a typical feature of cultivated salt marshes and could act to retain soil organic matter in the marsh. The absence of such a wall could result in carbon storage behavior that is more similar to that observed in the undisturbed salt marshes. A second explanation for the similarity lies in the fact that previously cultivated sites have been abandoned for a full century. Thus, the effect of past land use on accumulation rates may be short-lived and undetectable after 100 years (Bouchard and Kennedy 1990; Deur 2000).

## Research Priorities

The region-specific measurements of soil carbon in this study could become a component of a blue carbon assessment of tier 2 quality, according to IPCC guidelines (IPCC 2013). Specific work could include:

- Mapping the areal extent of salt marshes along the Pacific Coast. Many of the salt marshes in Clayoquot Sound are small, but given the average carbon accumulation rates of 173 g-C m<sup>-2</sup>•yr<sup>-1</sup>, estimates of the combined area of these marshes are required to appreciate the total carbon accumulation potential.
- Calculating carbon accumulation rates from low marsh areas to compare with high marsh areas. When combined with precise mapping, this could allow a much more complete picture of the radiative balance of salt marshes, especially in the context of changing sea levels and their effect on the low marsh.
- Experimental archaeology study on soil characteristics of marsh gardens following traditional First Nations management techniques to investigate co-benefits of marsh soil enhancement.



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