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SEDIMENT ORGANIC CARBON STOCKS IN COASTAL BLUE CARBON HABITATS: PILOT STUDY FOR TE TAUIHU

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Prepared for Tasman Environmental Trust

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1. INTRODUCTION

The world is in a climate change emergency, and first and foremost it is critical that humans reduce their carbon emissions to mitigate the problem. Nature-based solutions[1] that sequester carbon also have an important role in helping mitigation and adaptation to climate change. ‘Blue carbon’ is a catchphrase for carbon stored in the ocean. Salt marsh and seagrass are blue carbon habitats that sequester a large proportion of their carbon in the soil / sediment[2] beneath them (McLeod et al. 2011; Otero 2021). Salt marsh is salt-tolerant vegetation that is found in the upper intertidal reaches of coastal areas, and seagrass is a marine flowering plant that is found in salty and brackish waters on tidal flats and also under the sea (Figure 1).

In Aotearoa New Zealand, many saltmarsh and seagrass habitats have suffered degradation and in some areas have been lost altogether (Turner and Schwarz 2006; Denyer and Peters 2020). Such degradation limits the ability of these habitats to sequester and store carbon, and presents a restoration opportunity that could increase carbon sequestration. Other reasons for protecting and restoring these habitats include (but are not limited to) their importance in relation to indigenous values and cultural practices, their benefits to biodiversity (e.g. through habitat provision), their ability to improve water quality, and their sediment-trapping and seabed-stabilising abilities (Turner and Schwarz 2006; Thomsen et al. 2009). Blue carbon habitats, including salt marsh, can also help to protect vulnerable land and people from coastal flood risk (Van Coppenolle and Temmerman 2020), and therefore are an important climate adaptation solution.

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[1] Nature-based solutions generally refer to the sustainable management and use of natural features and processes to address socio-environmental challenges, including climate change.

[2] In this report we use the terms ‘sediment’ and ‘soil’ interchangeably. ‘Sediment’ is more commonly used in the marine context, so we have largely used this term.

Figure 1. Examples of saltmarsh landscape. Top: rushland (*Juncus* sp.) and herbfield (*Salicornia quinqueflora*). Bottom left: close-up of herbfield (*S. quinqueflora*). Bottom right: close-up of seagrass (*Zostera muelleri*). Note that these images are provided as examples and are not from our pilot study.

In Te Tauihu (the top of the South Island) estuaries, a recent carbon decomposition study, conducted using tea bags, indicated the importance of blue carbon habitats, such as salt marsh and seagrass, for carbon accumulation compared to terrestrial and wetland ecosystems in other locations (Zaiko and Pearman 2022). However, to our knowledge, soil organic carbon stocks have not been quantified for Te Tauihu estuaries.

Tasman Environmental Trust (TET)[3] is leading the Core and Restore project,[4] and, alongside key partners and supporters Cawthron Institute (Cawthron), Beca, Ngāti Apa ki te Rā Tō, Nelson City Council, Manawhenua ki Mohua, HealthPost Nature Trust and Department of Conservation (DOC), carried out a pilot study to collect coastal blue carbon soil stock (i.e. the amount of organic carbon stored in soil) data for Te Tauihu, with a focus on saltmarsh and seagrass[5] habitats. The intention was to get an indication of how much carbon is stored in coastal wetlands in Te Tauihu relative to the global range and published data from Aotearoa New Zealand, and to test methods for collecting blue carbon data to understand how best to achieve this at scale using community-based crews. Ultimately, TET would like to help the

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[3] Tasman Environmental Trust (tet.org.nz) is the community conservation hub for Nelson and Tasman.

[4] The Core and Restore project (https://www.tet.org.nz/projects/blue-carbon-core-and-restore) is included as a case study in the government's Emissions Reduction Plan report (Ministry for the Environment 2022).

[5] In Aotearoa New Zealand there is one species of seagrass – *Zostera muelleri*, which is also referred to as eelgrass, karepō, nana, rehia and rimurehia. It was previously known as *Z. capricorni* or *Z. novaezelandiae*.

community understand the carbon storage value of coastal blue carbon habitats and get involved in protecting and restoring them. The pilot study targeted saltmarsh and seagrass habitats in two estuaries: Waimeha / Waimea (hereafter Waimeha) Inlet in Te Tai-o-Aorere / Tasman Bay and Onetāhua / Farewell Spit (hereafter Onetāhua) in Mohua / Golden Bay. For salt marsh, the primary focus was on intact habitat (i.e. not observed to be obviously degraded), although some sampling was also carried out in habitat that we understand had begun to naturally recover from a degraded state. For seagrass, the focus was on habitat with varying levels of percent cover (i.e. density).

Cawthron contributed scientific leadership to the pilot study fieldwork and led the technical reporting of the results (presented in this report). Various other organisations and individuals also contributed to this pilot study (see Acknowledgements). The scope of this report is to present the pilot study soil organic carbon stock results and provide a brief discussion. Comparisons are also made between the amount of carbon stored in the different saltmarsh and seagrass habitats and study sites, and between results for slightly different sediment coring devices. The report will also put these in perspective compared to national and international data.

2. METHODS

2.1. Pilot study sites, timing and design

Three pilot study sites were selected within Waimeha Inlet (Figure 1), all of which were sampled on 29 November 2021.[6] We selected sites associated with herbfield and rushland because these are the dominant saltmarsh habitats in Waimeha Inlet (Stevens et al. 2020). The herbfield site, near the mouth of Neimann Creek, contained intact herbfield consisting primarily of *Salicornia*[7] *quinqueflora* (ureure, glasswort). The rushland site, a few kilometres northwest of the herbfield site, contained intact rushland consisting primarily of *Apodismia similis* (oioi, jointed wire rush). The third site, approximately 70 m south of the rushland site, contained herbfield that we understand, according to the landowner, had begun to naturally recover from a degraded state over a period of around 20 years. The dominant species was *Salicornia quinqueflora*, but taxa such as *Samolus repens* (mākoako, shore primrose) were also present. We also attempted to sample an additional farmland site (i.e. grazed pasture), inland and adjacent to Neimann Creek, but the soil was so compacted that the corers were barely able to penetrate it. The purpose of sampling this last site was to establish a baseline estimate of the blue carbon storage potential of degraded farmland if, hypothetically, it was restored to blue carbon habitat in the future.

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[6] The surface samples (0–2 cm depth) were collected at a later date, 25 September 2022.

[7] Previously *Sarcocornia*.

Three pilot study sites were selected on Onetāhua (Figure 2), and these were sampled on 11 May 2022. The sites were all situated relatively high up the shoreline, with each one representing seagrass cover of either approximately 25%, 75% or 100%. Seagrass is known to be inherently temporally variable in its spatial distribution (Turner and Schwarz 2006). However, we decided to focus our seagrass sampling on different percent cover categories to align with our saltmarsh sampling which related to different vegetation types. There are many factors that could have been tested, e.g. tidal heigh and distance from river or estuary mouth. However our capacity for this was limited given the small scale (i.e. pilot status) of the study. Distances between these sites ranged from approximately 70 to 180 m. The seagrass percent cover was determined using haphazardly placed 0.25 m^2 quadrats (divided into 36 equally sized squares). Cover was calculated by counting the number of gridline intersections that overlapped vegetation and converting the result to a percent. Coordinates for all study sites are detailed in Appendix 1.

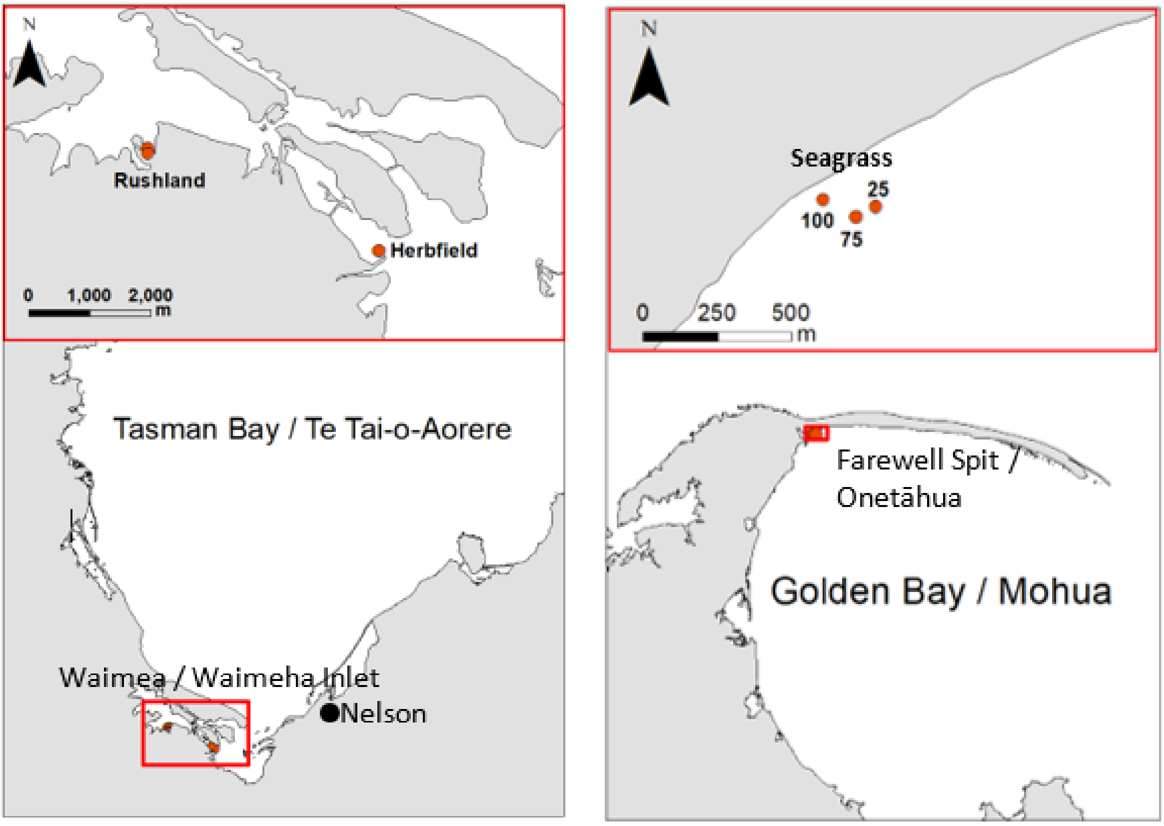

Figure 2. Left: Waimeha / Waimea Inlet showing the saltmarsh (rushland and herbfield) pilot study sites in the red box. A third site (herbfield [recovering]) can be seen in close proximity directly south of the rushland site. Right: Onetāhua / Farewell Spit pilot study sites in the red box, representing the three seagrass percent cover categories (25%, 75%, 100%).

At each intact rushland and herbfield pilot study site, there were two core collection areas separated by a distance of 6 m. At each core collection area, four soil cores were collected within a few metres of one another. We used a manual coring technique, and compared two slightly different coring devices (1 and 2; see Section 2.2 for details). Two of the cores were collected using coring device 1 and the other two using coring device 2. The exception to this was at the recovering herbfield site in Waimeha Inlet, where only one core was collected overall (using coring device 1). For the Onetāhua seagrass survey, the three pilot study sites were each sampled as described above for a core collection area (i.e. four cores were collected per site using the two different coring devices).

2.2. Sediment coring and sampling

We collected sediment organic carbon data largely following methods in the Blue Carbon Initiative manual (Howard et al. 2014). This was to ensure that results were robust, comparable and internationally credible, as well as suitable for use by other parties. Below we summarise our methods. Our focus was on below-ground carbon pools, relating to the sediment and below-ground plant biomass such as roots. However, for seagrass we also included above-ground carbon pool (e.g. seagrass leaves), given that it was difficult to separate this from the below-ground carbon pool. Further details can be found in our field protocol (Blue Carbon Field Protocol 2023 [forthcoming]). For all field trips we observed cultural safety practices, including tikanga such as karakia, as advised by iwi and as per the Blue Carbon Field Protocol pilot study (2023 [forthcoming]). After analysis, remaining sample material from Onetāhua was returned to Manawhenua ki Mohua[8] as requested.

The sediment cores were collected[9] (see Figure 3 for field images) to obtain soil samples for bulk density measurements and carbon content analysis. Cores were collected using manual coring with two slightly different coring devices. Coring device 1 had an internal diameter of 70 mm and a length of 125 cm, while coring device 2 had an internal diameter of 62 mm and length of 55 cm. Saltmarsh vegetation was largely removed from the surface prior to coring; however, this approach was impractical for seagrass, so vegetation (i.e. above-ground biomass) was retained in the seagrass cores. We aimed to reach a core depth of at least 50 cm, but the depth was less than this in some cases, e.g. due to the presence of harder substrates such as layers of gravel (especially at the Neimann Creek herbfield sites) and shell hash (at the seagrass sites). Effort was made to limit core compression; however, core compression was measured, and if detected, it was accounted for using a uniform compression compaction factor as per Howard et al. (2014). This approach assumed uniform compaction along the length of the core, which was not necessarily the case. The cores were extruded from the corers into

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[8] An iwi-mandated organisation that represents Ngāti Tama, Ngāti Rārua and Te Ātiawa within the area defined as the Mohua / Golden Bay catchment and Kahurangi National Park (i.e. western side of Tākaka Hill).

[9] All sample collection was conducted under Cawthron's Ministry for Primary Industries sample collections permit.

plastic ‘half pipes’ for sectioning. A photograph was taken of each core and core profiles were described.

We followed a depth-based sub-sampling strategy. Each core was divided into 10 cm sections using a knife, and then a 2 cm sample was cut from the middle of each section. Surface (i.e. top 2 cm) samples were also collected from the uppermost section (i.e. the 0–10 cm section). At the Waimeha Inlet saltmarsh study sites, these surface samples were collected at a later date from as close to the original coring area as possible, with each sample randomly assigned to a core during carbon calculations. All samples were kept chilled and sent to the National Institute of Water and Atmospheric Research (NIWA) for laboratory analysis.

Figure 3. Images from the saltmarsh / Waimeha Inlet (top four images) and seagrass / Onetāhua (bottom two images) field surveys.

2.3. Laboratory analyses

To determine sediment organic carbon stocks, we first quantified the sediment dry bulk density (mass of dried sediment / original volume). We then determined the total organic carbon (TOC) and used this and the bulk densities to calculate the carbon density of the sediment at specific depth intervals. Carbon content was analysed in all the Waimeha Inlet samples; however, due to budgetary constraints, representative samples only were analysed for the Onetāhua sites. These samples were selected to represent each of the three sediment 'types': surface sediment (0–2cm), sediment only (with little shell material) and sediment containing shell hash (these types were associated with varying sediment depths for each sediment 'type' depending on the core / site, but often the shell hash layer was seen in the deepest samples). Triplicate samples from each of these sediment types from each study site (representing 100%, 75% and 25% seagrass cover) were analysed. The average value of the triplicate analyses was then applied to all the samples of that seagrass cover and sediment type. Carbon analyses methods are summarised as follows:

- Sediment samples[10] were dried at 60 °C and weighed for bulk density.
- Prior to sub-sampling, some samples (i.e. all of the seagrass ones due to their composition) were ground up using a pestle and mortar in the laboratory to enable effective standardisation. Samples that contained larger-sized material (e.g. shell hash, stones and woody or vegetative debris) were sieved through a coarse mesh (size 2 mm), with the dry weight of vegetated and non-vegetated material from each sample measured separately.
- A sub-sample (of each sediment sample) was analysed for total carbon (TC) using an elemental analyser.[11] A representative sub-sample of the vegetative material (i.e. woody or soft plant material) collected on the 2 mm sieve was also analysed for TC (assumed to be the same as TOC in this case).
- To remove inorganic carbon, representative sediment samples[12] for each study site were then acidified (based on a 'fizz test' using 50% sulphuric acid). If no 'fizzing' (i.e. effervescence) was detected, we considered TC to equal TOC. If inorganic carbon was indicated to be present (through 'fizzing'[13]), then TOC[11] was analysed for that representative sample. No inorganic carbon was indicated as present in the saltmarsh samples. For the seagrass samples, 'fizzing' was indicated for some samples, especially those identified visually as containing shell hash.

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[10] All samples for Waimeha Inlet saltmarsh. Representative samples only for Onetāhua seagrass sites.

[11] Elementar Unicube analyser calibrated using acetanilide and using Reference soil for AQC checks. Catalytic comb @900 °C, sep, TCD, Elementar C/N analyser (method = MAM, 01–1090, detection limit = 0.05).

[12] For key sample types ($n = 3$), i.e. samples we deemed to be of a similar nature based on visual observation and / or origin. For example, key types for seagrass samples were surface, shell hash and sediment without obvious shell hash.

[13] If effervescence was observed, the sample was left overnight for the reaction to proceed. The next day a few more drops of acid were added. The tube was agitated and checked for any further effervescence. If evolution of gas had ceased, the acid was poured off and deionised water added to the sample. The liquid was swirled and poured off. This step was repeated twice more.

2.4. Data analysis

By extrapolating the results, we made various carbon stock calculations, including the average tonnes of sediment organic carbon per hectare and the average carbon down the core depth profiles based on calculations in Howard et al. (2014). The main values for tonnes of carbon per hectare presented and plotted in our report are calculated down to 40 cm sediment depth. There were fewer replicates for the 40 cm sediment depth in many cases; however, the values to 30 cm depth (for which there were more replicates) showed a similar pattern in relation to habitat type / site comparisons. Therefore, we presented the 40 cm depth data given that these were more reflective of the carbon stocks present overall. We also calculated saltmarsh and seagrass carbon stocks to 10 cm and 30 cm sediment depth to allow comparison with other studies. Data for any larger vegetative material still present in the samples following field collection were included in the sediment organic carbon stock values, given that they reflected overall carbon in the samples (regardless of whether or not it had been technically sequestered more permanently in the sediment).

To detect whether there was a statistically significant difference between carbon stocks in saltmarsh versus seagrass habitats, we conducted a two-sample *t*-test (assuming equal variances) on the average carbon stock for each study site ($n = 3$ for saltmarsh and seagrass habitats to 30 cm soil depth). In addition, we extrapolated the carbon stock results to estimate the amount of carbon stored (to 40 cm depth) overall in the estuaries based on the known area of each habitat. For seagrass, we used an average of values from the three percent cover categories combined. The extrapolated results for salt marsh and seagrass need to be interpreted with caution given that they are based on very limited spatial data. It is also important to note that our carbon stock values do not consider the amount of carbon stored per period of time (i.e. the sequestration rate), and that this would need to be quantified in a future study (see Section 4).

2.5. Evaluating social outcomes of project

At the end of the overall project pilot (which also included a teabag experiment led by Nelson City Council; Zaiko and Pearman 2022) we evaluated the social outcomes of the pilot. An overview of this evaluation, including methods and results, is provided in Appendix 5.

3. RESULTS AND DISCUSSION

Key sediment organic carbon stock results, including average values for tonnes per hectare (tC/ha to 40 cm soil depth) and soil carbon density (g/cm^3) down the core depth profile, are provided in Figures 4 and 5. These results are discussed in the following sections, including in the context of other carbon stock data for similar habitats from Aotearoa New Zealand as well as some examples from overseas (Table 1, including values to various sediment depths). Images of representative cores are presented in Appendix 2. Accompanying this report are the additional (i.e. more detailed) soil coring data (Excel file) provided to TET (Appendix 4). We recommend that including this resolution of data in reports or publications facilitates comparisons between different studies.

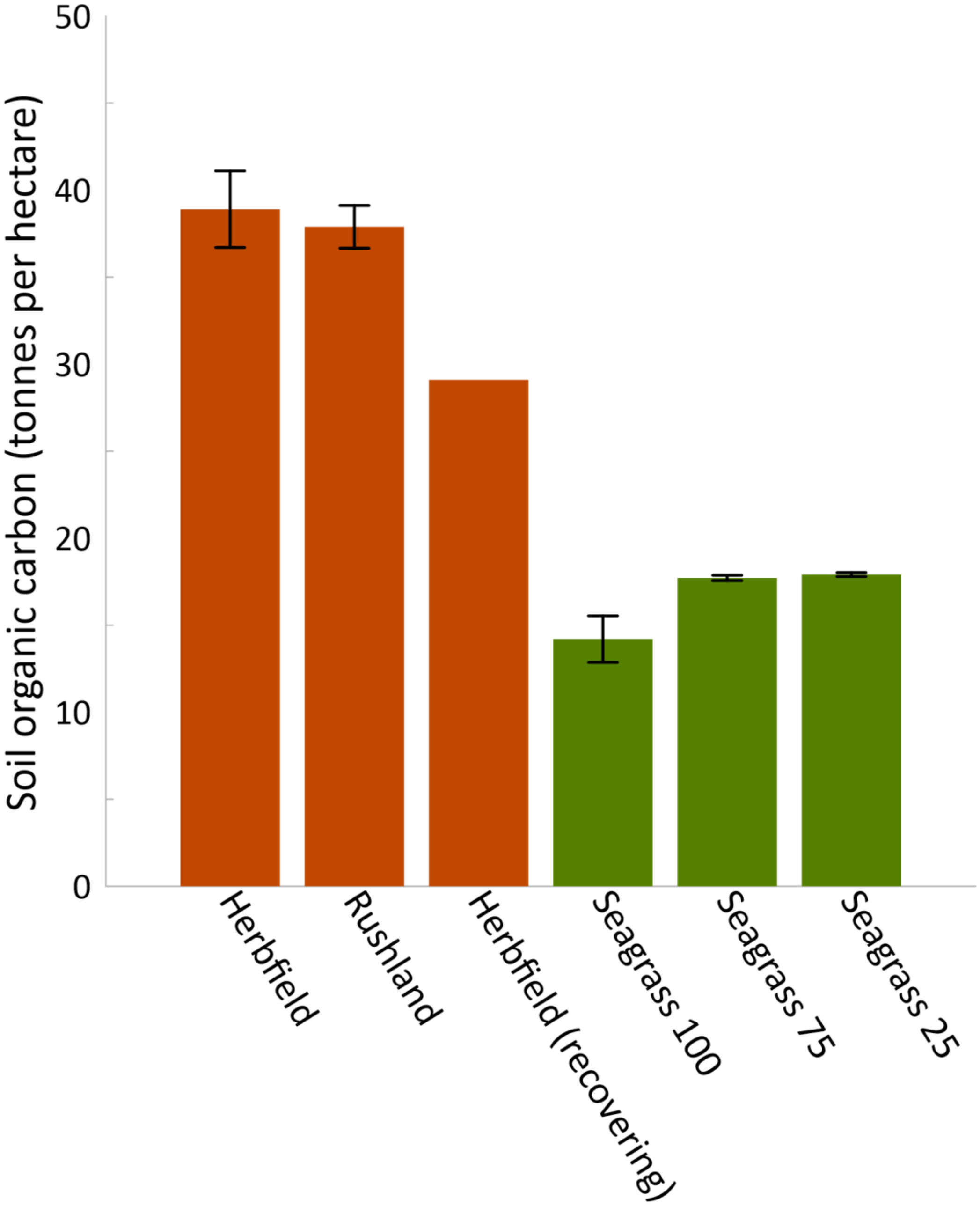

Figure 4. Soil (i.e. sediment) organic carbon stocks (tC/ha to 40 cm soil depth, average ± standard error) stored in Waimeha / Waimea Inlet saltmarsh (herbfield, rushland and herbfield [recovering] = red bars) and Onetāhua / Farewell Spit seagrass habitats (= green bars) representing three percent cover categories (100%, 75% and 25%) that included above-ground seagrass biomass. Replicate sample numbers ranged between *n* = 2 to *n* = 4 for the habitat types, except for herbfield (recovering), for which *n* = 1.

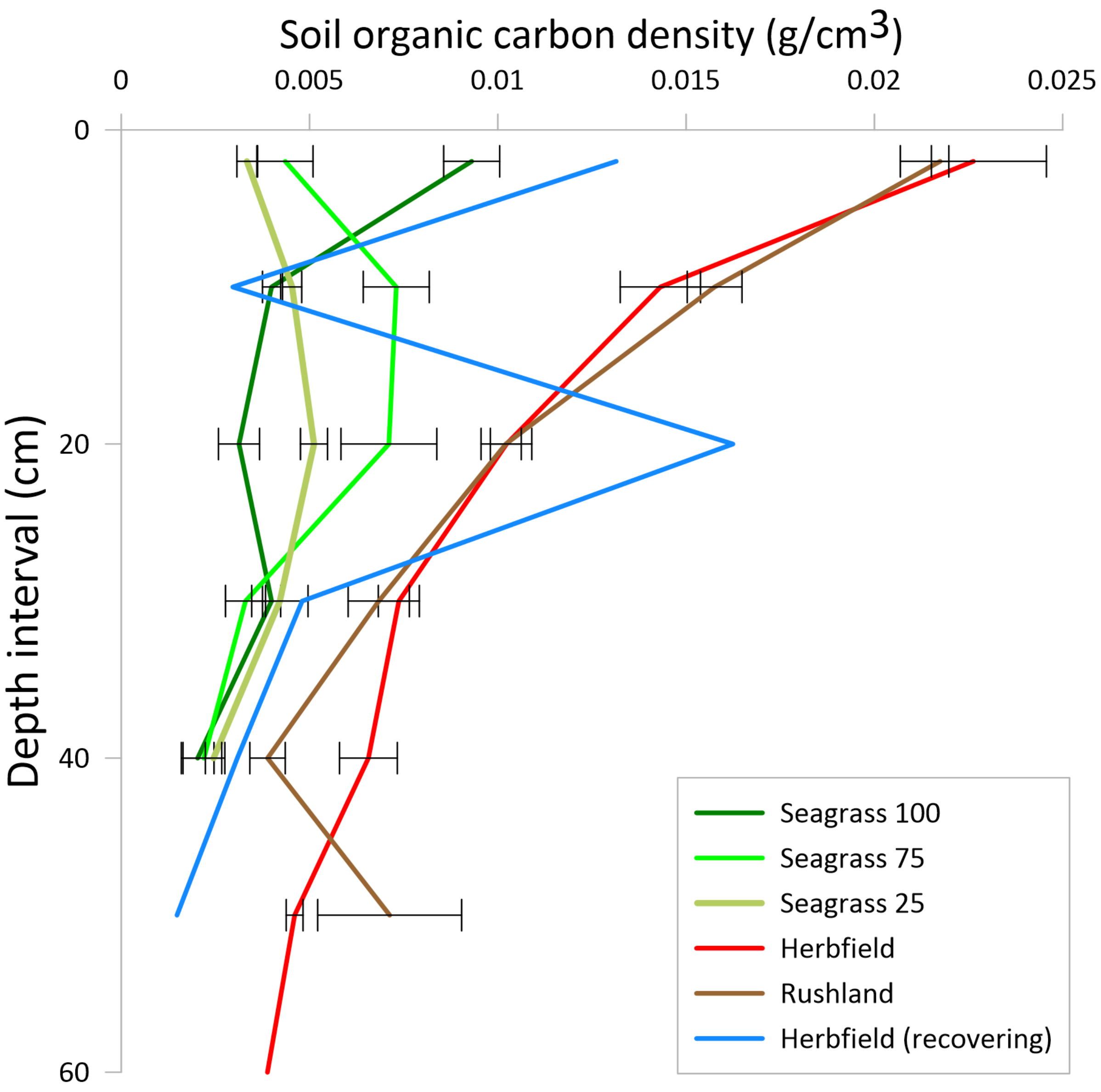

Figure 5. Soil (i.e. sediment) organic carbon density down the core profile (g/cm^3, average ± standard error) stored in Waimeha / Waimea Inlet saltmarsh (herbfield, rushland and herbfield [recovering]) and Onetāhua / Farewell Spit seagrass habitats representing three percent cover categories (100%, 75% and 25%) that included above-ground seagrass biomass. Replicate samples for each depth / habitat type range from *n* = 2 to *n* = 4, except for herbfield (recovering), for which *n* = 1.

3.1. Salt marsh: Waimeha Inlet

The average amount of sediment organic carbon stock (to 40 cm sediment depth) in intact saltmarsh habitats at Waimeha Inlet was similar for rushland and herbfield (38 tC/ha combined average[14]) (Figure 4, Table 1). The sediment carbon stock for the herbfield (recovering) site was lower (29.1 tC/ha). Our results also indicated relatively little variation in sediment carbon stocks within saltmarsh habitat types / sites. The sediment organic carbon density for the Waimeha Inlet salt marsh decreased substantially with depth for all three habitat types, especially at shallower (i.e. < 30 cm) depths (Figure 5). Variations in carbon content are typically most prominent at shallower soil depths in salt marshes (Howard et al. 2014); for example, Bulmer et al. (2020) found the majority of differences occur in the top 20–30 cm of cores.

Comparison of carbon stock values against other studies is not always straightforward given that these are often not standardised (e.g. they have been calculated to differing soil depths, and carbon stocks can change with depth). However, below we compare the sites we surveyed with soil carbon stocks reported from Aotearoa New Zealand and overseas for similar coastal wetland habitats (see Table 1 for all values).

The average intact saltmarsh carbon stocks in Waimeha Inlet were approximately half those recorded per hectare for rushland (*Juncus kraussii* was the dominant species) at Tairua Estuary in the North Island of Aotearoa New Zealand (Bulmer et al. 2020). However, the reported Tairua Estuary results were for more than twice the soil depth (i.e. 100 cm). The Waimeha Inlet average saltmarsh carbon stocks (to 10 cm soil depth) were lower than the range in averages from saltmarsh habitats representing various levels of intactness and degradation at four North Island sites (Albot et al. [in prep.]). To provide an international comparison for a similar habitat type, soil carbon stock to 30 cm depth was around one-third higher for indigenous salt marsh (e.g. *J. kraussii* and / or *Sarcocornia quinqueflora*[15]) in a Tasmanian estuary (Ellison and Beasy 2018) compared to the Waimeha Inlet saltmarsh values.

Our pilot study does not enable us to confirm the factors influencing the observed Waimeha Inlet saltmarsh carbon stock values. However, preliminary results from the North Island indicate that site differences in saltmarsh soil organic carbon stocks appear to be independent of the dominant vegetation type (Albot et al. [in prep.]). Albot et al. (in prep.) also found that geomorphic setting appeared to strongly influence organic carbon stocks, with fluvially influenced areas of the marshes having higher stocks than areas subject to only marine influence. Therefore, carbon stocks could have been influenced by the close proximity of the Neimann Creek river mouth to the herbfield site and the position of the saltmarsh sites in the inner estuary away from the inlet entrance. Knowledge of the ecological history of our survey sites could

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[14] For intact rushland the average was 37.9 tC/ha ± 1.2 SE, and for intact herbfield the average was 38.9 tC/ha ± 2.2 SE. The average for intact herbfield and rushland combined was 38.3 tC/ha ± 1.2 SE.

[15] Now *Salicornia quinqueflora*.

also aid with interpretation of the drivers of soil carbon stocks. Traditional knowledge is particularly valuable for understanding longer landscape processes.

Overall, we roughly estimate that there is approximately 6,306 tC stored in intact herbfield in Waimeha Inlet and 3,301 tC in intact rushland.[16] To estimate the total amount of carbon stored in Waimeha Inlet, other habitats – such as other saltmarsh types and unvegetated substrates – would also need to be accounted for. Furthermore, we expect the overall carbon stocks calculated for herbfield and rushland in our study are underestimated given that it is unlikely we cored deep enough into the soil to capture the full extent of the carbon deposit.[17] Salt marsh from different areas within the estuary (e.g. different geomorphic or hydrological settings) may also contain differing carbon stocks.

The results from the slightly different manual coring devices (1 and 2) per habitat type / site were generally comparable (see Appendix 3, Figure A3.1).

3.2. Seagrass: Onetāhua

The average sediment carbon stock[18] (to 40 cm sediment depth) in seagrass habitats at Onetāhua was similar for sites with 75% and 25% cover (18 tC/ha ± ~0.1 SE) and slightly lower for those with 100% cover (14 tC/ha ± 1.3 SE) (Figure 4, Table 1).

Down the core depth profile, there was a relative increase in sediment organic carbon density at around 10–20 cm soil depth (Figure 5), and we noted the presence of organic material (presumably decaying seagrass roots or vegetation) during field coring. Battley et al. (2011) also observed brown organic material, presumably originating from decaying seagrass, in Onetāhua soil in some areas. Another notable pattern was the higher sediment organic carbon density values in the sediment surface for the 100% cover site, which is not unexpected given the higher levels of surface / near-surface vegetation present (and incorporated in our sediment carbon data). In comparison, Bulmer et al. (2020) recorded relatively consistent carbon stock values with depth for seagrass in Tairua Estuary.

The average Onetāhua seagrass soil organic carbon stock values (to 40 cm depth) were lower than those reported for seagrass in Tairua Estuary (Table 1; Bulmer et al. 2020), although again the Tairua values were reported to 1 m depth (Table 1). To give an overseas comparison, the Onetāhua carbon stocks to 10 cm depth were comparable to those in Ricart et al. (2015) for *Zostera muelleri* (which were up to 6 tC/ha) in Queensland, Australia, to the same depth. However, they appeared to be much lower generally than *Z. muelleri* organic carbon stocks in an urban estuary in

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[16] Based on an area of 162.1 hectares for herbfield and 87.1 hectares for rushland (Stevens et al. 2020), and extrapolating from spatially limited data (to a soil depth of 40 cm) for intact herbfield from our study.

[17] The presence of saltmarsh foraminifera can be used to define the base of the marsh deposit (as per Albot et al. in prep).

[18] The seagrass sediment carbon stocks also contained above-ground seagrass biomass – refer to Methods section.

New South Wales, Australia, the average of which was reported to be 365 tC/ha to 50 cm depth (Brown et al. 2016).

In terms of potential factors influencing soil carbon stocks in Onetāhua seagrass habitats, we suspect that there were relatively limited nutrient and sediment inputs (which can boost carbon sequestration[19]) from the land influencing the study sites. This is based on observations of sandy (rather than muddy) sediments with ripples, which suggest relatively high water movement and, therefore, flushing. Seagrass meadows located in more sheltered environments or in closer proximity to sources of allochthonous organic material would potentially have higher carbon stocks. It is also important to note that seagrass patches can be dynamic, with percent cover known to vary seasonally and between years (Turner and Schwarz 2006). Therefore, the percent cover recorded during our survey may not reflect the coverage over long time periods that led to the accumulated carbon sequestration. Aligning with this concept, Battley et al. (2011) noted that historical changes in seagrass distribution at Onetāhua may have led to their observation of bare sand containing large volumes of brown organic material in some areas.

Overall, we calculate that there is approximately 115,453 tC stored in seagrass at Onetāhua.[20] This was based on an average of carbon stocks combining each of the three percent cover categories (25%, 75%, 100%). However, seagrass at Onetāhua has been previously described as being patchily distributed (Dixon 2009) and often occurring at low densities (Battley et al. 2005, 2011), and has not been mapped recently. Nevertheless, the relationship strength between seagrass percent cover and sediment carbon stocks for *Zostera muelleri* or this area is currently unknown.

3.3. Comparing carbon stocks in saltmarsh / Waimeha vs seagrass / Onetāhua habitats

Overall, average intact saltmarsh / Waimeha Inlet carbon stocks were more than double the average seagrass / Onetāhua carbon stocks,[21] with a statistically significant difference detected between these two broad habitat categories (Figure 4; t(18) = -13.8, $p < 0.001$). This finding aligns with Bulmer et al. (2020), who, in the Tairua Estuary, also found more below-ground carbon associated with salt marsh compared to seagrass. However, our results and those of Bulmer et al. (2020) show that differences between seagrass and saltmarsh carbon stocks are smaller at greater (e.g. > 30 cm) soil depths (Figure 5). Refer to the sections above for a

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[19] At higher levels, especially if driven by human activities, nutrients and sediments can be detrimental to estuary ecological health.

[20] Based on an area of 6,955 ha of seagrass calculated using the Aotearoa New Zealand mangrove and seagrass database (https://www.doc.govt.nz/nature/habitats/estuaries/our-estuaries/seagrass-and-mangrove-extent), and extrapolating from spatially limited data (to a soil depth of 40 cm).

[21] Calculated for a sediment depth of 30 cm. Average carbon stock to 30 cm depth for saltmarsh (both intact habitats combined) was 33.8 tC/ha; average carbon stock for seagrass (all percent cover categories combined) was 14.3 tC/ha.

discussion on carbon stocks at the study habitats and sites and the factors that may be driving them.

Table 1. Sediment organic carbon stocks for saltmarsh and seagrass habitats in Aotearoa New Zealand and overseas. Values from this report are highlighted grey. Carbon stocks are reported from either an average or individual value. To standardise carbon stock values, unit conversions were made where required.

Habitat type	**Sediment organic carbon stock (tC/ha, to a specified sediment depth)**	**Location (references given in table footnote)**
Salt marsh		
Herbfield	38.9 (to 40 cm sediment depth) 33.6 (to 30 cm sediment depth) 16.0 (to 10 cm sediment depth)	Waimeha Inlet, Aotearoa New Zealand[a]
Rushland	37.9 (to 40 cm sediment depth) 34.0 (to 30 cm sediment depth) 17.0 (to 10 cm sediment depth)	Waimeha Inlet, Aotearoa New Zealand[a]
Rushland	~85 (to 100 cm sediment depth)	Tairua Estuary, Aotearoa New Zealand[b]
Various salt marsh types	~30.7–48.3 (to 10 cm sediment depth)	Four sites across the North Island, Aotearoa New Zealand[c]
Rushland and / or herbfield	~49.5 (to 30 cm sediment depth)	Tasmania, Australia[d]
Seagrass		
Zostera muelleri	14.2–17.9 (to 40 cm sediment depth) 12.2–17.1 (to 30 cm sediment depth) 5.1–6.7 (to 10 cm sediment depth)	Onetāhua, Aotearoa New Zealand[a]
Zostera muelleri	~27 (to 100 cm sediment depth)	Tairua Estuary, Aotearoa New Zealand[b]
Zostera muelleri	Up to 6 (to 10 cm sediment depth)	Queensland, Australia[e]
Zostera muelleri	365 on average (to 50 cm sediment depth)	New South Wales, Australia[f]

[a] Berthelsen et al. (2023) (this study); [b] Bulmer et al. (2020); [c] Albot et al. (in prep.); [d] Ellison and Beasy (2018); [e] Ricart et al. (2015); [f] Brown et al. (2016).

4. FUTURE RECOMMENDATIONS

Our pilot study demonstrated a proof of concept for determining blue carbon stocks in saltmarsh and seagrass habitats in Te Tauihu. To obtain further information on or relating to this topic, either within or beyond the Core and Restore project, we recommend:

- The next step is to scale up this work by collecting more carbon stock data from other locations and habitat types (e.g. degraded salt marsh / farmland, unvegetated and restored sites). This would address the lack of spatial representation, which is a key limitation in this pilot study.

- Additional blue carbon–related information could also be collected from the cores, including the source of the carbon, as well as depth–age relationships in the sediment cores, which would provide critical information on the rate and longevity of carbon sequestration.
- As long as project partners agree, the fine-scale saltmarsh and seagrass carbon data collected could be added to international databases to help expand international knowledge, e.g. that managed by the Coastal Carbon Research Coordination Network.[22]
- Collection of data for other parameters (e.g. relating to environmental health indicators) may also be of interest. Ultimately, information obtained from this and future studies can inform the protection and restoration of coastal wetland habitats and be used for public engagement and education. Overall, we recommend a co-design process (facilitating inclusion of stakeholders) for further project development. Supporting mātauranga Māori and engagement of citizen scientists, where suitable, would also extend the community's connection and understanding of the carbon storage value of coastal blue carbon habitats and the need to protect and restore these significant areas.

5. ACKNOWLEDGEMENTS

5.1. Author contributions

A summary of author contributions is provided below, with authors presented in the order in which they appear in the report's author list (on the title page).

Anna Berthelsen (Cawthron) was the science technical lead for the pilot study in relation to measuring carbon stocks, and she participated in fieldwork and led the write-up of this technical report. **Lauren Walker** (TET, Lauren Walker Ltd) was the overall project lead, and she also participated in fieldwork and contributed to the report. **Jen Skilton** (Ngāti Apa ki te Rā Tō), **Dan Chamberose** (Beca), **Sean Waters** (Cawthron), **Sam Flewitt** (Beca) and **Elaine Asquith** (Cawthron) were key pilot study advisors and participated in fieldwork. **Jen** was also a key advisor and contributor to the pilot study from an iwi perspective. **James Butler** (Cawthron) led the evaluation of social outcomes of the pilot study, and wrote the component of the report relating to this (Appendix 5). **Helen Kettles** (Department of Conservation) provided overall project support and advice and contributed to fieldwork.

5.2. Other acknowledgements

Key project partners, supporters and funders are as follows:

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[22] https://serc.si.edu/coastalcarbon

- Key project partners: TET, Cawthron, Beca, Ngāti Apa ki te Rā Tō and Nelson City Council (NCC).
- Key supporters: Manawhenua ki Mohua, HealthPost Nature Trust, Department of Conservation (DOC).
- Funders / sponsors: TET, Pic's Peanut Butter, NCC, Live Ocean, HealthPost Nature Trust, Kidson Investments Ltd, Nelson Tasman Climate Forum.
- In-kind contributors: Lauren Walker Ltd, Cawthron, Beca, Ngāti Apa ki te Rā Tō, NCC, Manawhenua ki Mohua, HealthPost Nature Trust, DOC, Andy McDonald (NZ Andy).

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In addition, Mike Crump from NIWA conducted the laboratory analyses. Stacey Trevathan-Tackett from the Blue Carbon Lab (Deakin University, Australia) provided technical advice. Richard Bulmer (NIWA) provided a sounding board on sediment coring and sampling methods, lab analysis and comparisons of results.

Thanks also to Olya Albot (Victoria University of Wellington), who provided her preliminary sediment carbon results for us to compare against in our report.

6. APPENDICES

Appendix 1. Pilot study site coordinates

Study site	Coordinates (New Zealand Transverse Mercator)	
Waimeha herbfield 1	E1613288	N5427531
Waimeha herbfield 2	E1613294	N5427531
Waimeha rushland 1	E1609499	N5429213
Waimeha rushland 2	E1609497	N5429218
Waimeha herbfield (recovering)	E1609489	N5429140
Onetāhua 100% seagrass	E1578446	N5514471
Onetāhua 75% seagrass	E1578559	N5514413
Onetāhua 25% seagrass	E1578625	N5514448

Appendix 2. Representative core images

A2.1 Representative cores from Waimeha Inlet: intact herbfield and rushland (left and middle, respectively) and herbfield (recovering) (right). Core material comprised primarily of silty sediments

A2.2 Representative cores from Onetāhua: seagrass cover 100%, 75% and 25% (from left to right, respectively). Core material comprising primarily sandy sediments with shell hash layers and organic matter visually observed in some cores

Appendix 3. Comparison of soil carbon data collected from slightly different manual coring devices (1 and 2) for key saltmarsh habitats

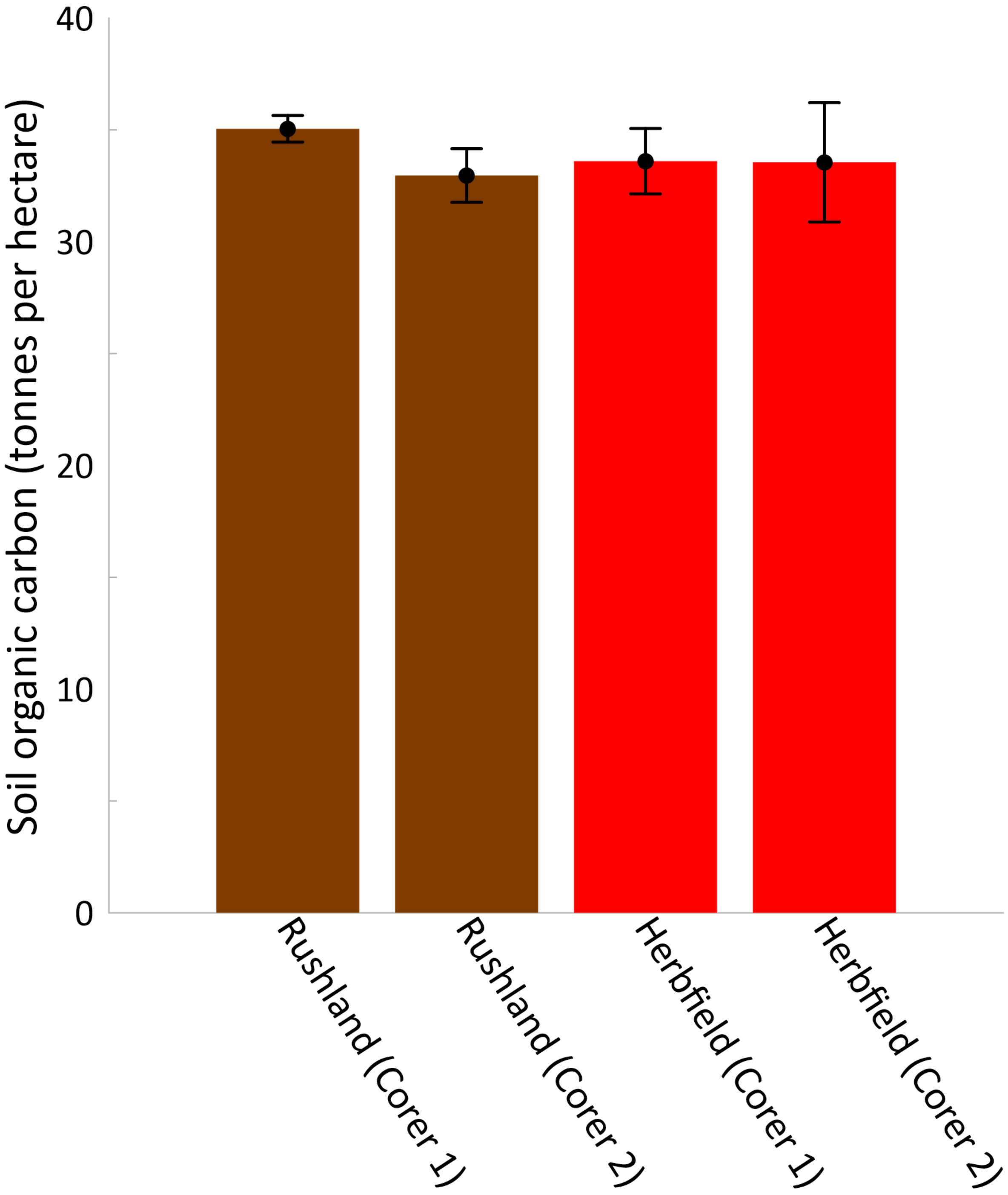


Figure A3.1. Soil organic carbon per area (tC/ha, average ± standard error, *n* = 4) stored in Waimeha / Waimea Inlet salt marsh (intact herbfield and rushland) to 30 cm soil depth using two slightly different manual coring devices (1 and 2 – see Section 2.2 for coring device descriptions).

Appendix 4. Sediment core data

File containing more detailed soil carbon results to those presented in this report. This is attached separately as a supplementary file (Excel) and titled ‘CoreandRestore_Pilot Study_CarbonStockData.xlsx’.

Appendix 5. Evaluating social outcomes from Core and Restore pilot study

A5.1 Context

Community-based projects that involve multiple stakeholders working together on a common environmental problem are known to generate benefits that are not necessarily intended. Although secondary, such outcomes are important because they generate adaptive capacity, defined as 'the potential for actors within a system to respond to drivers of change, and to shape and create changes in that system' (Chapin et al. 2006). With advancing climate change, locally led adaptation will become increasingly important, and the ability of stakeholders to work together across institutional, social and cultural boundaries in novel ways will be key to successful and flexible responses (Coger et al. 2022). Consequently, measuring adaptive capacity is becoming an important element of project evaluations (Butler et al. 2015).

In the case of the Core and Restore pilot study, multiple partners were engaged in different aspects of practical work and citizen science to examine the extent and condition of blue carbon ecosystems, but social outcomes were not a primary objective of the exercise.

A5.2 Indicator development

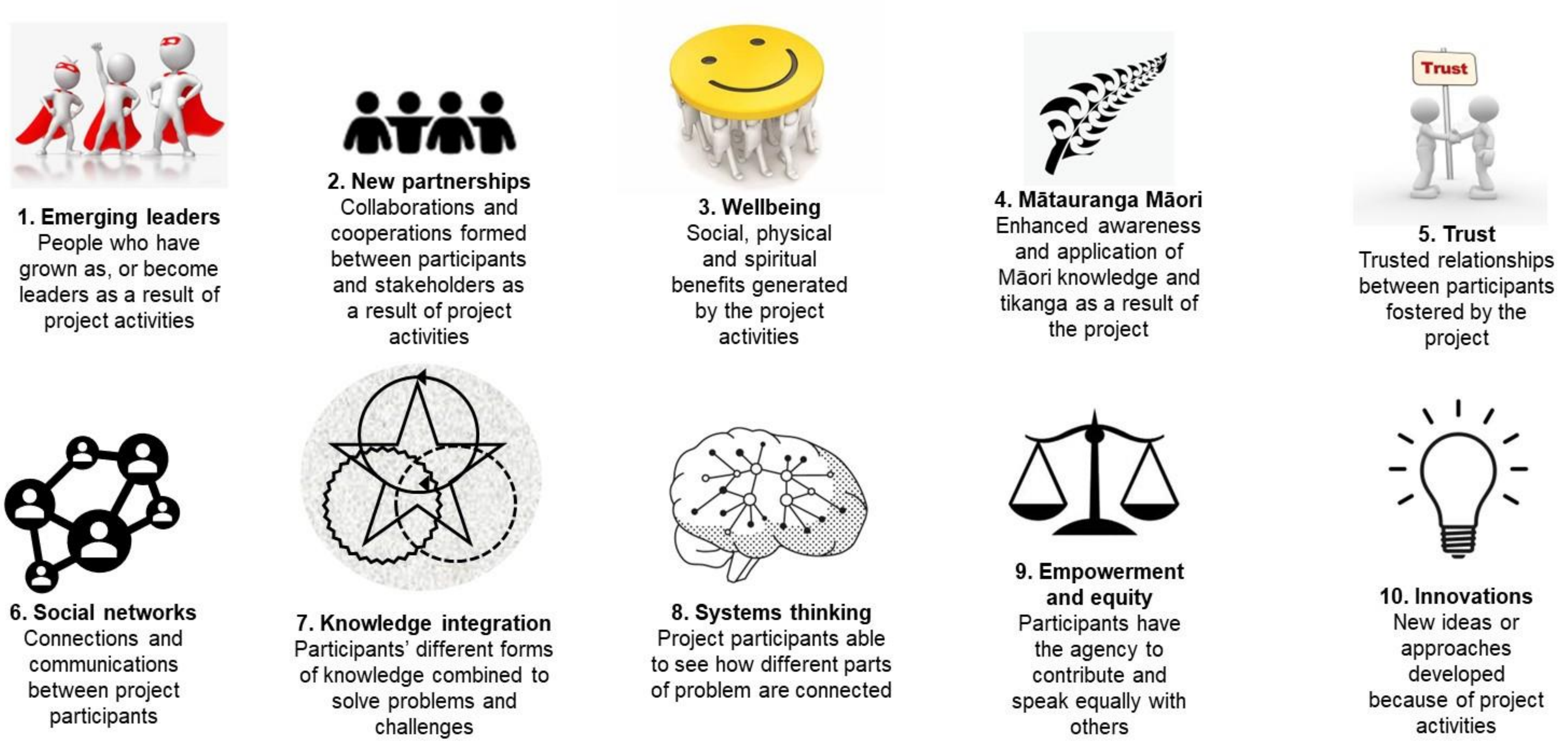
To test an approach for measuring social outcomes and adaptive capacity generated by community-based blue carbon projects, a set of indicators was developed (or agreed on) by members of the Core and Restore Project Team. Based on previous evaluations carried out by Cawthron, the Core and Restore Project Team was presented with a range of indicators designed to measure adaptive capacity generated through collaborative activities, also termed adaptive co-management (e.g. Plummer and Armitage 2007; Butler et al. 2016; Cox et al. 2020).

An initial set of 12 core outcome indicators was refined by the Core and Restore Project Team down to eight, and then two that were considered important for the Core and Restore pilot project were added: wellbeing and mātauranga Māori. The final 10 indicators and their explanations are given in Figure A5.1.

A5.3 Evaluation methodology

The Core and Restore Project Team agreed to evaluate the project outcomes by applying the indicators at the Core and Restore Hui, held in Richmond in the Tasman Region on 28 March 2023. It was agreed to use participatory evaluation, whereby project participants self-reflect on outcomes. Such an approach is known to add further value to adaptive capacity by enabling partners in an initiative to collectively assess progress, acknowledge successes and agree to redress any shortcomings, all of which promotes social learning and gives the partners agency and self-empowerment (Trimble and Plummer 2018; Quintana et al. 2020).

Two tools were used to measure outcomes: a Likert scale ranging from 0 (highly negative) to 5 (highly positive), and stories of change. For the Likert scale, participants were asked to score the indicator from their perspective, and then explain their scoring in writing. At the workshop, participants were divided into five groups of four to seven people from mixed institutional and professional backgrounds. Each group was given A4 printouts of two indicators, with text transposing each indicator into a question (see Table A5.1). Following verbal consent given by participants (in accordance with the Cawthron Institute Human Research Ethics protocol), over a period of 15 minutes they discussed and scored their indicators before reporting back to the workshop. In plenary, the results were discussed and reflections made about the usefulness of the approach.



1. Emerging leaders
People who have grown as, or become leaders as a result of project activities

2. New partnerships
Collaborations and cooperations formed between participants and stakeholders as a result of project activities

3. Wellbeing
Social, physical and spiritual benefits generated by the project activities

4. Mātauranga Māori
Enhanced awareness and application of Māori knowledge and tikanga as a result of the project

5. Trust
Trusted relationships between participants fostered by the project

6. Social networks
Connections and communications between project participants

7. Knowledge integration
Participants' different forms of knowledge combined to solve problems and challenges

8. Systems thinking
Project participants able to see how different parts of problem are connected

9. Empowerment and equity
Participants have the agency to contribute and speak equally with others

10. Innovations
New ideas or approaches developed because of project activities

Figure A5.1. The 10 outcome indicators selected for use to evaluate the social outcomes of the Core and Restore pilot study.

Table A5.1. The adaptive capacity indicators, the question posed to workshop (local hui) participants, and their scores and explanations for each.

Indicator	**Core and Restore context / question**	**Score (0 = strongly negative; 5 = strongly positive)**	**Explanatory comments**
1. Emerging leaders	Did the project encourage the emergence of leadership among the partners?	4	‘Citizen science – people keen to be involved in something new’ ‘Repeated community samples wanting to know the results’ ‘Professionally more opportunities’ ‘Community conservation leaders result in healthier biodiversity from land to sea, which increases mauri’ ‘Provides a platform for new leadership to sprout from rangatahi’
2. New partnerships	Did the project create any new partnerships?	4.5	‘It was important to have Lauren there to help pull together partners and make connections meaningful’ ‘From an iwi perspective, this project may have been pushed to one side, had it not been for Lauren’s perseverance’
3. Wellbeing	How much happiness and positivity did the project generate for the participants?	N/A	
4. Mātauranga Māori	Did the project encourage and promote mātauranga Māori and tikanga?	3	‘Knowledge of what estimates used need to be clearer’ ‘Observations of change over time were not incorporated’ ‘Ownership of who controls the financial benefits need to be considered’ ‘Need to discuss black mud’
5. Trust	How much trust has the project generated between participants and stakeholder groups?	4	‘Much effort put into relationship building between partner organisations – especially iwi, DOC, Nelson Port – led to high level of trust’ ‘Room to move organisations’ research competition in this space, e.g. NIWA and Cawthron’
6. Social networks	Have social networks been grown by the project, especially across levels (e.g. community–government)?	4.5	‘Great cross-representation across the community brought together many sectors – local government, DOC, citizen science, iwi, business, social knowledge’ ‘Potential to grow more or be replicated in other areas’ ‘Potential flagship for climate-positive action’
7. Knowledge integration	Has the project successfully integrated different kinds of knowledge (e.g. about blue carbon, estuaries, restoration and climate change)?	5	‘Engineering / science / whānau / council / citizen science / social science working together to enrich each other’s experiences’ ‘Understanding tikanga (e.g. returning knowledge to whenua) and long-term nature of environmental change’ ‘Knowledge exchange through working together’

8. Systems thinking	Has the project encouraged people to think more about how different issues are connected?	4	‘Participants have explored and seen lots of different / varied parts of the problem, and there is a diversity of people – lots to build on’ ‘It “makes sense”’ ‘Comparing nationally, internationally and globally’ ‘Thinking across spatial scales’
9. Empowerment and equity	Did the project empower its participants, and give everyone an equal voice?	5	‘As a landowner, I felt part of the team from the beginning, able to speak equally’ ‘Lauren’s facilitation skills are off the scale / good – that made all the difference’ ‘Participants are friends and really interested in understanding what blue carbon is, and they are able to share their knowledge’ ‘Today (at the workshop), having all organisations, people, agencies contributing presentations’ ‘Teabag report back was complementary, and added breadth to the project’
10. Innovations	Did any new ideas or innovations emerge from the project?	4.5	‘Developing scientific protocol and turning it into a guide for community-based blue carbon sampling’ ‘Hard / soft science (scientists versus citizens)’ ‘Innovative way of connecting iwi and community in coastal habitat teabag experiment’ ‘Developing blue carbon expertise’ ‘Leaders in NZ blue carbon’ ‘Blue carbon is a new field internationally – NZ might be seen as one of the first projects’

A5.4 Results

‘Knowledge integration’ and ‘empowerment and equity’ were the highest-scoring indicators, both scoring a maximum of 5 (Table A5.1). For knowledge integration, observations included ‘engineering / science / whānau / council / citizen science / social science working together to enrich each other’s experiences’ and ‘understanding tikanga (e.g. returning knowledge to whenua) and long-term nature of environmental change’. For empowerment and equity, comments included ‘as a landowner, I felt part of the team from the beginning, able to speak equally’ and ‘participants are friends and really interested in understanding what blue carbon is, and they are able to share their knowledge’. ‘New partnerships’, ‘social networks’ and ‘innovations’ also scored very highly (4.5).

The lowest-scoring indicator was ‘mātauranga Māori’, which was given a 3, and therefore intermediate. Explanations included ‘knowledge of what estimates used need to be clearer’, ‘observations of change over time were not incorporated’ and ‘ownership of who controls the financial benefits (of blue carbon) need to be considered’. In addition, there was a point made in plenary about the ‘need to discuss black mud’, which is a characteristic of estuarine areas that is poorly understood by science but well known in mātauranga Māori. Overall, it was felt that there was great potential to apply and recognise mātauranga Māori in future blue carbon research and monitoring, but it required more time and resources to do so effectively. However, it was also noted that the involvement of whānau had contributed greatly to the maximum score given to ‘knowledge integration’ (see above).

There was specific mention made of Lauren Walker’s contribution to the project, which was strongly reflected in ‘new partnerships’ (‘it was important to have Lauren there to help pull together partners and make connections meaningful’; ‘from an iwi perspective, this project may have been pushed to one side, had it not been for Lauren’s perseverance’), and in ‘empowerment and equity’ (‘Lauren’s facilitation skills are off the scale / good – that made all the difference’).

Finally, due to a clerical error no data were collected for ‘wellbeing’. However, in plenary discussion it was agreed that the overall sense of positivity was high due to everyone working together successfully.

Overall, the indicators and narratives suggested that the social outcomes, and hence adaptive capacity, generated by the Core and Restore pilot study had been significant, providing a useful foundation for future collaborative activities and climate action. There were no negative comments, although participants may have been averse to criticising one another in public. Hence, it is possible that there was some level of positivity bias in their responses, which could be a weakness in the participatory method that was applied. Closed interviews and scoring with individual participants may have provided a more realistic assessment, but the benefits of group discussion, immediate feedback and resultant social learning would have been lost.

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