The Distribution and Abundance of 'Blue Carbon' within Corangamite

A report for the Corangamite Catchment Management Authority

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Cover photo: Saltmarsh at Breamlea

Executive Summary

Vegetated coastal habitats—seagrasses, saltmarshes and mangroves—have recently been identified as one of the most effective carbon sinks on the planet. Such habitats can bury carbon at a rate 35-57 times faster than tropical rainforests and can store carbon for thousands of years. Recent global data estimate that vegetated coastal habitats contribute 50% of carbon burial in the oceans – termed “blue carbon”. These features make vegetated coastal habitats ideal candidates for carbon offset programs and nature-based climate mitigation initiatives.

In 2014 the Corangamite Catchment Management Authority (CMA) identified a lack of information on the distribution and abundance of blue carbon within the catchment. Such information is critical for guiding the spatial prioritisation of conservation efforts. To address this knowledge gap, the Corangamite CMA commissioned researchers from Deakin University to conduct Corangamite’s first blue carbon stock assessment, focussing on sedimentary organic carbon. The major findings of this program are as follows:

- Corangamite has an estimated total blue carbon sediment stock of 431,502.02 Mg and a total carbon value of $6,472,530 over the top 30 cm of sediment at $15 Mg^{-1}.
- It should be noted that because current sampling was confined to the top 30 cm of sediment, the carbon estimates given here are highly conservative. In fact, since organic carbon is stored at depths up to several metres, the true value of these habitats is even greater.
- The average soil carbon content is 4.96%, and 64.24 Mg C_{org} ha^{-1} (over the top 30 cm).
- The carbon stock in Corangamite is comprised mostly of saltmarsh (62%) and seagrass (37%), with mangroves contributing < 1%, in spite of their high carbon stocks, due to their limited distribution.
- Saltmarsh habitats comprised almost half of the vegetated coastal habitat samples in Corangamite (48.2% of samples) and were found to have high carbon stocks ha^{-1}, with exceptionally high (>20% C_{org}) values recorded at Aireys Inlet (AIR), Inner Breamlea (BRM), Lake Connewarre (CON), Hospital Swamp (HOS), Indented Head (IND), and Swan Bay (SBS and SBN).
- The saltmarsh at inner Breamlea (BRM) had the highest carbon stock values (and therefore monetary worth of $2,217.34 ha^{-1}, Table 2). Areas of Breamlea are protected as part of the Breamlea Flora and Fauna Reserve and do not appear to be threatened by direct human impacts at this time. Parts of the Barwon River estuary shows visual signs of erosion, threatening the blue carbon storage capacity (particularly for mangroves) in some areas. Additionally, the mangroves in the area appear to suffer trampling effects due to local fishing and other recreational activities.
- Across the sample sites in Corangamite, areas higher in the estuaries (or closer to fluvial inputs) were associated with higher carbon stocks (Fig 4c).
- Additionally, the seagrass maps used do not include offshore seagrass distribution, or any seagrass west of Port Phillip Bay, and are, therefore, underestimates of seagrass extent in Corangamite.

This report summarizes the valuable soil carbon stocks in blue carbon ecosystems across Corangamite. Saltmarsh makes up the largest portion of blue carbon in Corangamite due to the high sediment carbon content (around four times the average of seagrass), while occupying only 57% of the area of seagrass. Based on their limited mapped distribution, seagrasses account for over a third (37%) of Corangamite's blue carbon. Updated and extended distribution maps of seagrass are necessary to accurately estimate the seagrass carbon stock and identify highest-priority areas for seagrass conservation.

We identified a number of areas that should be prioritised for conservation because of their notably high carbon stocks. This includes saltmarsh in Breamlea, Lake Connewarre and both saltmarsh and seagrass in Swan Bay. These locations currently represent varying levels of protection for saltmarsh. Further, the trends identified in blue carbon soil stocks and carbon heat maps provide valuable insight for identifying appropriate locations for revegetation (and potentially, carbon offset) programs. With carbon sequestration initiatives firmly on the national agenda, both protecting and improving these habitats will only become more important.

With a growing Australian push to 'get blue carbon to market', we recommend further research into opportunities for blue carbon offset projects within Corangamite, through strategic preservation (e.g. through additional fencing) or restoration of former blue carbon habitats (e.g. bund/dyke wall removals), and through management of catchment-level processes to enhance blue carbon sequestration within existing habitats (e.g. restore natural hydrology). Though the goal of such activities would be carbon enhancement, there would be broad environmental, social, and economic benefits (e.g. biodiversity and fisheries enhancement, shoreline stabilisation, climate change buffering, improved shoreline amenity).

In sum, we recommend the following actions be taken to maximize blue carbon stocks in Corangamite:

1) Prioritize blue carbon hotspots for conservation
2) Produce updated and extended seagrass distribution maps
3) Focus revegetation projects on saltmarsh ecosystems and/or estuarine environments closer to fluvial inputs in estuarine environments
4) Restore natural hydrology to enhance blue carbon sequestration
5) Research into the distribution and carbon storage potential of freshwater wetland ecosystems in Corangamite

Introduction

Saltmarsh, mangroves, and seagrass meadows—collectively known as vegetated coastal habitats or “Blue Carbon” habitats —together sequester nearly equivalent quantities of organic carbon (C_{org}) as their terrestrial counterparts, in spite of their comparatively limited biomass (0.05% of terrestrial plant biomass). Blue Carbon habitats are reported to store organic carbon at almost 40 times the rate of terrestrial systems (Fourqurean *et al.* 2012a). Estimates from some parts of the world indicate that carbon is sequestered at a rate of up to 151.0 g C m^{-2} yr^{-1} in saltmarsh, 139.0 g C m^{-2} yr^{-1} in mangroves, and 83.0 g C m^{-2} yr^{-1} in seagrass (Smith 1981; Duarte *et al.* 2005; McLeod *et al.* 2011). The relatively anaerobic soils of vegetated coastal habitats prevent organic carbon remineralisation and tend to promote long-term sequestration (Mateo *et al.* 1997; Pedersen *et al.* 2011). As such, carbon may be stored for centuries to millennia, as opposed to the decadal scales typical for terrestrial systems, and never become saturated due to the vertical accretion of sediment in these habitats. Vegetated coastal habitats both produce and store their own carbon (autochthonous carbon), but also trap carbon produced from other locations (allochthonous carbon). Their ability to trap particles and suspended sediment means that vegetated coastal habitats may appropriate large quantities of the allochthonous organic carbon that originates from adjacent habitats, both terrestrial and marine (Gacia and Duarte 2001; Agawin and Duarte 2002; Hendriks *et al.* 2008; Kennedy *et al.* 2010).

However, degradation and loss of vegetated coastal habitats via mismanagement could shift them from carbon sinks to carbon sources, releasing atmospheric CO_2 equivalent to annual damages of US$6 to 42 billion globally (Pendleton *et al.* 2012). While natural disturbance events can lead to the loss of stored organic carbon (Macreadie *et al.* 2013), anthropogenic impacts including clearing of land, land fill, tidal restriction, stock grazing, and degradation of water quality have consistently driven more severe losses. The current global estimates of saltmarsh and mangrove habitat loss are around 25-35% (Valiela *et al.* 2001, Alongi 2002, IPCC 2007, Bridgham *et al.* 2006), though lower rates are estimated in Australasia (18% loss for mangroves). Total seagrass loss is similar, at an estimated 18-50% over the last 20 years (Green and Short 2003, Waycott *et al.* 2009). The rate at which such declines are occurring (based on multiple decades of data) was >1% y^{-1} for seagrasses (Duarte 2002, Short and Green 2003, Duarte *et al.* 2005b), but have now accelerated to 7% y^{-1} since the 1990s (Waycott *et al.* 2009).

In addition to their important role in carbon sequestration, vegetated coastal habitats are also worth trillions of dollars annually through the range of ecosystem services they provide (Costanza 1998). Vegetated coastal habitats serve as nursery habitat for many fisheries species, supplying valuable nutrition for around 3.5 billion people (Nellemann *et al.* 2009). Seagrasses are also the primary food source for endangered species of turtles and dugongs. Saltmarshes and mangroves play a critical role in shoreline stabilisation, which is increasingly important with respect to sea-level rise and increasing frequency and intensity of extreme weather events associated with climate change (King & Lester 1995, Gedan *et al.* 2011). This service was particularly highlighted through a number of recent catastrophic events such as the December 2004 Indian Ocean tsunami (Danielsen *et al.* 2005, Kathiresan & Rajendran 2005, Alongi 2008) and Haiyan, the November 2013 typhoon that hit the Philippines (Gross 2014).

While the ecosystem benefits of saltmarsh, mangroves and seagrasses are relatively well-known, reliable data on their stocks of soil organic carbon are limited to sites within the Mediterranean, Northern Atlantic, and eastern Indian Oceans. Thus, our ability to estimate global carbon sequestration may be heavily influenced by values from these geographic regions (Fourqurean *et al.* 2012a), making it difficult to predict carbon storage levels in regions that have never been sampled. In addition, even for areas that have been sampled, available data indicates that considerable variation in organic carbon storage exists among locations (Fourqurean *et al.* 2012a). Variation in organic carbon storage has been attributed to multiple biological and environmental factors that can strongly influence the rate of organic carbon deposition (Lavery *et al.* 2013).

While substantial efforts are being made to understand and capitalise on carbon sequestration on land, the status of carbon stocks in vegetated coastal habitats is simply unknown in many regions of the globe (Nellemann *et al.* 2009). Improving our understanding of the factors influencing variability in carbon storage requires expanding the global dataset of carbon inventories. This study aimed to i) quantify belowground carbon in vegetated coastal habitats and ii) identify 'hotspots' (areas of above-average organic carbon storage) across the Victorian coastline in south eastern Australia.

This report summarizes the findings for blue carbon habitat stocks in the Corangamite catchment for the Corangamite Catchment Management Authorities (CMA).

Methods

Site selection for blue carbon sampling

To quantify and characterise the carbon sequestration capacity of blue carbon habitats across Corangamite, we relied heavily on existing habitat mapping to appropriately sample these habitats across the state. Saltmarsh and mangroves have been mapped comprehensively across the entire state of Victoria (Boon *et al.* 2010). In contrast to these habitats, the mapping of seagrass in Victoria was conducted between 12-18 years ago, only included estuarine or large embayment's, and did not extend west of Port Phillip Bay (Roob and Ball 1997, Roob *et al.* 1998, Blake *et al.* 2000, Blake and Ball 2001a, Blake and Ball 2001b). Hence, our sampling approach was informed by the mapping that did exist, however for seagrass habitats, was also guided by our own knowledge of where seagrass habitats are likely to exist.

Saltmarsh, seagrass, and mangroves were all represented in the Corangamite carbon stock assessment sampling (Figure 1, 2). Saltmarsh dominated the sampling scheme (n=95), followed by seagrasses (n=66) and mangroves (n=36; Table 3). The seagrass area recorded was likely underestimated, as only inlet and estuarine seagrass in Port Phillip Bay were included.

Figure 1. Representatives of blue carbon habitats sampled in Victoria (a-i) and sediment coring techniques utilized to analyse soil carbon (j-l). Seagrass (a-c) samples included *Zostera muelleri* (a), *Zostera nigracaulus* (b, c- with high sedimentation). Mangrove samples represent the one species of mangrove present in Victoria, *Avicennia marina* (d- mangrove plants, e- flowers, and f- seeds). Several types of saltmarsh habitats were sampled, including wet saltmarsh herbland (g- *Sarconia sp.*, h- *Suaeda sp.*) and wet saltmarsh shrubland (i- *Tecticornia sp*.). Sediment cores were taken to 30cm deep using 50cm length PVC pipes (j), cores were extracted and sectioned in the lab (k), and sediment samples were dried, weighed, and analysed for C_{org} content (l).

Blue carbon habitats in Corangamite were generally clustered in a few main areas, notably the Barwon River Estuary (Lake Connewarre) and Swan Bay areas (Figure 2). The number of cores sampled at each site reflected the types of blue carbon habitats present. For example, a site with only seagrass would result in three replicate cores, while a site with all three blue carbon habitats would have three sets of three replicates for each, and thus a total of nine cores (or 27 samples). All sites were sampled between 17 July and 23 September 2014. Geographic location and 1 m^2 quadrat photos were taken at all sites. Quadrat photos were used to calculate percentage cover using the image analysis program CPCe (Kohler and Gill).

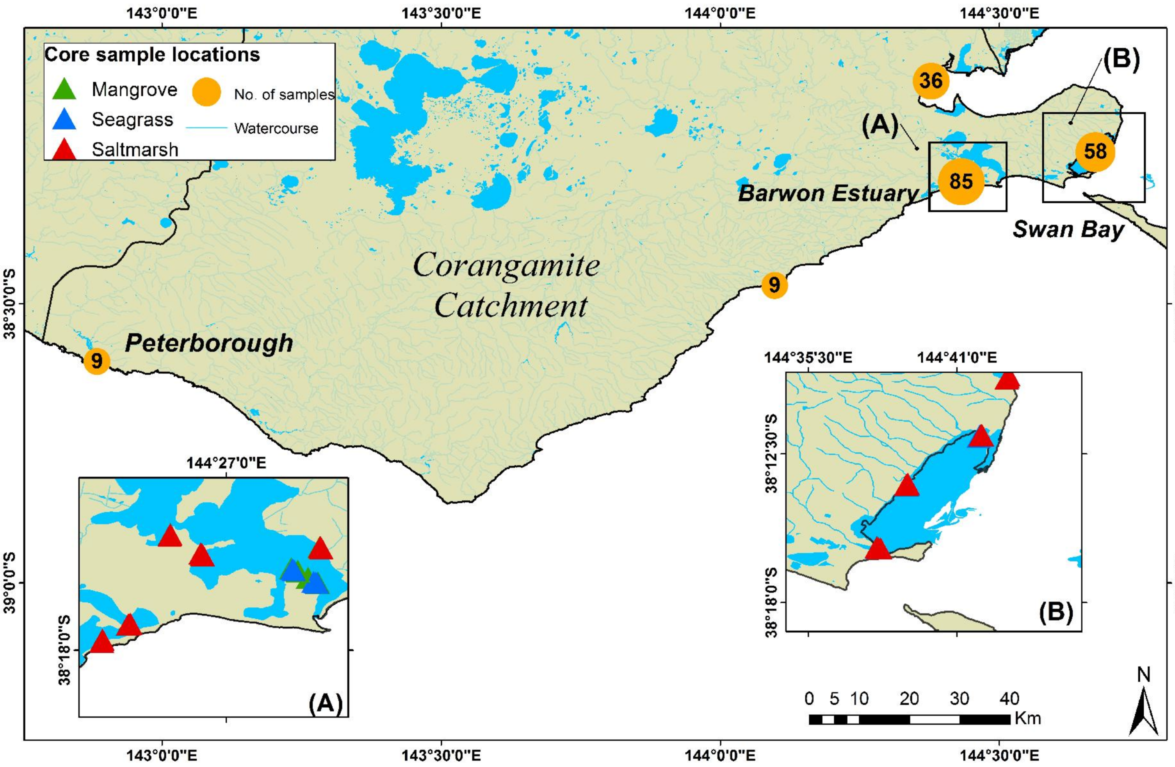

Figure 2. Blue carbon habitat sampling sites within the Corangamite catchment. The majority of samples were taken from the Barwon River Estuary (Lake Connewarre) (A) and Swan Bay area (B). The number of samples collected in each area are represented by the size of the orange circles on the main map (larger circles equal more samples collected), while blue carbon habitat types are represented in the inset maps by blue triangles (seagrass), red triangles (saltmarsh), and green triangles (mangroves).

Within blue carbon habitats, carbon is stored in living plant biomass for relatively short time scales (years to decades), while carbon sequestered in soils can be extensive and remain trapped for very long periods of time (centuries to millennia) resulting in very large carbon stocks (Duarte *et al.* 2005; Lo Iacono *et al.* 2008). As such, we focused on the belowground carbon pool by collecting soil sediment cores. Sediment cores were collected haphazardly within a given habitat location (with at least 50 m between each habitat core). Cores were collected via a piston corer, which involved hammering a PVC tube (50 mm internal diameter) into the sediment until a depth of 300 mm was reached and using suction from the tightened piston located within the tube to hold the sediment in place while the tube was extracted. Subsequent processing of the cores was performed back in the laboratory.

Sediment carbon content analyses

The sediment in the tube was extruded and divided into the following sections 0-2, 14-16, and 28-30 cm. These samples were then placed into sterile plastic tubes and dried at 60°C for at least 120 hours. To enable carbon stock to be calculated, we first calculated dry bulk density (g cm^{-3}) for each sediment depth by dividing the mass of the dried sediment by the original (pre-dried) volume of the sample.

After drying, all samples were homogenized by breaking up aggregates with an agate mortar and pestle. Samples were then quantitatively split down to 8 g subsamples which were finely ground on a Retch MM400 Mixer Mill using tungsten carbide grinding jars and balls. Samples were ground for 180 seconds at an oscillation frequency of 28 Hz, a duration determined to be necessary to produce a homogenous sample with repeatable mid infrared (MIR) spectra (Baldock *et al.* 2013).

Diffuse reflectance Fourier-transform MIR spectra across a spectral range of 8700-400 cm^{-1} at 8 cm^{-1} resolution were then obtained on all samples on a Thermo Nicolet 6700 FTIR spectrometer equipped with a Pike AutoDiff automated diffuse reflectance accessory following the protocols of Baldock *et al.* (2013). Spectra were then imported into the Unscrambler X ver 10.1 software as default OMNIC files. After Baseline Offset preprocessing and truncating the spectral range to 6000-1030 cm^{-1}, a principal components analysis (PCA) was used to visualize the variability in the total sample set. The Kennard-Stone Algorithm (Kennard and Stone 1969) was used on the first 6 principal components to pick the most representative 200 samples from the entire sample set.

Total carbon (TC), total organic carbon (TOC), total nitrogen (TN), and inorganic carbon (IC) were then determined in the laboratory on these 200 samples. All 200 samples were analyzed for TC and TN by high temperature oxidative combustion on a LECO Trumac CN analyzer at a combustion temperature of 1350°C and an extended purge and lance oxygen flows to ensure complete combustion of carbonate materials. For non-calcareous samples, determined by visual inspection of the MIR spectra (absence of a reflectance peak at 2500 cm^{-1}), TC = TOC and no further analyses were performed. For calcareous samples, carbonate removal was accomplished by acidification in 4% HCl. Two grams of sediment were weighed into 50 ml centrifuge tubes, 4% HCl was added slowly in 5 ml increments with vortexing between aliquots of acid. After 30 ml was added, tubes were capped and left on a shaker table overnight. Samples were then centrifuged at 3000 rpm for 8 minutes and supernatant was decanted. Samples were washed twice with 30 ml of ultrapure water followed by centrifuging before being lyophilized and reweighed. These acidified samples were then run again on the elemental analyzer for carbon and TOC data were reported back on original sample mass basis. For the calcareous samples, IC = TC – TOC.

The laboratory data were then used in a partial least squares regression (PLSR) to build algorithms which were then used to predict TC, TOC, TN and IC for the full set of samples. Full details of the MIR-PLSR procedure can be found in Baldock *et al.* (2013). Briefly, the PLSR models were built using the preprocessed MIR spectra and analytical data using a Random Cross Validation approach available in the Unscrambler 10.3 software (CAMO Software AS, Oslo, Norway). It was necessary to use square-root transformed TC, TOC, IC and TN data in order to reduce non linearity and improve homogeneity of residuals of calibration models. The quality of the derived PLSR models for predicting contents of TC, OC, IC, and TN was evaluated using a range of statistical parameters applied in the chemometric analysis of soil properties (Bellon-Maurel *et al.* 2010; Bellon-Maurel and McBratney 2011). The relationship between measured and PLSR predicted values was characterised by the slope, offset, correlation coefficient (r), R-squared, the root mean square error (RMSE), bias and the standard error (SE) of calibration (SEC) and validation (SEP). The ratio of performance to deviation (RPD) was used to define the quality of the derived models. To calculate RPD, the standard deviation (s) of measured samples used in the cross validation (s_{cv}) was calculated and divided by the appropriate standard error term (SE).

Chang *et al.* (2001) suggested that RPD values >2, between 1.4 and 2, and <1.4 could be used to distinguish excellent, fair, and non-reliable models, respectively. The Unscrambler software determined the optimum numbers of factors for each calibration model and n refers to the number of observations included in each analysis. Each calibration model was then used to predict values of sqrt TC, sqrt OC, sqrt IC, and sqrt TN for all sediment samples. It was necessary to back transform all data to obtain values for TC, OC, IC and TN. All data are reported as g C (or N) per kg sediment mass. An indication of the confidence of the prediction is given by the deviation statistic. This was used with the back transformed data to produce an upper and lower limit value for prediction which approximates a 95% confidence interval. In addition, each predicted value's status as an outlier was assessed by two measures: Inlier distance and Hotelling's T^2 distance. The inlier distance assessed the distance of the predicted value to the nearest calibration value, while the Hotelling's T^2 distance assessed the distance to the centre of the calibration values. If the ratio of the inlier distance to the inlier limit for a predicted value exceeded 1.0, the predicted value was identified as being an outlier in the sense that it was too far distant from the nearest calibration point. Similarly, if the ratio of the Hotelling's T^2 distance to the Hotelling's T^2 limit exceeded 1.0, the predicted value was identified as being an outlier in the sense that it was too distant from the centre of the calibration set.

Table 1. Summary statistics for MIR/PLSR models derived for square root transformed TC, OC, IC and TN content data (sqrt_TC, sqrt_OC, sqrt_IC and sqrt_TN, respectively) for Victorian coastline sediment samples.

Variable		Factors	n	Slope	Offset	r	R^2	RMSE [2]	Bias	SE [3]	s	RPD [4]
sqrt_TC	Calibration	4	199	0.962	0.289	0.981	0.962	0.819	0.000	0.821	4.22	5.14
	Validation		199	0.953	0.354	0.978	0.956	0.887	0.000	0.889	4.22	4.75
sqrt_OC	Calibration	5	199	0.975	0.156	0.987	0.975	0.733	0.000	0.735	4.63	6.30
	Validation		199	0.968	0.192	0.985	0.970	0.808	-0.007	0.810	4.63	5.72
sqrt_IC [1]	Calibration	4	89	0.971	0.160	0.985	0.971	0.403	0.000	0.405	2.38	5.87
	Validation		89	0.945	0.307	0.976	0.953	0.517	0.000	0.520	2.38	4.57
sqrt_TN	Calibration	5	200	0.962	0.064	0.981	0.962	0.216	0.000	0.217	1.11	5.13
	Validation		200	0.952	0.086	0.974	0.949	0.251	0.005	0.252	1.11	4.42

[1] Only samples that gave a positive fizz test were used to generate the IC model.

[2] RMSE = RMSEC for calibration samples and RMSEP for validation samples

[3] SE = SEC for calibration samples and SEP for validation samples

[4] RPD = RPD_C for calibration samples and RPD_P for validation samples.

Total carbon stock calculations

We followed the approach for calculating total sedimentary carbon stock as outlined by Howard *et al.* (2014). For each interval of the core analysed, we calculated the sedimentary organic carbon density as follows:

Step 1.
Soil carbon density (g/cm^3) = dry bulk density (g/cm^3) * (% C_{org}/100)

We then calculated the amount of carbon present in each section of the core by multiplying the soil carbon density value obtained in step 1 by the thickness of the core section (2 cm):

Step 2.
Carbon content in core section (g/cm^3) = Soil carbon density (g/cm^3) * Thickness of core section (2 cm)

As subsamples were taken along the core, we averaged the amount of carbon in each of the sections and then multiplied over the total depth sampled to get the total carbon stock. We then converted the total core carbon into MgC/hectare using the following unit conversion factors: 1,000,000 g = 1 Mg (megagram), and 100,000,000 cm^2 = 1 hectare:

Step 3.
Total sedimentary carbon (MgC ha^{-1}) = Averaged core carbon (g/cm^3) * (1 Mg/1,000,000 g) *(100,000,000 cm^2/1 hectare)

Replicate cores for each habitat within a single location were averaged to obtain an estimate of the carbon stock within the habitat at a given location. These carbon stock estimates were then averaged by habitat across all locations to estimate the average amount of carbon per habitat within the catchment. To calculate the total carbon stock across the catchment, we multiplied the average carbon value for each habitat (MgC ha^{-1}) by the total area of each habitat (in hectares) in the catchment, then summed the total carbon values for each habitat to determine the total sedimentary carbon stock in all the blue carbon habitats in Corangamite.

Carbon Hotspot Analysis

Hotspots were identified in Corangamite and generally reflect trends in organic soil carbon stock related to habitat type, patch size and location. Maps conveying estimates of blue carbon (tonnes, i.e. Mg) by habitat patch were derived using field samples of carbon stock combined with existing habitat maps of coastal and aquatic vegetation in the Corangamite catchment. Geographic distribution of intertidal vegetation including saltmarsh, mangroves and other wetland habitat was extracted from Boon *et al.* (2010) describing the condition and extent of Ecological Vegetation Classes (EVCs). The distribution of seagrass vegetation in Corangamite inlets was extracted from habitat maps produced by Blake *et al.* (2000). Mean carbon stock was calculated from sediment core replicates in the Corangamite catchment

(See locations - Figure 2). Using core samples for each habitat type, carbon values (Mg C ha^{-1}) were extracted at different locations within Barwon Estuary and the Swan Bay area. ArcMap 10.1 was used to georeference sample cores with habitat types at different locations within each inlet. Carbon stock values were then extrapolated to all habitat patches and an estimate of carbon (tonnes, i.e. Mg) for each patch was calculated by multiplying the average carbon stock of the habitat by patch area.

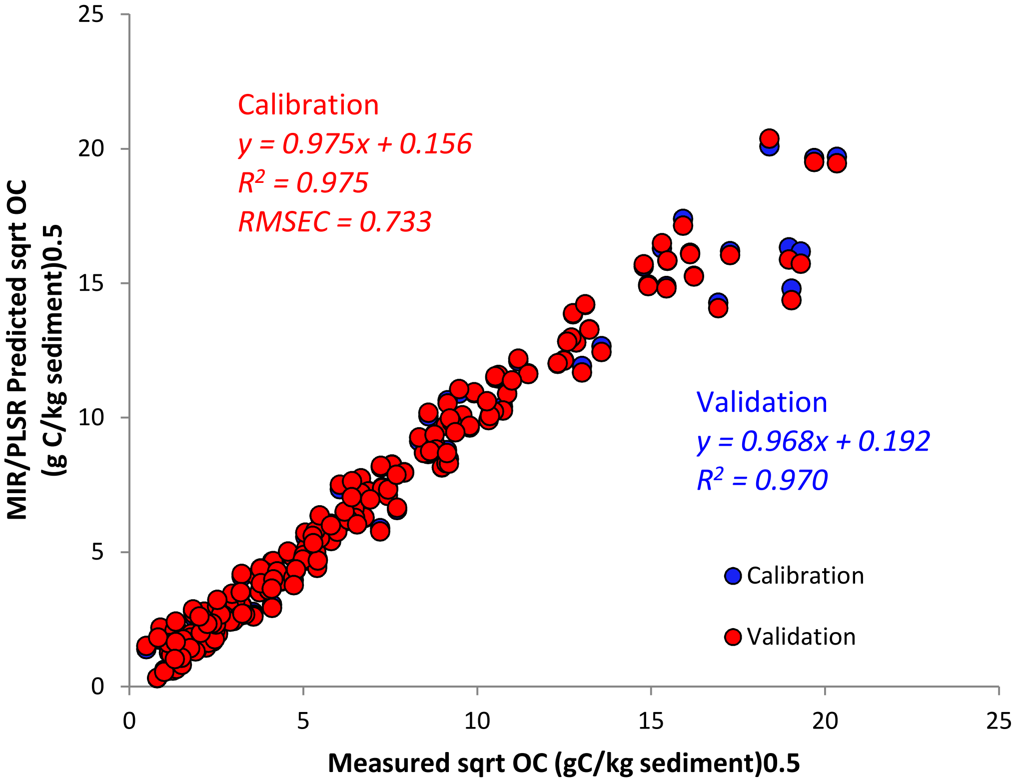

Figure 3. Relationship between measured and predicted data obtained for square-root transformed sediment OC contents.

Table 2. Summary of site locations, including site region, shortened site name, GPS coordinates, average percent cover of salt marsh habitat within a square-meter quadrat, number of cores taken, average carbon soil stock, and average monetary value of soil carbon stocks per hectare.

Site Name	Region	Shortened site name	Habitats Sampled	Latitude (^{0}N)	Longitude (^{0}E)	Saltmarsh % cover	# Cores	Mg C_{org} ha^{-1} (top 30cm)	Average $ value ha^{-1} (at $15 per Mg)
Peterborough	Shipwreck Coast	PET	SG	-38.60322778	142.8835278	n/a	3	27.335	410
Aireys Inlet	Surf Coast	AIR	SM	-38.46666667	144.0971222	59.41	3	118.915	1784
Breamlea Outer	Surf Coast	BRE	SM	-38.29506667	144.3861667	66.33	3	59.586	894
Breamlea Inner	Surf Coast	BRM	SM	-38.28669583	144.4000479	76.56	3	147.823	2217
Hospital Swamp	Barwon River Estuary	HOS	SM	-38.24078889	144.4210667	61.67	3	63.786	957
Lake Connewarre South	Barwon River Estuary	CON	SM	-38.25088125	144.4376354	88.38	3	71.620	1074
Wallington	Barwon River Estuary	WAL	MG, SM	-38.24726111	144.4985583	-	6	72.889	1093
Barwon Heads Inner	Barwon River Estuary	BAR	MG, SG	-38.25883333	144.4851933	n/a	5	35.098	526
Barwon Heads Outer	Barwon River Estuary	BAH	MG, SG	-38.26487778	144.4956778	n/a	6	41.582	624
Swan Bay South	Swan Bay	SBS	SG, SM	-38.2665	144.6346462	82.41	5	55.277	829
Swan Bay Jetty	Swan Bay	SBJ	SG, SM	-38.22747222	144.6525167	57.00	6	71.539	1073
Swan Bay North	Swan Bay	SBN	SG, SM	-38.19721944	144.697625	81.00	6	67.648	1015
Indented Head	Bellarine	IND	SM	-38.16114444	144.7143722	92.67	3	58.331	875
Geelong	Corio	GEE	SG	-38.13638333	144.3561556	n/a	3	45.811	687
Limeburners Bay	Corio	LIM	MG, SG, SM	-38.06138889	144.4043796	81.91	9	62.630	939

Results and Discussion

Soil sample analysis

The median dry bulk density (DBD) of the sediment samples (0.88 g cm^{-3}) was lower than the global median (0.92 g cm^{-3}), and reflects the variety of sediment compositions related to local site conditions (Figure 4a). Visually, samples varied across depth, habitat, and site in amount of plant material (including peat), sediment grain size, compaction, and soil composition.

The median percent organic carbon of all samples pooled (1.89%) was higher than the global median (1.4%, Figure 4b). Several of the samples had percent organic carbon levels much higher than the median (up to 41%), and may reflect a combination of causes, such as habitat type and specific site conditions.

As expected, average carbon stocks were highest near the surface of the sediment (0-2 cm depth), followed by mid-depth sediment (14-16 cm), and lowest in the deepest section of sediment (28-30 cm; Figure 5a).

There were clear differences in soil carbon levels based on habitat type. Saltmarsh had the highest average carbon stock values (29.57 mg C_{org} cm^{-3}), followed by mangroves (20.58 mg C_{org} cm^{-3}), then seagrasses (10.12 mg C_{org} cm^{-3}, Figure 5b). This pattern was consistent when comparing carbon stock values across locations and habitat types represented.

Carbon stocks across sites and carbon hotspots

Carbon stocks varied across sampling site locations in Corangamite, but all blue carbon habitats sampled represent valuable carbon sinks, both ecologically and economically (Table 2). The differences in carbon storage (and the resulting differences in monetary value) across adjacent sampling sites reflects the high variability in carbon stocks within small geographic scales, which likely results from a complex combination of environmental variables and habitat quality.

Notably, high carbon stock values were often associated with locations higher up in estuarine areas (or closer to fluvial inputs) and in locations where saltmarsh was included as one of the habitats sampled. Inner Breamlea (BRM) was the location with the highest average carbon stock, and although adjacent to the outer Breamlea site (BRE), it is located higher up in the estuary. Aireys Inlet (AIR) also contained high carbon stocks, possibly due to the type of saltmarsh sampled and nature of the estuary, which is often closed to the coast and appeared to be less saline than most other saltmarshes sampled in the area. The sampling in Petersborough contained only seagrasses, and therefore reflects low carbon stock values per unit area. Within the Barwon River Estuary, saltmarsh accounted for

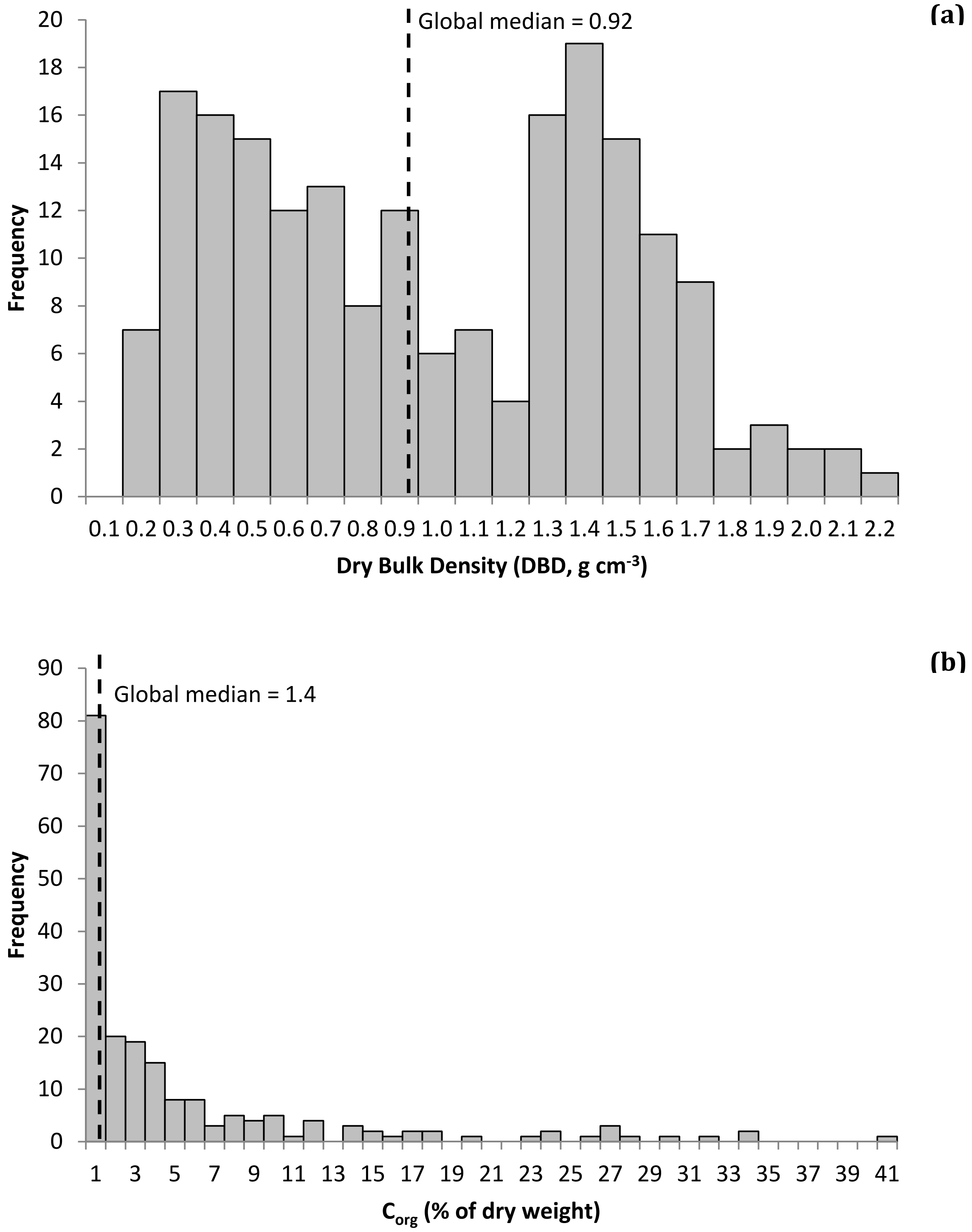

Figure 4. Frequency of soil sample (a) dry bulk density (DBD, g cm^{-3}, n=197) and (b) organic carbon content (% C_{org}, n=197) samples across Corangamite catchment (pooled by habitats and depths). The global median for DBD and percent C_{org} are indicated by dashed lines, correspondingly, according to Campbell *et al.* (2014).

most of the blue carbon stock. Among the highest were Hospital Swamp (HOS) and Lake Connewarre (CON) in the upper estuary that represent two different types of saltmarsh. The lower carbon stocks in the area at inner Barwon Heads (BAR) and outer Barwon Heads (BAH) each represent a combination of both seagrass and mangrove samples. Wallington (WAL), located high in an estuary tributary, also had high carbon stocks. All of the Swan Bay locations (SBS, SBJ, and SBN) had high carbon stocks due to the presence of saltmarsh in each location. The low values at Geelong reflect that only seagrasses were sampled in this area. The range of carbon values at Limburners Bay (LIM) is particularly high due to one extremely high carbon saltmarsh sample (145.2 mg C_{org} cm^{-3}).

Vulnerability of blue carbon habitats seemed to vary across locations within the catchment. Parts of Breamlea are included in the Breamlea Flora and Fauna Reserve, which provides them some level of protection. However, coastal infrastructure and catchment level processes, including nutrient and sediment run-off from agriculture and storm water, are just some of the other threats facing this and many other locations in Corangamite (Jenkins 2013). Although some of the high-valued blue carbon sinks in Corangamite are unlikely to be disturbed by direct anthropogenic disturbance, the Barwon River estuary shows visual signs of erosion, threatening the blue carbon storage capacity in some areas. Additionally, the mangroves in the area suffer trampling effects due to local fishing and other recreational activities. Threats to blue carbon stocks in Corangamite should be monitored and minimized to ensure the preservation of these carbon stocks into the future. Disturbance and loss of blue carbon habitats can shift them from serving as powerful carbon sinks to major sources of carbon emissions to the atmosphere.

Table 3. Summary of habitats sampled, including total habitat area within Corangamite, total habitat area within Victoria, and percentage of the habitat in Corangamite relative to all of Victoria. Carbon soil stocks (in the top 30 cm) in Corangamite across each habitat are based on the average carbon storage multiplied by the total habitat area within Corangamite. Habitat area estimates are based on state-wide mapping performed by Boon *et al.* (2010), Blake *et al.* (2010) and Roob *et al.* (2007). Seagrass mapping has not been completed across the entire state of Victoria. Estimates of seagrass distribution in Corangamite do not include offshore seagrass or anything west of Port Phillip Bay, and are, therefore, likely to be underestimates of seagrass extent.

Habitat type	Corangamite Area (Ha)	Victorian Total Area (Ha)	Corangamite as % of state	Corangamite Mg C_{org}	Total $ Value (at $15 per Mg)
Saltmarsh	3,010.13	20,625.74	14.59	267,037.23	4,005,559
Mangrove	58.31	5,186.58	1.12	3,600.78	54,012
Seagrass	5,296.34	42,812.63	12.37	160,864.01	2,412,960
Grand Total	8,364.77	63,328.61	28.08	431,502.02	6,472,530

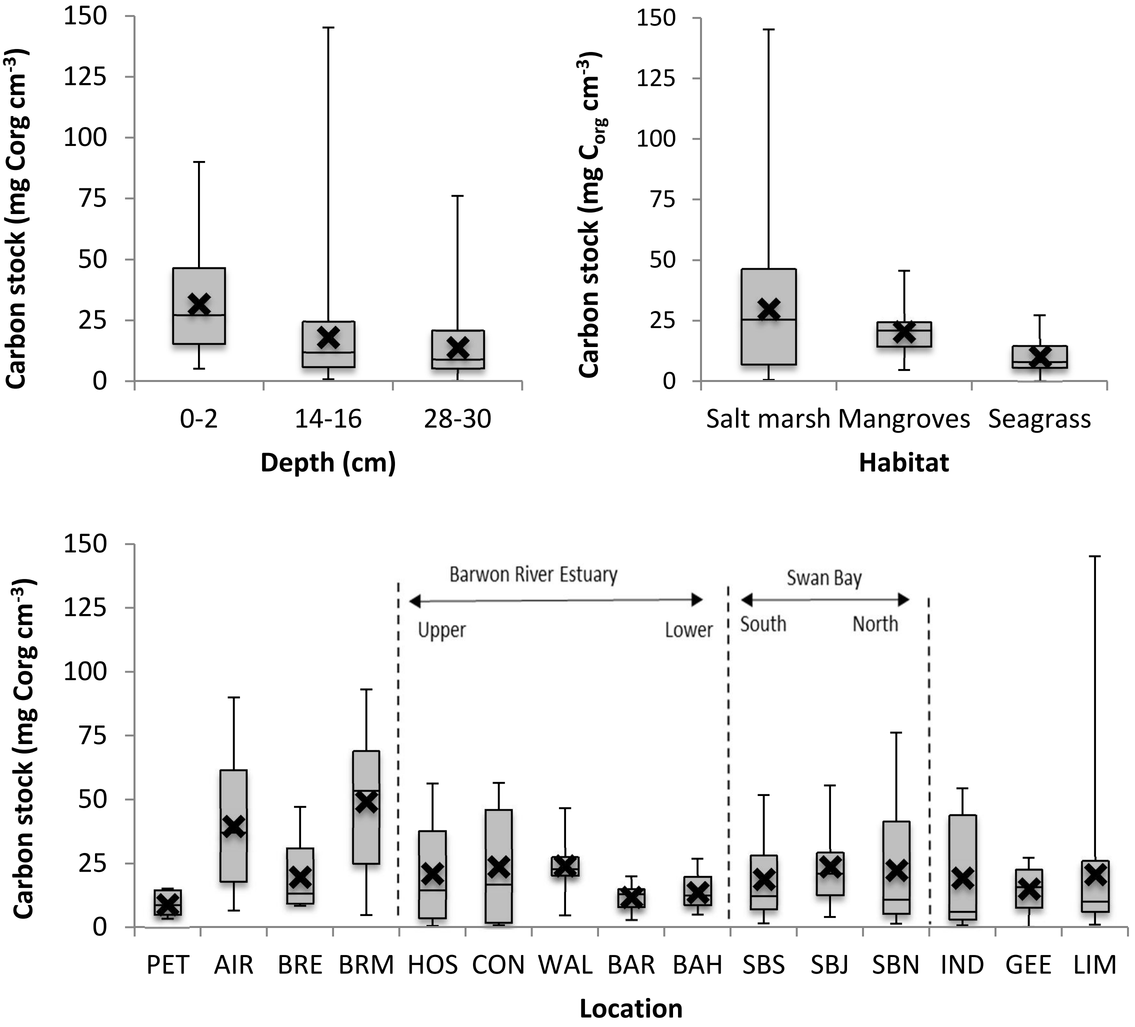

Figure 5. Carbon stock (mg C_{org} cm^{-3}) in blue carbon habitat soils by (a) depth, (b) habitat type, and (c) sampling location (west to east from left to right) within Corangamite catchment. Box plots represent the minimum and maximum values (tails), the middle 50% range (box), and the median (line bisecting box) for each sample group. Mean carbon stock values are represented by “x” symbols.

Despite the relatively low C_{org} values per hectare of seagrass, the large area of this habitat type in Corangamite means it makes up a substantial carbon stock in the catchment (Table 3, Figure 6). However, the long time period since the habitat was last mapped on a large scale and the fact that a recent study of a few locations has shown declines in seagrass area since 2001 (Ball *et al.* 2014) suggest that previous maps are no longer reliable. This issue may be rectified by mapping the current distribution of seagrass in Corangamite and sampling the sediment carbon stock where seagrass has been lost. While loss of this habitat results in decreased potential for future carbon sequestration, we have little understanding of how belowground carbon stock is affected by seagrass loss. If seagrass cover across the catchment has indeed experienced declines, there are significant implications for the carbon stock in Corangamite, including its shift from carbon sink to carbon source.

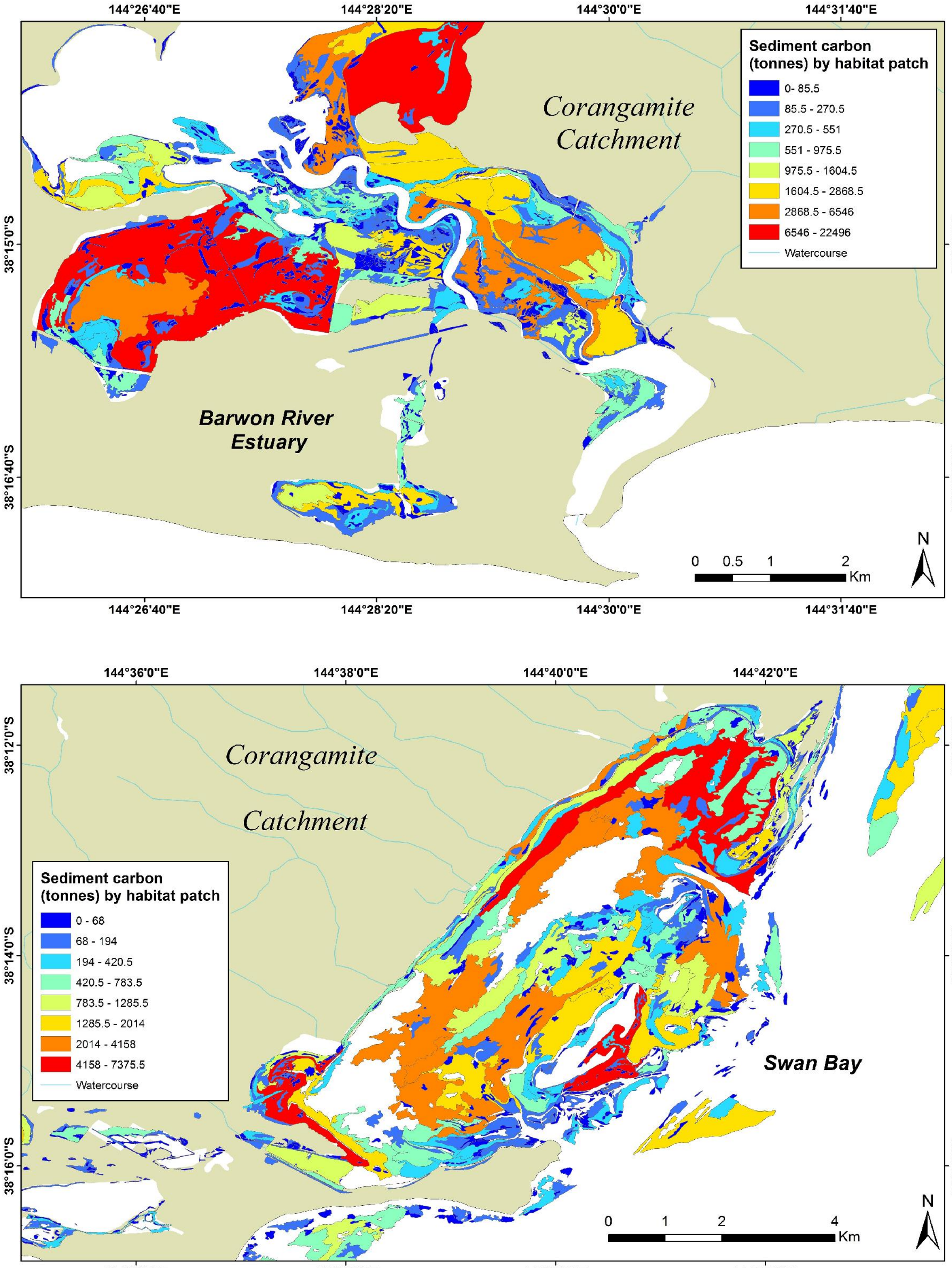

Figure 6. Carbon heat maps for two regions of blue carbon habitats in Corangamite catchment, Barwon River Estuary (top) and Swan Bay area (bottom). Blue carbon values represent tonnes of organic carbon stored in the top 30cm of the soil in seagrass, mangrove, and saltmarsh habitat areas.

The Carbon Hotspot Analysis is a combination of both the soil carbon content and the size of particular habitat patches. It provides a method for identifying high value habitat patches using spatial information. The current analysis highlights the saltmarsh in the upper regions of the Barwon River Estuary/Lake Connewarre and the large seagrass patches in Swan Bay as the highest value blue carbon locations. Unfortunately, some sections of the Barwon Estuary are under threat from erosion and trampling by people (Figure 7a, b). Protecting these habitats is a vital measure to ensure retention of this valuable carbon stock. While we don't have information on the amount of sediment loss in the Barwon estuary, in the Port Phillip and Westernport catchment, erosion rates have been quantified for the Lang Lang coast. Here, based upon work by Tomkins *et al.* (2014), we were able to apply percent carbon values from our sampling of the area to calculate the total carbon loss. This equated to 244 ± 168 Mg carbon per year or $3,660 ± 2520 per year. While the bank at Lang Lang is higher and the coastline longer (~7 km), this example provides insight into the effects of erosion on carbon sediment stocks.

There are also some large areas that have been historically cleared of saltmarsh vegetation in the regions of Lake Connewarre and Breamlea, which both have high value carbon stocks (Boon *et al.* 2010). These would be ideal candidate revegetation sites as they would provide great value for protection/revegetation effort. While it appears as though some protection measures have been put in place (Figure 7d), some are working better than others (Figure 7c). A range of protection and revegetation options should be considered for these areas to preserve and increase Corangamite's valuable blue carbon stock into the future.

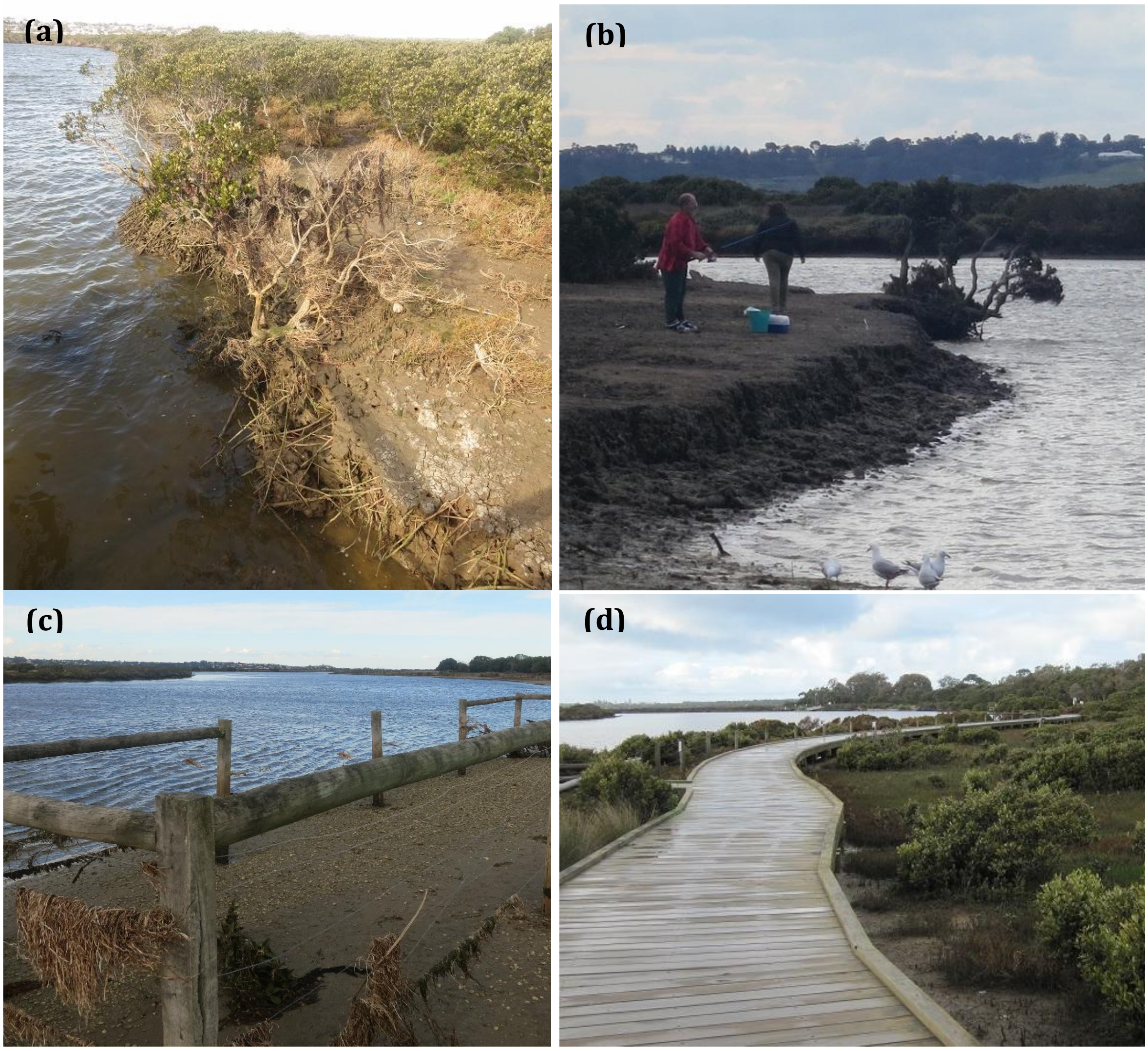

Figure 7. a) Eroding banks are present along much of the inner section of the Barwon River estuary with **b)** fisher-people commonly observed walking along banks and likely contributing to the problem. It appears as though a number of different methods of protection have been trialled, including **c)** fencing off particular sections of mangroves (which in this case are no longer present), or **d)** creating boardwalks

Major conclusions

Corangamite contains a valuable portion of the blue carbon ecosystems present across Victoria. The information gathered for this report can help the Corangamite CMA understand their current blue carbon stocks, conserve high-priority areas of blue carbon ecosystems, and plan for future protection and restoration of blue carbon for sequestration and myriad ecological purposes. The highest-value carbon stock areas (‘hotspots’) in Corangamite have been identified as the saltmarsh in the upper regions of the Barwon River Estuary/Lake Connewarre and the large seagrass patches in Swan Bay. Unfortunately, some sections of the Barwon Estuary are under threat from erosion and trampling and require action to preserve these valuable carbon stocks. Further, saltmarshes have the highest carbon stock per unit area of all the blue carbon habitats, but seagrasses in Corangamite still stores an impressive 37% of the catchment’s sedimentary carbon due to their large distribution. Based on these data, the largest potential for soil carbon loss is through decline or degradation of saltmarsh habitat, which is responsible for 62% of the catchment’s carbon stock. However, because these seagrass estimates are based on reports of seagrass distribution from 14 or more years ago (Roob and Ball 1997, Blake *et al.* 2000), updated mapping is essential to estimate seagrass carbon stocks and ensure effective management of Corangamite CMA’s blue carbon. Given the high efficiency of saltmarsh ecosystems in Corangamite to sequester high densities of carbon, revegetation or protection programs centred on this habitat may be the most cost efficient (in terms of potential carbon storage per area).

With a growing Australian push to ‘get blue carbon to market’, we recommend further research into opportunities for blue carbon offset projects within Corangamite, through strategic restoration of former blue carbon habitats (e.g. bund/dyke wall removals), and through management of catchment-level processes to enhance blue carbon sequestration within existing habitats (e.g. restoring natural hydrology). Though the goal of such activities would be carbon enhancement, there would be broad environmental, social, and economic benefits (e.g. biodiversity and fisheries enhancement, shoreline stabilisation, climate change buffering, improved shoreline amenity).

While not covered as part of this report, wetlands (which include alpine peatland, freshwater wetland and coastal wetlands) are also thought to be significant carbon sinks. Though they only represent about 4% of terrestrial land area, it's estimated that freshwater wetlands are currently storing about 33% of the carbon in terrestrial soils (Euliss et al. 2006). However, there is currently little known of these habitats in Corangamite, least of all their spatial distribution. Sampling in the Glenelg-Hopkins suggests that these habitats store similar quantities of carbon to saltmarsh and mangroves. Some concerns regarding natural methane release in freshwater wetlands have arisen, but in the long run, the benefits of carbon dioxide storage appear to outweigh the costs associated with carbon release in the form of methane (Euliss et al. 2006). Further research into the distribution and the effects of restoration of these habitats on carbon sequestration is required to capitalise on the carbon storage capacity of these blue carbon ecosystems in Corangamite.

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