CSIRO PUBLISHING
Soil Research, 2021, **59**, 619–629
https://doi.org/10.1071/SR20040

Quantifying blue carbon and nitrogen stocks in surface soils of temperate coastal wetlands

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Abstract. Coastal wetlands are carbon and nutrient sinks that capture large amounts of atmospheric CO_2 and runoff of nutrients. 'Blue carbon' refers to carbon stored within resident vegetation (e.g. mangroves, tidal marshes and seagrasses) and soil of coastal wetlands. This study aimed to quantify the impact of vegetation type on soil carbon stocks (organic and inorganic) and nitrogen in the surface soils (0–10 cm) of mangroves and tidal marsh habitats within nine temperate coastal blue carbon wetlands in South Australia. Results showed differences in surface soil organic carbon stocks (18.4 Mg OC ha^{-1} for mangroves; 17.6 Mg OC ha^{-1} for tidal marshes), inorganic carbon (31.9 Mg IC ha^{-1} for mangroves; 35.1 Mg IC ha^{-1} for tidal marshes), and total nitrogen (1.8 Mg TN ha^{-1} for both) were not consistently driven by vegetation type. However, mangrove soils at two sites (Clinton and Port Augusta) and tidal marsh soils at one site (Torrens Island) had larger soil organic carbon (SOC) stocks. These results highlighted site-specific differences in blue carbon stocks between the vegetation types and spatial variability within sites. Further, differences in spatial distribution of SOC within sites corresponded with variations in soil bulk density (BD). Results highlighted a link between SOC and BD in blue carbon soils. Understanding the drivers of carbon and nitrogen storage across different blue carbon environments and capturing its spatial variability will help improve predictions of the contribution these ecosystems to climate change mitigation.

Keywords: blue carbon, coastal wetlands, mangroves, soil carbon, soil nitrogen, temperate wetlands, tidal marshes.

Received 11 February 2020, accepted 22 April 2021, published online 25 June 2021

Introduction

Occurring at the interface between land and sea, vegetated coastal wetlands are dynamic ecosystems that play an important role in global carbon and nutrient cycles (Duarte *et al*. 2013). These ecosystems, including mangrove forests, tidal marshes and seagrass meadows, absorb significant amounts of carbon dioxide (CO_2) from the atmosphere and capture nutrients leached or eroded from their adjacent environments (Chmura *et al*. 2003; Moseman-Valtierra *et al*. 2011; Sanders *et al*. 2014; Atwood *et al*. 2017). Coastal carbon (organic), termed 'blue carbon', is stored in the above- and below-ground biomass, sediment and soils with soils representing the largest (49–99%) long-term organic carbon (OC) storage pool in these ecosystems (Donato *et al*. 2011; Siikamäki *et al*. 2013). Organic matter deposited by *in situ* vegetation or entering a coastal wetland through tidal inundation/runoff becomes trapped in the vegetations extensive root systems and buried by additional sediment depositions (Bouillon *et al*. 2003; Saintilan *et al*. 2013; Sanders *et al*. 2014; Hayes *et al*. 2017). This organic matter, rich in carbon and nitrogen, is subject to slow decomposition and can accumulate in the ecosystem for long periods of time (Duarte *et al*. 2013; Mitra and Zaman 2014; Kelleway *et al*. 2016*b*; Howard *et al*. 2017).

The global stock of blue carbon was estimated to be 11.25 Peta-grams (Pg C) when carbon contained in the above- and below-ground biomass and soils to a depth of 1 m were combined (Siikamäki *et al*. 2013). Mangrove ecosystems have the largest reported carbon stores; they account for 6.5 Pg C of the global blue carbon stocks, followed by seagrasses (2.3 Pg C) and then tidal marshes (2 Pg C) (Duarte *et al*. 2013; Siikamäki *et al*. 2013). The distribution of mangroves is largely concentrated in tropical latitudes, while salt marshes are prevalent in temperate regions and seagrasses are globally dispersed (Twilley *et al*. 1992; Alongi 2002; Siikamäki *et al*. 2013; Feher *et al*. 2017). To our knowledge, global estimates for nitrogen in the blue carbon environments are not available. However, regional assessments have shown higher soil nitrogen stocks in disturbed wetlands (Breithaupt *et al*. 2014; Sanders *et al*. 2014; Saderne *et al*. 2020). Quantification of nitrogen stocks in wetlands is important as nitrogen availability can increase primary productivity of coastal vegetation, and promote algal growth that may increase soil organic carbon (SOC) storage in blue carbon environments (Lovelock *et al*. 2007; Reddy and DeLaune 2008; Sanders *et al*. 2014). However, high nutrient loads can also increase mineralisation of organic matter and reduce carbon stocks in these ecosystems (Sanders *et al*. 2014).

In some regions, inorganic carbon (IC; i.e. calcium carbonate, $CaCO_3$) accumulates in coastal soils through the burial of calcified shells and skeletons of wetland fauna (e.g. crabs, snails, bivalves, sea stars) (Saderne *et al*. 2019). The production of 1 mol of $CaCO_3$ results in the release of 0.63 mol of CO_2 to the atmosphere (Macreadie *et al*. 2017; Saderne *et al*. 2019). Thus, in areas where $CaCO_3$ production exceeds 0.63 times $CaCO_3$ burial, the CO_2 sink benefit associated with the accretion of organic carbon in blue carbon environments can be counteracted (Macreadie *et al*. 2017; Saderne *et al*. 2019). The IC content of soil in blue carbon studies is not often reported but can represent a significant proportion of stored carbon when present. Therefore, it is important to quantify IC stocks in blue carbon environments to identify areas where high IC is present as it may indicate the potential for blue carbon environments to act as a CO_2 source depending on the relative rates of $CaCO_3$ production and burial.

The accumulation and storage of carbon (SOC and IC) in blue carbon habitats is inherently linked to the characteristics of their environmental setting (Bouillon *et al*. 2008; Lovelock *et al*. 2014; Lavery *et al*. 2019; Ewers Lewis *et al*. 2020; Owers *et al*. 2020). For example, the temperature, precipitation patterns, geomorphology and hydrodynamics of an environment influence the structure and colonisation of the coastal vegetation, and the deposition of organic matter (Owers *et al*. 2016*b*; Ewers Lewis *et al*. 2020). As such, variability of SOC stocks in blue carbon environments is primarily considered to be a function of the *in-situ* vegetation given their significant contribution of carbon inputs to the soil (Saintilan *et al*. 2013). The type of above-ground vegetation may therefore provide an indication of below-ground soil carbon stocks resulting from autochthonous carbon additions (primary productivity) and allochthonous carbon capture (sediment accumulation) (Bouillon *et al*. 2003; Lamb *et al*. 2006; Ewers Lewis *et al*. 2020). This highlights the importance of understanding soil carbon dynamics under different types of vegetation to gain better understanding of SOC storage in the blue carbon system.

Previous studies have found SOC contents and stocks to be highly variable across different geomorphic settings. For example, Chmura *et al*. (2003) found that mangrove soils (0.055 ± 0.004 g OC cm^{-3}) had significantly larger soil carbon densities than tidal marshes (0.039 ± 0.003 g OC cm^{-3}) when compared globally. However, a large proportion of sites included by Chmura *et al*. (2003) were tropical mangrove sites that typically have larger primary productivity compared to sub-tropical or temperate latitudes where tidal marshes are found (Sanders *et al*. 2016; Feher *et al*. 2017). In contrast, studies in temperate regions have found average tidal marsh SOC stocks and densities were larger than in mangrove soils, but also differed within each ecosystem (Howe *et al*. 2009; Livesley and Andrusiak 2012; Ewers Lewis *et al*. 2018). Comparable studies have not been undertaken in South Australia with most Australian studies focused on blue carbon systems along the country's north to south-eastern coastlines.

In South Australia, there are 164 km^2 of mangrove and 198 km^2 of tidal marsh habitats across the Gulf St Vincent and Spencer Gulf region (Foster *et al*. 2019). In addition to mitigating climate change, these habitats provide a suite of ecosystem services such as providing nursery habitats for commercially important finfish and feeding grounds for migratory shore birds, prevention of coastal erosion, protection of the coast during storm surges and filtering nutrients from entering coastal waters (Edyvane 1999; Baker 2015). However, there is a lack of regional-specific data for SOC stocks for coastal wetlands in SA. Focusing on adjacent tidal marsh and mangrove environments, this study aimed to quantify the impact of vegetation type on stocks of soil carbon (OC and IC) and nitrogen in the surface soils (0–10 cm) of temperate blue carbon environments in South Australia. Given the information available from previous blue carbon studies we hypothesised that: (i) South Australian mangroves will have larger carbon and nitrogen stocks than tidal marshes, driven by larger inputs from vegetation and more efficient trapping of allochthonous organic matter; and (ii) that tidal marsh environments would demonstrate higher intra-site variability than mangroves due to irregular patterns of tidal inundation and limited allochthonous sediment supply.

Materials and methods

Study site and sample collection

Nine sites along South Australia's coastline spanning the eastern side of Gulf St Vincent and Spencer Gulf were sampled (Fig. 1*a*) during the (Austral) spring of 2016 and 2017 (Department of Environment and Water, permit number U26525–1). Study sites included Mutton Cove, Torrens Island, Port Gawler, Port Wakefield, Clinton, Port Broughton, Port Pirie, Port Paterson and Port Augusta, characterised according to Bourman *et al*. (2016) in Table 1. At all sites, vegetation was dominated by beaded samphire (*Sarcocornia quinqueflora*) and scrubby samphire (*Tecticornia arbuscular*) tidal marshes and the single mangrove species occurring in South Australia, the grey mangrove (*Avicennia marina*). At each site, three 35 m transects that spanned across the tidal marsh to mangroves vegetation were sampled. The transects were anchored (mid-point) at the transition between vegetation types, evidenced by mangrove seedlings (30 cm) within the tidal marsh dominant vegetation (Fig. 1*b*). The first mangrove core (position 5) was sampled where greater than 80% of the vegetation was defined as mangrove. All sampling points were 5 m apart, running from tidal marsh (transect positions 1–4) to the mangrove (positions 5–8), as depicted in Fig. 1*b*. Surface soils (0–10 cm) were sampled by intact coring (8 cm internal diameter) from each transect sampling position. Shallow sampling depths were chosen with the aim of capturing the influence of overlying vegetation rather than historical influences deeper in the profile (Yando *et al*. 2016; Kelleway *et al*. 2017*b*; Owers *et al*. 2020). Additionally, the transect sampling approach was taken to account for the tidal gradient typically observed in blue carbon environments

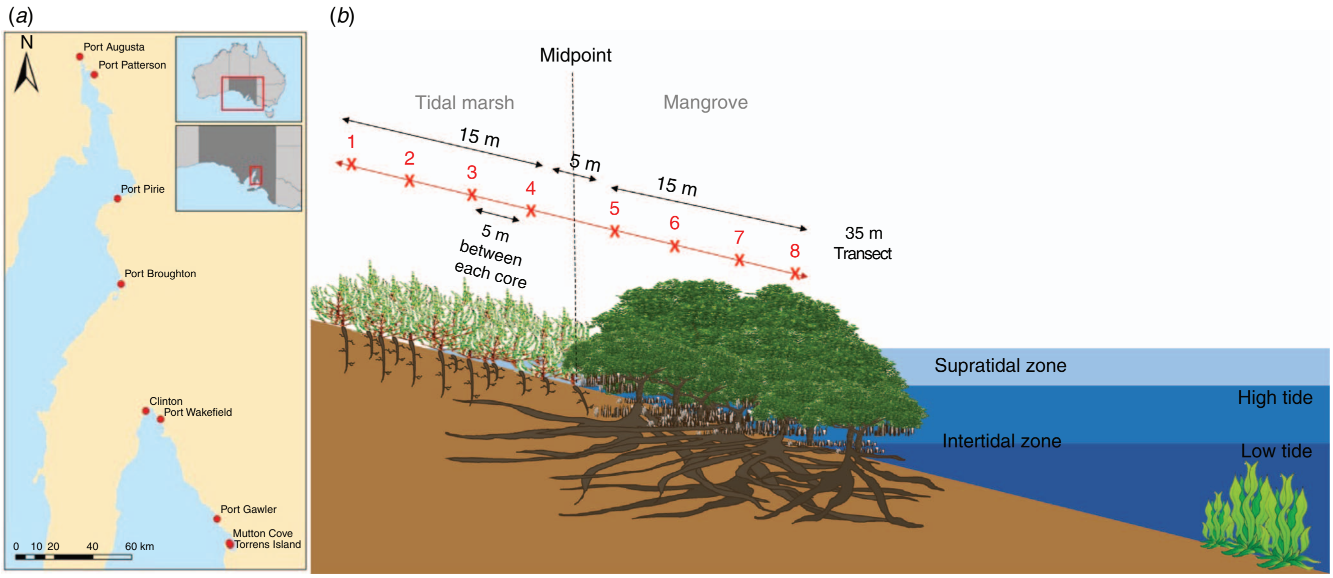

Fig. 1. (*a*) Location of nine South Australian coastal wetland study sites comprising both tidal marsh and mangrove ecosystems and (*b*) schematic sampling transects (3 per site, 35 m) were anchored from the midpoint point (first established mangrove) with four sampling points extending into each vegetation type at 5 m intervals.

and allowed for visualisation of the occurrences of spatial tends.

A total of 216 (108 tidal marsh and 108 mangrove forest) soils were collected across the nine sites. Following collection, intact cores were stored at <4°C for transportation before being stabilised through freezing and lyophilisation (Cuddon freeze dryer, Blenheim, New Zealand) before analysis.

Soil processing and analysis

All soil samples were weighed, dried to a constant weight (freeze-dried), crushed and sieved to ≤2 mm. A riffle box (12 × 13 mm slotted box; Civilab Australia, Sydney, Australia) was used to collect a representative sub-sample (approx. 25 g) of the ≤2 mm sample for fine grinding (Standard Ring Mill, SRM-RC-3P; Rocklabs Ltd, Auckland, New Zealand, fitted with a stainless-steel head, CARB-40-BLP). Fine ground samples were further analysed for total carbon (TC) and total nitrogen (TN) concentration (mg g^{-1}) by high temperature dry combustion (LECO TruMac CN analyser, LECO Corporation, St. Joseph, MI, USA). Soil dry bulk density (BD) was calculated as the dry sample weight (g) of the soil divided by the original wet sample volume (cm^3). To account for the >2 mm portion of the soils, a gravel correction was later applied in the stock calculation.

The presence of inorganic carbon (IC) in samples was determined on fine ground samples using diffuse reflectance infrared (IR) spectra collected as described in Baldock *et al.* (2013) using a Nicolet 6700 FTIR spectrometer (Thermo Fisher Scientific Inc., Waltham, MA, USA). Inorganic carbon has a distinct and easily observable absorption at a frequency of 2560–2480 cm^{-1} (Vohland *et al.* 2014). Samples identified to contain IC were repeatedly acidified (1 M hydrochloric acid, ~25 mL) until effervescence ceased, washed (three times) with deionised water, frozen and lyophilised. Organic carbon (OC) concentration (mg g^{-1}) was then determined on the acidified samples by dry combustion as described above. The IC concentration (mg g^{-1}) was calculated as the difference between TC and OC. For the soils containing no IC, their OC concentrations were equated to the measured TC. Soil OC (SOC) and TN concentrations were used to calculate carbon to nitrogen ratios (C:N) as an indicator of nitrogen limitation/enrichment. Surface stocks (Mg ha^{-1}) of SOC, IC and TN associated with the ≤2 mm soil fraction were calculated according to Eqn 1 using SOC as an example with units associated with each term given in parentheses after the term.

$$SOC_{stock}\left(\frac{Mg\ fine\ fraction\ OC}{ha\ whole\ soil}\right)$$
$$= SOC\left(\frac{g\ fine\ fraction\ OC}{100g\ OD\ fine\ fraction}\right) \times BD\left(\frac{g\ OD\ whole\ soil}{cm^3\ whole\ soil}\right) \quad (1)$$
$$\times D\ (cm\ whole\ soil) \times \left(1 - P_g\left(\frac{g\ OD\ gravel}{g\ OD\ whole\ soil}\right)\right)$$

Statistical analysis

The influence of vegetation (tidal marsh vs mangrove) on the measured soil properties was determined across the entire sample population (216 samples), and individually within the nine sites. A restricted maximum likelihood (REML) linear mixed model was used to determine differences in SOC, IC, TN, C:N and BD between tidal marsh and mangrove environments. Within the model, vegetation type (i.e. mangrove vs tidal marsh) was set as the fixed effect and site, vegetation type nested within site and position nested within transect then vegetation type and site were set as random terms. Homoscedasticity and normality was confirmed for all test parameters. Likelihood ratio tests were applied to the full model with effect of vegetation type included against the model without the effect in

Table 1. Region and site characteristics of temperate coastal wetlands sampled. Summarised from Bourman *et al.* (2016)

Region	Location	Estuary type	Tidal range	Primary influences	Sedimentation/deposition	Saltmarsh	Mangrove
Gulf St Vincent	35°13′S, 138°23′E	Tidal, inverse, low energy	~3 m	Tide dominant; high evaporation; low freshwater inputs	Pleistocene and Holocene marine sedimentation	Beaded samphire *(Sarcocornia quinqueflora)* and scrubby samphire *(Tecticornia arbuscular)*	The grey mangrove *(Avicennia marina)*
Mutton Cove	34°78′S, 138°51′E	Tidal (reinstated), low energy	<2 m	Tide dominant; subject to flooding; riverine influence; anthropogenic inputs	Carbonate/organic material	Supratidal samphire	Regenerated woodland (14 years)
Torrens island	34°79′S, 138°53′E	Tidal, low energy	<2 m	Tide dominant; riverine influence; subject to flooding; anthropogenic inputs	Carbonate/organic material	Intra- and supratidal samphire	Intertidal woodlands
Port Gawler	34°65′S, 138°48′E	Tidal and freshwater input	<2 m	Tide dominant; occasional storm water; riverine influence	Carbonate/organic material	Supratidal samphire	Intertidal woodlands
Port Wakefield	34°18′S, 138°15′E	Tidal, sheltered, low energy	~3 m	Tidal inlet; storm water	Allochthonous marine sediments	Supratidal and stranded samphire	Continuous woodland
Clinton	34°22′S, 138°02′E	Tidal, sheltered, low energy, shallow	~3 m	Tide dominant; wind driven waves; rocky coastline	Allochthonous marine sediments	Inter-, intra- and supratidal samphire flats	Continuous woodland
Spencer Gulf	34°30′S, 136°98′E	Tidal, inverse, low energy	2.5–4.1 m	Tide dominant; high evaporation; high water salinity (34–49 ppt); high water temperatures (13–38°C)	Pleistocene and Holocene marine sedimentation	Beaded samphire *(Sarcocornia quinqueflora)* and scrubby samphire *(Tecticornia arbuscular)*	The grey mangrove *(Avicennia marina)*
Port Broughton	33°58′S, 137°94′E	Complex	2.5–3.0 m	Tidal inlet	Holocene marine sediments	Inter-, intra- and supratidal samphire flats	Intertidal fringe woodland
Port Pirie	33°17′S, 138°01′E	Tidal, low energy; shallow	2.5–3.0 m	Tide dominant; anthropogenic inputs	Holocene marine sediments	Inter-, intra- and supratidal samphire flats	Intertidal fringe woodland
Port Paterson	32°55′S, 137°82′E	Shallow coastal plain, low energy	Amplified tidal range (4.1 m)	Tide dominant	Slow accumulation of sand, shell, silt, clay	Inter-, intra- and supratidal samphire flats	Fringe woodland
Port Augusta	32°49′S, 137°79′E	Protected, sheltered, low energy	Amplified tidal range (4.1 m)	Tide dominant; anthropogenic inputs	High biogenic accumulation	Inter-, intra- and supratidal samphire flats	Intertidal woodlands

Table 2. Averages and (±) s.d. of surface soil properties for mangroves and tidal marshes

Vegetation	Carbon content (%)	Bulk density (g cm^{-3})	Carbon density (g cm^{-3})	OC stock (Mg OC ha^{-1})	IC stock (Mg IC ha^{-1})	TN stock (Mg TN ha^{-1})	C:N
Mangroves	4.4 ± 4.0	0.59 ± 0.2	0.019 ± 0.008	18.4 ± 7.3	31.9 ± 17.6	1.8 ± 0.6	9.9 ± 2.4
Tidal marshes	4.3 ± 3.7	0.66 ± 0.7	0.019 ± 0.009	17.6 ± 9.2	35.1 ± 16.8	1.8 ± 0.7	9.4 ± 2.1

question to obtain P values. Univariate analysis was applied to the SOC, IC and TN stocks, and BD data with the linear model as described above. Three sites (Torrens Island, Mutton Cove and Port Broughton) were excluded from the analysis of IC due to the absence or low number of soil samples that contained IC. Additionally, the corresponding bivariate ANOVA with random effects of site and site by vegetation was performed for SOC and TN. REML indicated that the variance introduced by site was greater than the residual variance and could not be ignored, thus was analysed further. Therefore, the subsequent results presented are for the response of each soil property to vegetation type, across and within sites, explored with bivariate and univariate ANOVA. Statistical analysis and graphic outputs were performed using GenStat 19 (VSN International 2017) and R studio for R (RStudio Team 2016; R Core Team 2017) with packages 'lme4' (Bates *et al*. 2015); 'ggplot2' (Wickham 2016) and 'grid extra' (Auguie 2016).

Results

The surface soil BD of tidal marshes was significantly larger than that of mangroves ($P = 0.05$; Table 2). In contrast, surface SOC, IC, TN and C:N did not differ significantly with vegetation type. Average carbon (SOC and IC) and TN stocks, C:N and soil BD are summarised in Table 2.

At a site level, soil properties (SOC, IC, TN, C:N and BD) between the tidal marsh and mangrove ecosystems differed significantly with location (Fig. 2). Tidal marsh surface SOC and TN stocks, and C:N ratios at Torrens Island (33.7 ± 6.3 Mg OC ha^{-1}; 2.7 ± 0.4 Mg TN ha^{-1}; and C:N = 12.6 ± 0.6 for tidal marshes and 25.5 ± 4.4 Mg OC ha^{-1}; 2.1 ± 0.3 Mg TN ha^{-1}; and C:N = 12.1 ± 0.5 for mangroves; Fig. 2*a*, *c*) were larger than the mangrove surface soils ($P < 0.001$ for SOC and $P < 0.05$ for TN and C:N, respectively). At Port Paterson and Port Augusta, IC stocks were also larger in tidal marsh surface soils (41.3 ± 5.1 Mg IC ha^{-1} at Port Paterson and 18.6 ± 5.0 Mg IC ha^{-1} at Port Augusta) when compared to the mangroves (24.3 ± 8.6 Mg IC ha^{-1} at Port Paterson and 11.7 ± 6.5 Mg IC ha^{-1} at Port Augusta; $P < 0.001$ for both; Fig. 2*b*). The surface soil BD of the tidal marshes at Port Paterson were also larger than the mangrove soils (0.96 ± 0.06 g cm^{-3} vs 0.81 ± 0.10 g cm^{-3}; $P < 0.001$). Tidal marsh surface soil BD was also larger than mangrove soils (0.71 ± 0.06 g cm^{-3} vs 0.58 ± 0.21 g cm^{-3}; $P = 0.05$; Fig. 2*e*) at Port Pirie but mangroves had larger C:N ratios than the tidal marshes (C:N = 9.6 ± for mangroves vs C:N = 8.6 ± and for tidal marshes; $P < 0.05$; Fig. 2*d*). At Mutton Cove, the C:N ratio of the tidal marsh surface soils were larger than that of the mangrove soils (12.4 ± 0.4 for tidal marshes vs 11.3 ± 0.6 for mangroves; $P < 0.001$; Fig. 2*d*). However, the BD of the mangrove surface soils at Mutton Cove were higher than the tidal marsh soils (0.46 ± 0.07 g cm^{-3} vs 0.31 ± 0.07 g cm^{-3}; $P < 0.0001$; Fig. 2*e*).

The surface soils of mangroves at Clinton had larger SOC and TN stocks, and C:N ratios than tidal marshes (16.9 ± 1.2 Mg OC ha^{-1}; 1.9 ± 0.3 Mg TN ha^{-1}; and C:N = 9.0 ± 1.5 for mangroves vs 12.5 ± 4.4 Mg OC ha^{-1}; 1.6 ± 0.5 Mg TN ha^{-1}; and C:N = 7.5 ± 0.9 for tidal marshes; $P < 0.001$ for OC and $P < 0.05$ for TN and C:N; Fig. 2*a*, *c*, *d*). However, the BD of the surface soils at Clinton were smaller for the mangrove soils than the tidal marshes (0.48 ± 0.08 g cm^{-3} vs 0.95 ± 0.23 g cm^{-3}; $P < 0.0001$; Fig. 2*e*). Again at Port Augusta, mangroves had larger SOC stocks and C:N ratios than tidal marshes (9.8 ± 3.2 Mg OC ha^{-1} and C:N = 11.4 ± 3.5 for mangroves vs 6.5 ± 3.3 Mg OC ha^{-1} and C:N = 9.0 ± 1.1 for tidal marshes; $P < 0.05$; Fig. 2*a*, *d*). Within the other sites, there were no statistically significant differences in carbon (SOC and IC) and TN stocks, C:N and soil BD.

The spatial distribution of the surface soil carbon (OC and IC) stocks and BD were variable with sampling position within vegetation and site (Fig. 3; Table 3). Variability in OC stocks across the mangroves and tidal marsh samples ranged 7–51%. Port Gawler, Port Broughton and Port Augusta had the largest variability (greater than 25%) in OC stocks in both vegetation types. At Port Wakefield, Clinton and Port Paterson, the tidal marsh samples had larger variability in OC stocks than the mangroves. However, the OC stocks of the mangrove samples at Port Pirie had larger variability than the tidal marshes (21% vs 14%; Fig. 3*a*; Table 3). The variability of mangrove IC stocks was also larger than its variability in tidal marshes at Port Wakefield, Port Pirie, Port Paterson and Port Augusta (Table 3). Conversely, at Clinton, variability in the IC stocks of the tidal marsh samples was larger than the mangroves. At Port Gawler, there was above 50% variability in the IC stocks in both the mangrove and tidal marsh samples (Fig. 3*b*; Table 3). Variation of soil BD ranged 7–55% with larger variability across mangrove samples than tidal marshes at Port Wakefield, Port Broughton, Port Pirie and Port Paterson. The variability of soil BD in tidal marsh samples were larger than the mangrove samples at Mutton Cove, Torrens Island, Port Gawler, Clinton and Port Augusta (Fig. 3*c*; Table 3).

Discussion

In contrast to other studies (Chmura *et al*. 2003; Howe *et al*. 2009; Livesley and Andrusiak 2012), the average carbon densities for tidal marsh and mangrove (0.019 g OC cm^{-3} for both) soils did not differ across the blue carbon sites in this study. These results do not support our first hypothesis, and

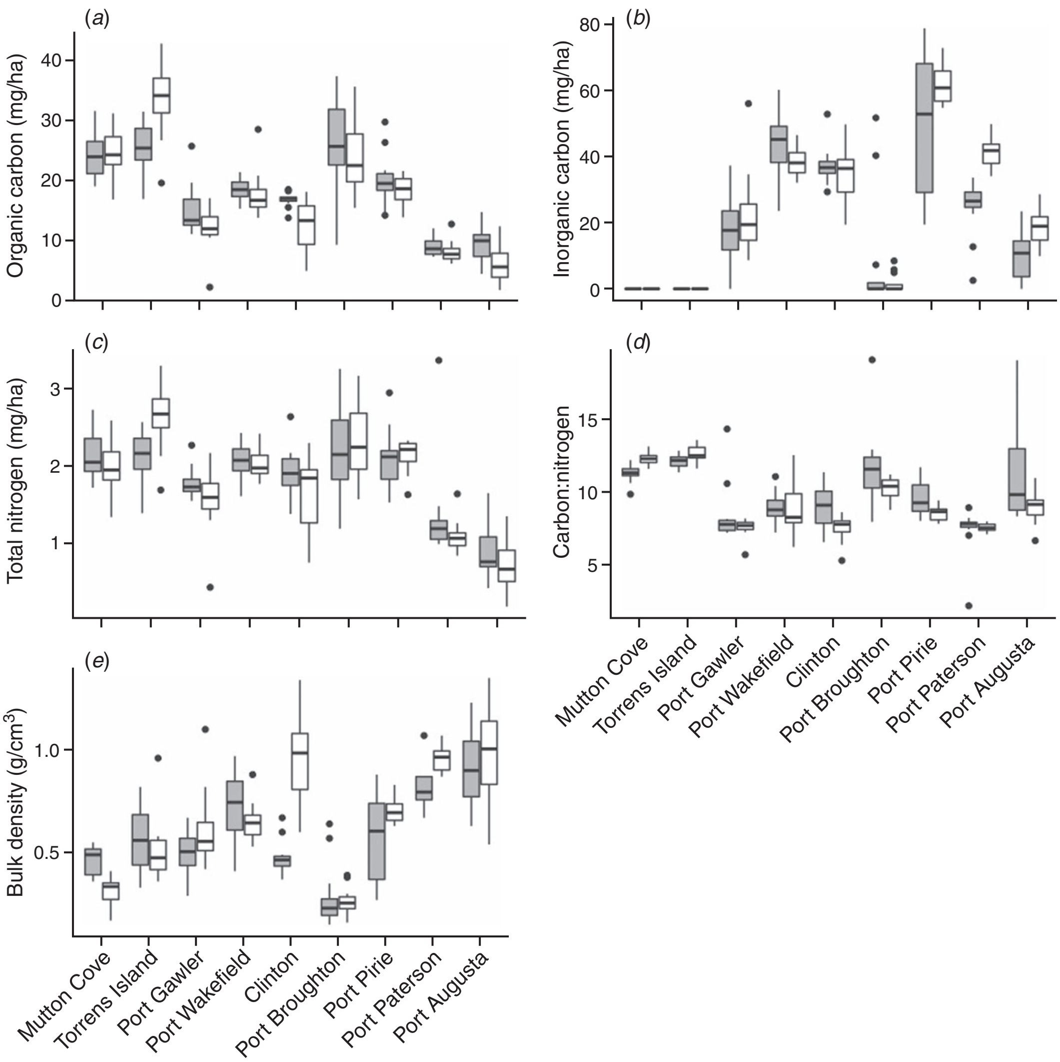

Fig. 2. Distribution of soil (*a*) organic carbon stocks, (*b*) inorganic carbon stocks, (*c*) total nitrogen stocks (Mg ha^{-1}), (*d*) C:N ratios and (*e*) bulk density (g cm^{-3}) in mangrove (grey; *n*, 12) and tidal marsh (white; *n*, 12) surface soils within each of the nine temperate wetland sites sampled. Box and whiskers represent the largest observation + 1.5*IQR, 75% quartile, median, 25% quartile, and smallest observation –1.5* the IQR, including outliers (●).

this is potentially a result of the temperate environment and lower primary productivity rates of mangroves in South Australia. Surface SOC stocks (17.6 Mg OC ha^{-1}) for South Australian tidal marshes were lower than stocks (32.1 Mg OC ha^{-1}) reported for temperate tidal marshes of Victoria (Livesley and Andrusiak 2012). The mangrove surface SOC stocks (18.4 Mg OC ha^{-1}) were, however, comparable to stocks (17.6 Mg OC ha^{-1}) of temperate mangroves in Victoria (Livesley and Andrusiak 2012). The average SOC densities (0–10cm) were also lower than those reported across Australia's eastern coastline for tidal marshes (0.03–0.04 g OC cm^{-3}) but within range of the mangroves (0.01–0.04 g OC cm^{-3}) (Saintilan *et al*. 2013). Additionally, the average SOC density for both the tidal marsh and mangroves (0.019 g OC cm^{-3} for both) were also lower than those reported globally (0.039 and 0.055 g OC cm^{-3}, respectively) (Chmura *et al*. 2003). However, global estimates were derived from coastal wetlands from the Indian Ocean to the north-eastern Atlantic Ocean and so do not reflect carbon stocks from temperate coastal ecosystems. Furthermore, our data is restricted to the top 10 cm and is unrepresentative of the of the entire ecosystem SOC stocks as global estimates have done.

At the local scale, there was no consistent pattern in the surface carbon (SOC and IC) and TN stocks, C:N or soil BD across the tidal marsh and mangrove habitats. Three sites that had larger SOC stocks in the mangroves or tidal marsh soils also had larger C:N ratios within the same vegetation type. Larger C:N implies more cellulose and lignin-like material and is perhaps indicative of less processed carbon (Kelleway *et al*. 2017*a*). Torrens Island and Port Augusta occur in densely populated areas and are likely subject to high anthropogenic

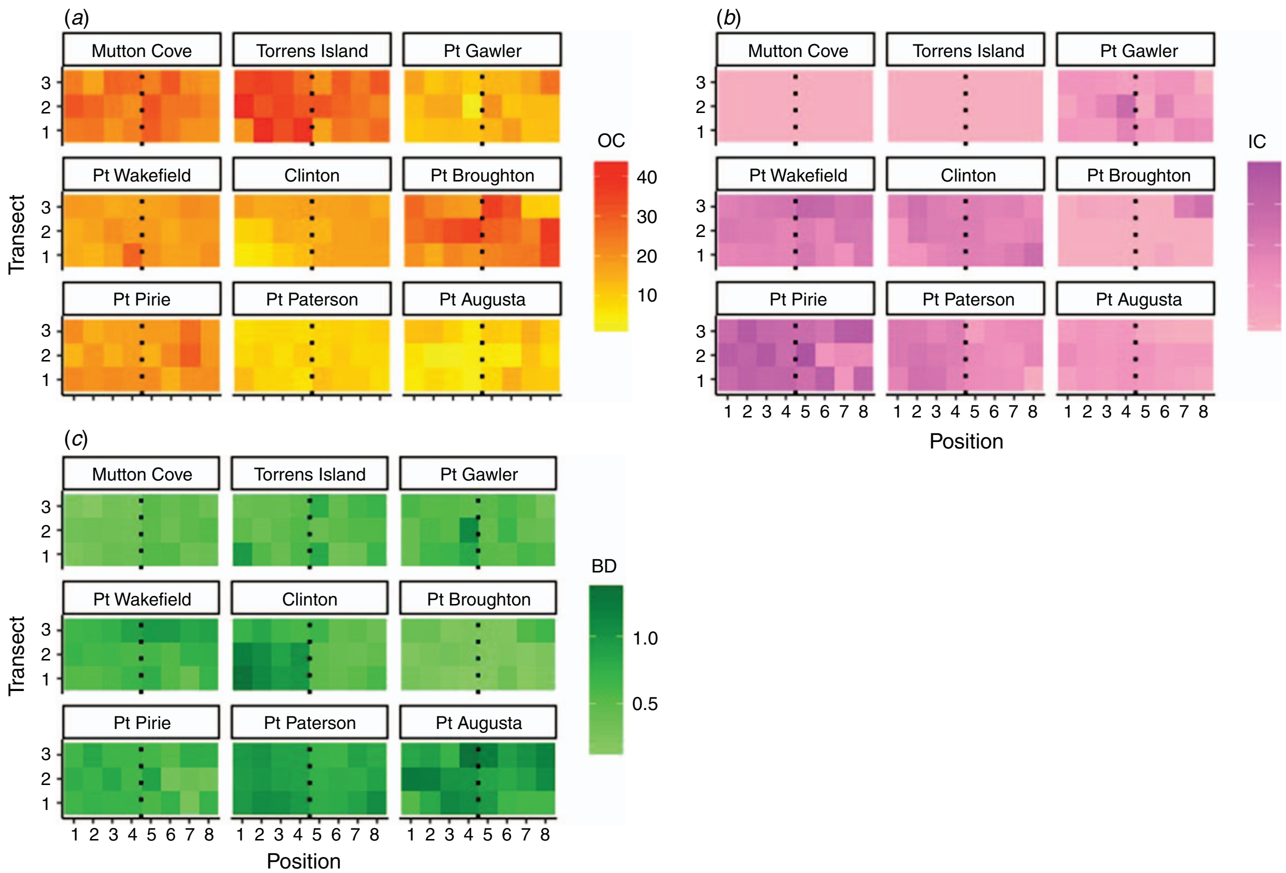

Fig. 3. Heat maps representing surface soil (0–10 cm) characteristics across tidal marsh (positions 1–4) and mangrove (positions 5–8) transects (1–3) at nine coastal wetlands in South Australia, including (*a*) organic carbon stocks (Mg ha^{-1}), (*b*) inorganic carbon stocks (Mg ha^{-1}) and (*c*) bulk density (g cm^{-3}). Dashed line indicates division between tidal marsh and mangrove environments.

Table 3. Summary table of CV (%) and s.e. values for spatial distribution of soil properties across tidal marshes and mangrove at nine coastal wetlands in South Australia

Soil property	Summary	Mangrove	Tidal marsh	Mangrove	Tidal marsh	Mangrove	Tidal marsh
		Mutton Cove		Torrens Island		Port Gawler	
OC	CV, %	18	16	17	19	28	31
	s.e.	1.25	1.16	1.27	1.18	1.23	1.09
IC	CV, %	n.a.	n.a.	n.a.	n.a.	59	56
	s.e.	n.a.	n.a.	n.a.	n.a.	2.69	3.74
BD	CV, %	16	21	28	31	21	31
	s.e.	0.02	0.02	0.05	0.05	0.03	0.05
		Port Wakefield		Clinton		Port Broughton	
OC	CV, %	9	21	7	35	35	25
	s.e.	0.49	1.10	0.35	1.28	2.61	1.77
IC	CV, %	24	12	16	28	n.a.	n.a.
	s.e.	3.01	1.31	1.70	2.80	6.65	0.53
BD	CV, %	24	15	17	24	55	26
	s.e.	0.05	0.03	0.02	0.06	0.05	0.02
		Port Pirie		Port Paterson		Port Augusta	
OC	CV, %	21	14	16	21	33	51
	s.e.	1.25	0.77	0.42	0.52	0.93	0.96
IC	CV, %	42	10	35	12	76	27
	s.e.	6.05	1.81	2.47	1.48	1.88	1.44
BD	CV, %	36	9	13	7	22	24
	s.e.	0.06	0.02	0.03	0.02	0.06	0.07

inputs from the surrounding area. Clinton is less populated but is in close proximity to the densely populated city of Port Wakefield. The main supply and deposition of sediment in Clinton is marine derived allochthonous material that combined with a sheltered and low energy environment would promote carbon and nitrogen accumulation (Table 1). Sanders *et al*. (2014) showed eutrophic wetlands had higher OC and TN accumulation rates than undisturbed sites. Therefore, larger nutrient loads, reflected in the larger TN stocks of tidal marshes and mangroves at Torrens Island and Clinton, respectively, would also increase primary productivity of the vegetation. An increase in primary productivity of the ecosystem could cause the larger SOC stocks that were observed at Torrens Island and Clinton (Sanders *et al*. 2014).

Previous studies have reported that in low energy tidal environments, such as our sites, mineral sediments are deposited closer to the tidal source (mangroves) (Howe *et al*. 2009; Livesley and Andrusiak 2012; Breithaupt *et al*. 2019). This reflects larger SOC contents in sediments deeper in the wetland (tidal marshes) (Howe *et al*. 2009). Sediment deposition in the interior of the wetland would account for larger SOC in tidal marshes at Torrens Island but is unsupported at Port Augusta and Clinton. However, unlike Torrens Island and Clinton, the tidal marshes at Port Augusta had significantly larger IC stocks than the mangroves. This is likely driven by the high production and accumulation of calcifying fauna and flora and/or amplified tidal range (4.1 m) depositing mineral sediments deeper in the wetland at Port Augusta (Table 1). The larger IC stocks in the tidal marshes at Port Paterson further supports this hypothesis with amplified tides (4.1 m) potentially causing the accumulation of sand and shells deeper in the wetland (tidal marshes). Mineral sediments (siliciclastic and carbonate) make up most of the material buried within sediments of blue carbon environments and are a likely source of the IC stocks at the sites (Saderne *et al*. 2019). The production of IC in the blue carbon environment can result in a release of CO_2 to the atmosphere that counteracts the effects of SOC burial while dissolution of IC would add to the sink capacity (Macreadie *et al*. 2017). The quantification of IC stocks in blue carbon habitats could therefore be used to highlight regions that may be a potential source or larger sink than estimated from SOC stocks alone.

Changes in SOC concentration were directly correlated with soil BD. The BD of a soil is affected by differences in soil properties (e.g. texture, water content, depth, organic matter content) and processes that loosen or compact the soil (e.g. mixing, traffic, plant growth) (Heuscher *et al*. 2005; Turner *et al*. 2006; Ruehlmann and Körschens 2009). Previous assessments have found 25% of the variation in BD can be explained by the SOC contents alone, and 33% if the square root SOC content is used (Heuscher *et al*. 2005). In this study, surface soil BD across sites was variable (0.15–1.35 g cm^{-3}) and had a negative exponential relationship with the variations in surface soil OC concentrations (mg g^{-1}) (Fig. 4). Therefore, increase in soil BD over time could reflect decreases SOC stocks. To investigate the relative

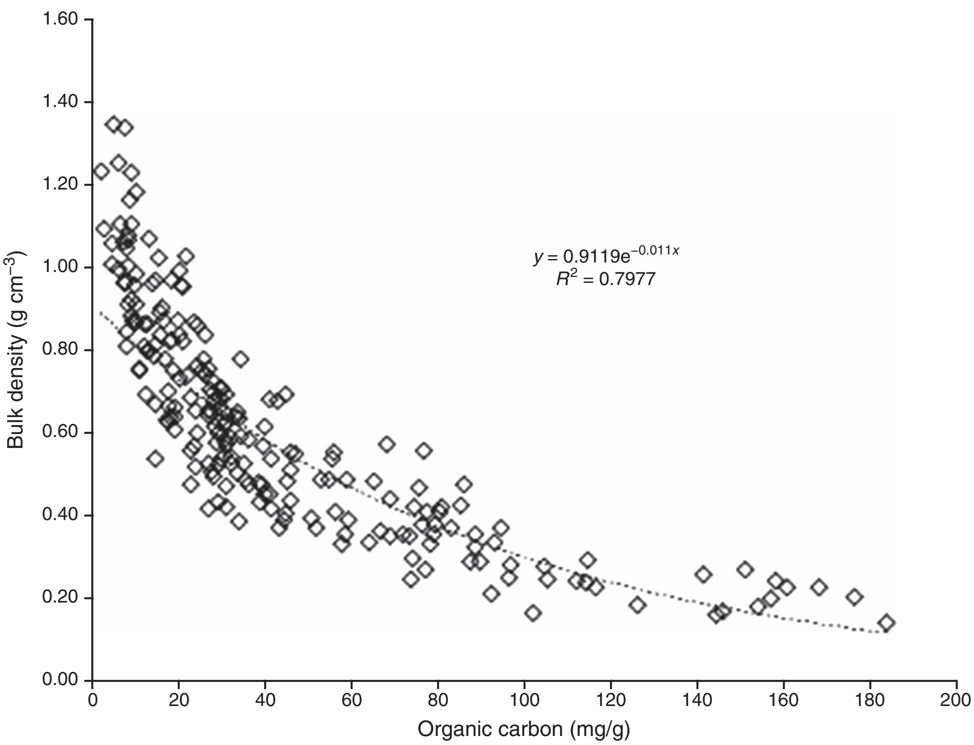

Fig. 4. The relationship between bulk density (g cm^{-3}) and organic carbon concentration (mg g^{-1}) in mangrove and tidal marsh surface (0–10 cm) soils from temperate vegetated coastal wetlands in Southern Australia.

importance of SOC content (mg g^{-1}), soil BD (g cm^{-3}), and the proportion of gravel (g) to defining the SOC stocks, we performed a correlation analysis. For this dataset, the most important variable in accounting for variation in SOC stock (Mg OC ha^{-1}) was SOC content (mg g^{-1}) (R^2 = 0.56). However, the correlation analysis also showed that soil BD (g cm^{-3}) (R^2 = 0.44) and gravel content (g) (R^2 = 0.16) could also independently account for a portion of the variation in SOC stock. For tidal marshes and within some sites (Port Paterson, Port Pirie and Mutton Cove), the larger soil BD did not correspond with lower SOC stocks. This could be driven by differences in the packing density of the organic matter fraction and mineral fraction of the soils. For example, variations in the volumetric fraction of minerals in coastal soils have been shown to account for variations in soil BD (Breithaupt *et al*. 2017). Tidal marshes also hold a higher position in the tidal frame that could drive faster decay rates of the organic matter, due to greater oxygen exposure, that would lower soil BD. In addition, greater terrestrial sediment deposition through runoff would occur on the landward side of a wetland resulting in the accumulation of mineral rather than organic sediments.

The variability of the soil properties (OC, IC and BD) did not follow a consistent pattern with vegetation type and appeared to be driven by site specific differences. Additionally, spatial patterns of TN and C:N ratio were similar to that of SOC. The second hypothesis was therefore unsupported by these results as the spatial distribution of stocks was variable within both vegetation types. Significant variability in the distribution of blue carbon soil stocks have been consistently observed across different geomorphic settings, vegetation structure, soil type and soil depth (Chmura *et al*. 2003; Donato *et al*. 2011; Kauffman *et al*. 2011; Livesley and Andrusiak 2012; Saintilan *et al*. 2013; Adame *et al*. 2015; Kelleway *et al*. 2016*a*; Owers *et al*. 2016*a*; Hayes *et al*. 2017; Ewers Lewis *et al*. 2018; Owers *et al*. 2020). The only difference between our vegetation types within each of our study sites was at the broad scale; i.e. mangrove vs tidal marsh and soils were only sampled to the top 10 cm. Therefore, it is probable that geomorphic setting and soil type are the main drivers of the spatial variability in SOC and IC stocks found within our sites. These results indicate future sampling strategies of blue carbon habitats need to consider the variability of carbon stocks in an ecosystem for accurate stock estimates.

Most of the variation in SOC contents between mangroves and tidal marshes are likely due to differences in sediment supply and the tidal inundation patterns of a region (Chmura *et al*. 2003; Howe *et al*. 2009; Saintilan *et al*. 2013). Short-term SOC accumulation rates in South Australia have been estimated to range 4.3–94.1 g OC m^{-2} $year^{-1}$ in tidal marsh systems and 9.3–97.1 g OC m^{-2} $year^{-1}$ in mangroves (Lavery *et al*. 2019). The mean accumulation rates for tidal marshes and mangroves is estimated at 31.1 g OC m^{-2} $year^{-1}$ and 38.8 g OC m^{-2} $year^{-1}$, respectively (Lavery *et al*. 2019). These results suggest South Australian mangroves should have higher SOC stocks than tidal marshes. However, these values are only representative of a few locations and may not account for the variability in SOC stocks as highlighted across our study sites.

Conclusion

Despite their potential to mitigate climate change, coastal wetlands are being degraded and lost as a direct result of anthropogenic activity (EPA 2021). Blue carbon habitats have been suggested as long-term sinks for carbon and nutrients due to their high sediment accumulation rates and slow decomposition of organic matter. Yet, the drivers of carbon accretion and patterns of carbon storage in the blue carbon environment remain uncertain. This study showed that surface soils in tidal marsh and mangrove ecosystems have comparable surface SOC stocks, indicating that vegetation type has little impact on surface SOC stocks for regional assessments (i.e. state-wide) in South Australia. Within smaller spatial scales, however, there can be variability in surface SOC stocks within, and among, sites. Capturing the spatial variability of SOC stocks in the blue carbon environment will be important in improving future estimates of the contribution these habitats have in mitigating climate change.

Conflicts of interest

The authors declare no conflicts of interest.

Declaration of funding

This work was supported by The University of Adelaide Research Training Program Scholarship and The Goyder Institute for Water Research [CA-16–04].

Acknowledgements

Dr Oleana Kravchuk from the biometry hub at The University of Adelaide and Dr Dan Pagendam from Data61, CSIRO are acknowledged for assistance and advice with statistical analysis. Assistance in field work and soil sample collection from Nick Asanopoulos, Dr Nina Welti, Thi Thanh Hue Ngo, Matthias Salomon, Dr Anthelia Bond, Rebecca Stonor, Dr Jessica McKay, Stephen Lang, Dr Olivia Cousins, A/Prof. Ronald Smernik and Dr Ashlea Doolette are acknowledged. Further thanks to Sophie Russell for helping to generate Fig. 1.

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Handling Editor: Helen Glanville