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Heterogeneous tidal marsh soil organic carbon accumulation among and within temperate estuaries in Australia

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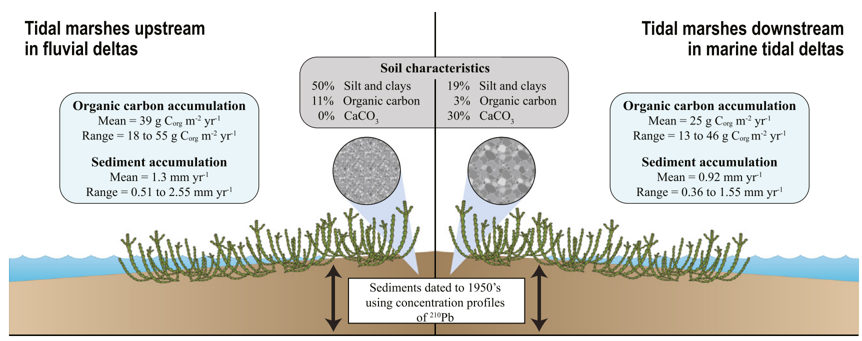
HIGHLIGHTS

- Carbon accumulation rate in SW Australian marshes is 5-fold lower than global mean.
- Hotspots of soil carbon stocks not linked to carbon sequestration hotspots.
- Recent and historic sea level stability likely explain low carbon accumulation rates.
- Baseline estimates for national carbon inventories and blue carbon projects

GRAPHICAL ABSTRACT



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ABSTRACT

The scarcity of data on tidal marsh soil accumulation rates (SAR) and soil organic carbon accumulation rates (CAR) globally precludes a comprehensive assessment of the role of tidal marshes in climate change mitigation and adaptation. Particularly few data exist from the southern hemisphere and for Australia in particular, which contains ~24% of globally recognised tidal marsh extent. Here we estimate SAR and CAR over the last 70 years using ^{210}Pb-based geochronologies in temperate estuarine tidal marsh ecosystems in southern Western Australia (WA). Specifically, we assessed tidal marsh ecosystems situated in two geomorphic settings (marine vs. fluvial deltas) within 10 wave-dominated, barrier estuaries. Overall, average SAR (1.1 ± 0.3 mm yr^{-1}) and CAR (32 ± 9 g m^{-2} yr^{-1}) estimates were 5-fold lower than global mean estimates. Furthermore, we showed that hotspots of soil organic carbon stocks are not indicative of current hotspots for CAR. The lack of significant differences ($P > 0.05$) in SAR, CAR, and excess ^{210}Pb inventories between marine and fluvial settings can be explained by the high heterogeneity among and within estuaries throughout the region. The relative stability of recent and Holocene relative sea-levels in WA likely explains the limited CAR potential in tidal marshes under relatively stable sea-level conditions. However, further research exploring interactions among biotic and abiotic factors within estuaries is required to shed more light on the small spatial-scale variability in SAR and CAR across tidal marsh ecosystems in WA and elsewhere. This study provides baseline estimates for the inclusion of tidal marshes in national carbon inventories, identifies hotspots for the development of blue carbon projects, and supports the use of site-specific assessments opposed to regional means for estimating blue carbon resources.

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1. Introduction

Tidal marsh ecosystems are globally important carbon sinks that can accumulate and preserve sedimentary carbon reservoirs over millennia (McLeod et al., 2011; Nellemann et al., 2009). However, their value in the sequestration and storage of atmospheric CO_2 is threatened by 1–2% year^{-1} global loss rates in habitat extent (Gedan et al., 2009), which in turn can result in greenhouse gas emissions from the sedimentary carbon reservoirs (Pendleton et al., 2012). The capacity of tidal marsh and adjacent vegetated coastal ecosystems (namely seagrasses and mangroves) to function as organic carbon (C_{org}) sinks has led to the development of blue carbon strategies aimed at mitigating climate change (Nellemann et al., 2009; Serrano et al., 2019). Such strategies focus on ecosystem conservation and/or restoration through the preservation of habitat functions (such as C_{org} sequestration) and the abatement of CO_2 emissions from ecosystem disturbance (Kelleway et al., 2017b; Macreadie et al., 2017a; McLeod et al., 2011).

The efficacy of tidal marsh ecosystems to accumulate C_{org} in their soils is partly attributed to the growth and preservation of belowground roots and rhizomes (i.e. autochthonous production), as well as the deposition of autochthonous C_{org} (i.e. local plant detritus) and/or allochthonous C_{org} inputs from adjacent terrestrial and marine habitats. A number of factors influence the balance of these inputs and vary at a range of spatial scales (Kelleway et al., 2016; Rogers et al., 2019; Roy et al., 2001; Saintilan et al., 2013). Understanding the variability of tidal marsh soil C_{org} accumulation rates (CAR) at different spatial scales can aid the development and implementation of blue carbon strategies to mitigate climate change. Improved understanding of the drivers of regional and estuary-scale variability can guide the development of tier 2 and 3 estimates of CAR, enhancing the capacity to model carbon abatement and accounting in nationally determined contributions (NDC's; Kelleway et al., 2017b; Serrano et al., 2019) and carbon-trading mechanisms (Needelman et al., 2018). Differences in rates of relative sea-level rise, precipitation, and periodicity and intensity of inundation events have been shown to influence soil CAR in tidal marsh ecosystems at global and regional spatial scales (Connor et al., 2001; Kelleway et al., 2017a; Kirwan and Mudd, 2012; Rogers et al., 2019). This is attributed to amplified inundation events increasing the availability and supply of suspended sediments, while also increasing vertical and lateral accommodation space within tidal marsh ecosystems (Christiansen et al., 2000; Rogers et al., 2019). At the within-estuary spatial scale, geomorphic setting (e.g. sediment type, soil elevation and position along the estuarine gradient), salinity, and the production and/or deposition of biogenic carbonates influence tidal marsh soil C_{org} stocks, and therefore likely influence sediment accumulation rates (SAR) which underpin modern soil CAR estimates (Baustian et al., 2017; Gorham et al., 2021; Saderne et al., 2019).

Australia contains ~24% of globally recognised tidal marsh extent and constitutes up to 35% of the global tidal marsh soil C_{org} stock estimates (Mcowen et al., 2017; Serrano et al., 2019). Of this, ~22% of tidal marsh extent within Australia is located in the western third of the continent, constituting ~5% of total worldwide tidal marsh ecosystems (Bucher and Saenger, 1991; Mcowen et al., 2017; Serrano et al., 2019). The coastline of Western Australia (WA) is approximately 21,000 km in length, encompassing a range of climatic and geomorphic settings which support tidal marshes (Bucher and Saenger, 1991; Geoscience Australia, 2004). WA's estuarine evolution was greatly influenced by sedimentation yields during the Holocene marine transgression (8000 to 4000 years ago), with deposits of carbonate sands and quartz, Holocene in age, occurring from below ~30 cm depth in tidal marsh soils (Hodgkin and Hesp, 1998; Semeniuk, 2000). The extent of tidal marsh and the variability in habitat characteristics make this a significant region to study the variability in soil CAR driven by environmental factors acting at regional and within-estuary spatial scales. This becomes increasingly necessary as sea level rise accelerates and urban infrastructure limits the availability of accommodation space necessary for habitat migration (Nazarnia et al., 2020). To date, however, the CAR of WA's tidal marshes remain poorly understood (Macreadie et al., 2017b). Here we provide a new soil CAR dataset in tidal marsh ecosystems encompassing 10 estuaries in temperate WA. As previous research from temperate WA has identified tidal marsh soil C_{org} stocks vary between geomorphic settings (Gorham et al., 2021), this work attempted to identify differences in CAR driven by the depositional setting of tidal marsh ecosystems. As such, we explore key drivers influencing regional C_{org} accumulation in tidal marsh ecosystems, assisting in the identification of blue carbon hotspots and aiding future research and management strategies. Here we hypothesised that, owing to the higher soil C_{org} stocks sequestered in fluvially-situated tidal marsh throughout the relative stability of WA's Holocene sea-levels, tidal marsh positioned in fluvially-influenced geomorphic settings will support similarly higher CAR compared to those situated in marine flood tidal deltas.

2. Methods

2.1. Study sites

Ten wave-dominated, barrier estuaries (Swan-Canning River, Peel-Harvey Estuary, Leschenault Estuary, Hardy Inlet, Walpole-Nornalup Inlet, Wilson Inlet, Oyster Harbour, Wellstead Estuary, Gordon inlet and Culham inlet; (Ryan et al., 2003)) were sampled in 2017 along the temperate coast of WA (Fig. 1). The mean annual temperature in WA's temperate region is 15 °C (Department of the Environment, 2015), and across the sampling locations mean annual rainfall varies from 450 mm to 1400 mm, dominated by winter rain and dry summers (Table 1; Bureau of Meteorology, 2020).

2.2. Sample collection and analysis

The variability in tidal marsh SAR and CAR were assessed by sampling 16 soil cores in fluvial deltas and marine tidal deltas (hereby referred to as 'fluvial' and 'marine' settings respectively) across ten estuaries (Table 1). Owing to the geomorphological characteristics and land-use management of each estuary, it was not possible to sample marine-influenced tidal marsh in all estuaries, resulting in an unbalanced design (ten cores sampled in fluvial settings and six cores sampled in marine settings). Soil cores were sampled by manual percussion using 1 m-long PVC corers within the middle distribution of tidal marsh (i.e. between water's edge and the landward limit of fringing vegetation) at each location. Linear compaction of soils during coring was recorded by measuring differences in surface soil elevation inside and outside the corer (Glew et al., 2005). All results presented hereafter refer to linearly decompressed depths unless otherwise stated.

For eight coring sites within five of the studied estuaries, surface elevation was estimated using real-time kinematic global positioning systems (RTK GPS). For the Swan-Canning Estuary, Peel-Harvey Estuary and the Leschenault Inlet, measurements were made with a Trimble R8s GNSS receiver with measurements corrected via connection to a Continuously Operating Reference Stations network, allowing high precision estimates of elevation (mean $\pm$ 1 SD vertical precision = 1.6 $\pm$ 0.3 cm). For Wilson Inlet and Oyster Harbour, a Trimble R10 receiver was used with GNSS corrections delivered via satellite (mean $\pm$ 1 SD vertical precision = 5.5 $\pm$ 1.2 cm).

The sediment cores were sliced at 1 cm intervals for the top 20 cm, and at 5 cm intervals thereafter. Each sample was oven dried to constant weight at 60 °C (i.e., dry weight, DW). Sediment grain size, $\%CaCO_3$ content, soil $\%C_{org}$ content and stable isotope composition ($\delta^{13}C$) analyses were conducted at seven depths along the top 30 cm of the cores ('compressed' sections 0–1 cm, 3–4 cm, 6–7 cm, 9–10 cm, 14–15 cm, 19–20 cm, 25–30 cm) following the methodology described in (Gorham et al., 2021).

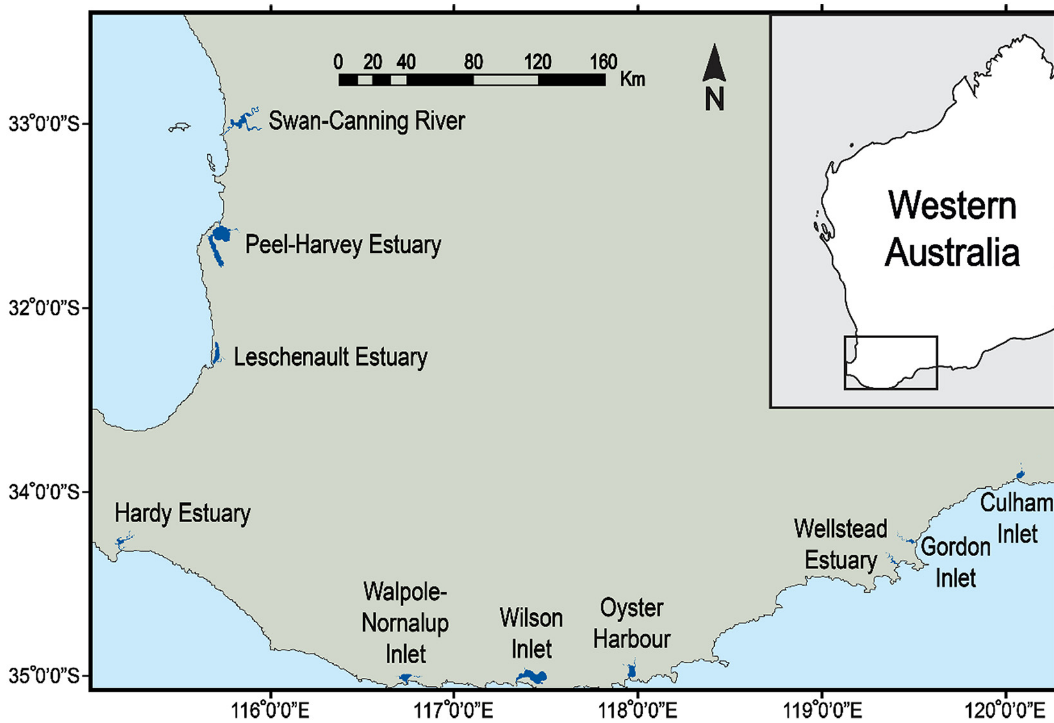

Fig. 1. Location of the ten estuaries sampled along the temperate southwest coastline of Western Australia. Dark blue areas along the coastline represent the position and size of each estuary sampled. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.3. Isotopic analysis

Isotopic (δ^{13}C) analyses were conducted at the University of Hawaii's Hilo analytical laboratory. Powdered soil samples were loaded into tin or silver capsules, depending on the presence of inorganic carbon (C_{inorg}; Kennedy et al., 2005), and analysed with an elemental analyser-isotope ratio mass spectrometry (EA-IRMS), model Thermo DeltaV. Two quality control isotopic references were run alongside each sample to verify accuracy and precision of isotope data. Measurement errors (±1 SD) were recorded at 0.2‰ for δ^{13}C. Isotope ratios are expressed as delta (δ) values in parts per thousand (‰) relative to the Vienna PeeDee Belemnite (VPDB) standard and were determined using the formula:

$$\delta^{13}\mathrm{C}\ (‰) = \left(\frac{R\mathrm{sample}}{R\mathrm{standard}} - 1\right) \times 1000$$

where $R = {}^{13}\mathrm{C}/{}^{12}\mathrm{C}$.

2.4. Age-depth chronology

Concentration profiles of lead-210 (^{210}Pb) along the upper 30 cm in each of the 16 cores sampled with the five estuaries were determined by measuring ^{210}Po (in equilibrium with ^{210}Pb) activities by alpha spectrometry via Passivated Implanted Planar Silicon (PIPS) detectors (CANBERRA, Mod. PD-450.18 A.M.) after the addition of ^{209}Po as an

Table 1
Summary of mean rainfall, total catchment area, mean ± SD accumulated excess lead-210 ($^{210}Pb_{ex}$), sediment accumulation rates (SAR), soil organic carbon accumulation rates (CAR) and soil surface elevation (m AHD) of tidal marsh ecosystems located in fluvial and marine geomorphic settings across ten estuaries in temperate Western Australia. "–" = not assessed.

Estuary	[a]Mean annual rainfall (mm yr^{-1})	[b]Catchment area (km^2)	Geomorphic setting	$^{210}Pb_{ex}$ (Bq m^{-2})	SAR (mm yr^{-1})	CAR (g C_{org} m^{-2} yr^{-1})	Soil elevation (m AHD)
Swan-Canning River	807	122,960	Fluvial	85 ± 12	–	–	0.11
Peel-Harvey Estuary	635	11,434	Fluvial	249 ± 11	–	–	−0.02
Leschenault Estuary	717	1800	Marine	860 ± 30	0.36 ± 0.02	18.6 ± 1.3	0.36
			Fluvial	2400 ± 90	–	–	0.13
Hardy Inlet	938	13,660	Marine	1270 ± 50	1.55 ± 0.13	46 ± 4	–
			Fluvial	480 ± 20	1.26 ± 0.15	56 ± 7	–
Walpole-Nornalup Inlet	1300	5740	Fluvial	160 ± 30	0.83 ± 0.09	28 ± 3	–
Wilson Inlet	1008	2178	Marine	620 ± 40	0.98 ± 0.13	13.4 ± 1.7	0.32
			Fluvial	1700 ± 60	–	–	0.23
Oyster Harbour	888	3000	Marine	920 ± 30	0.80 ± 0.06	20.1 ± 1.5	0.06
			Fluvial	2540 ± 60	2.55 ± 0.10	55 ± 2	0.05
Wellstead Estuary	569	715	Fluvial	152 ± 7	–	–	–
Gordon Inlet	611	1770	Marine	410 ± 30	–	–	–
			Fluvial	2460 ± 130	–	–	–
Culham Inlet	487	2370	Marine	36 ± 4	–	–	–
			Fluvial	122 ± 6	0.51 ± 0.04	18.0 ± 1.2	–

[a] Mean rainfall data sourced from Bureau of Meteorology, 2020
[b] Catchment area data sourced from Hodgkin and Hesp, 1998

internal tracer and acid digestion of soil samples (Sanchez-Cabeza et al., 1998). Selected composite samples from each core were used to quantify ^{226}Ra by gamma spectrometry through the emission lines of its decay products ^{214}Bi and ^{214}Pb. Profiles of excess ^{210}Pb concentrations ($^{210}Pb_{ex}$; Bq kg^{-1}) and excess ^{210}Pb inventories (Bq m^{-2}) were determined by the subtraction of ^{226}Ra (supported ^{210}Pb) from total ^{210}Pb.

Mean mass accumulation rates (MAR; g cm^{-2} yr^{-1}) and soil accumulation rates (SAR; mm yr^{-1}) could be estimated for eight out of the 16 cores analysed, using the Constant Flux: Constant Supply (CF:CS) model (Krishnaswamy et al., 1971). A variety of processes occurring within tidal marsh soils (e.g. mixing, accumulation of reworked sediment and/or lack of net accumulation of sediment) precluded obtaining a reliable geochronology in the other eight cores (Arias-Ortiz et al., 2018). CAR (Mg C_{org} ha^{-1} yr^{-1}) were estimated by multiplying the MAR of each core by the fraction of C_{org} accumulated to the depth corresponding to 1950, as determined by the ^{210}Pb-derived age-model. CAR were standardised for the past ~70 years based on the mean maximum chronologies retrievable across the eight cores to allow throughout comparisons.

2.5. Statistical analysis

Statistical analyses were performed using univariate General Linear Models (GLMs) in SPSS v. 26. The GLMs were run to test for significant effects of geomorphic setting (marine and fluvial) on the soil C_{org} content (%C_{org}), stable carbon isotope values of soil C_{org} (δ^{13}C, ‰), silt and clay content (%), calcium carbonate content (%$CaCO_3$) and $^{210}Pb_{ex}$ inventories (Bq m^{-2}). Geomorphic setting was treated as a fixed factor and where appropriate response variables were square-root transformed prior to analyses to achieve homogeneity of variance. Owing to limited available SAR (mm yr^{-1}) and CAR (g C_{org} m^{-2} yr^{-1}) data between geomorphic settings (Table 1), statistical analyses were not run on these variables to avoid the potential of introducing a false lack of statistically significant difference (statistical type 2 error).

A stable isotope mixing model was run in R using simmr and rjags packages (Parnell, 2019; Parnell et al., 2013). This model used δ^{13}C to assess the proportional contribution of source material between marine and fluvial geomorphic settings in temperate tidal marsh soils. The source materials were broadly categorised as 'Enriched in ^{13}C' or 'Depleted in ^{13}C'. This broad categorisation distinguished seagrass, macroalgae and marine seston as 'Enriched in ^{13}C', and tidal marsh halophytes plus supratidal vegetation as 'Depleted in ^{13}C'. The isotopic signature reference library used for this model was sourced from Smit et al. (2005), Svensson et al. (2007), and Gorham et al. (2021).

3. Results and discussion

Overall, the CAR in tidal marshes along the temperate WA coastline ranged from 13 to 56 g C_{org} m^{-2} yr^{-1} (Mean ± SD = 32 ± 9 g C_{org} m^{-2} yr^{-1}; Table 1), and are similar to previous estimates for eastern Australia (39 g C_{org} m^{-2} yr^{-1}; Serrano et al., 2019), but lower than estimates from the United States (155 g C_{org} m^{-2} yr^{-1}; Boyd and Sommerfield, 2016), Italy (132 g C_{org} m^{-2} yr^{-1}; Roner et al., 2016), and China (100 g C_{org} m^{-2} yr^{-1}; Zhang et al., 2021). Similarly, the mean CAR measured in this study is 5-fold lower than recent global estimates (168 ± 7 g C_{org} m^{-2} yr^{-1}; Wang et al., 2020), which are largely biased toward tidal marshes situated in the northern hemisphere. The lower CAR estimates from Australian tidal marshes are likely related to the relative stability of Australia's sea-level over the past few decades to millennia, which effectively diminished the available vertical accommodation space within Australia's intertidal ecosystems (Gehrels and Woodworth, 2013; Rogers et al., 2019). Australia's relatively stable Holocene sea-level has promoted mineral-dominated tidal marshes located high in the tidal frame, which are expected to be less conducive to soil C_{org} retention as accommodation space decreases (Rogers et al., 2019). Furthermore, modern (since 1950) changes in sea-level have been more stable in the southern hemisphere compared to those in the northern hemisphere (Gehrels and Woodworth, 2013). This hypothesis is supported by the similar % C_{org} content measured in temperate WA (7.4 ± 9.4%C_{org}; ranging from 0.1 to 33.8%C_{org}), eastern Australia (7.1 ± 7.6%C_{org}; Macreadie et al., 2017b) and globally distributed tidal marshes (8.7 ± 9.0%C_{org}; Rogers et al., 2019), suggesting similarities in the contribution of organic and mineral materials from surrounding catchment areas to soil composition. Australia's lower CAR may reflect the relatively low SAR measured in temperate WA tidal marshes (1.1 ± 0.3 mm yr^{-1}; ranging from 0.36 to 2.55 mm yr^{-1}; Table 1) and eastern Australian counterparts (2.09 mm yr^{-1}; Macreadie et al., 2017b), compared to global SAR estimates from tidal marsh ecosystems in the northern hemisphere (6.73 mm yr^{-1}; Duarte et al., 2013).

The SAR in temperate WA are likely further impeded by the microtidal regime which, depending on habitat elevation, limits the availability of depositional mineral and organic material entering tidal marsh ecosystems (Palinkas and Engelhardt, 2019). Tidal marsh ecosystems are complex depositional environments, influenced by resuspension and erosion, bioturbation and sediment reworking processes that may have precluded estimating SAR based on ^{210}Pb radionuclides in ~50% of the cores analysed. However, another plausible explanation is that little-to-no net SAR and CAR occurred over the last ~70 years in some of the tidal marsh ecosystems studied here, which is supported by the very low inventories of $^{210}Pb_{ex}$ and is indicative of the depositional environment in some sites (Marbà et al., 2015; Arias-Ortiz et al., 2018). Nevertheless, the results presented in this study provide estimates to understand the role of tidal marshes in WA in C_{org} sequestration and climate change mitigation, as well as baseline estimates to facilitate the implementation of conservation and restoration of tidal marshes benefiting from e.g. Emission Reduction Fund carbon crediting scheme in Australia (Kelleway et al., 2020).

The soil characteristics of temperate WA tidal marshes differed between fluvial and marine settings (Table 2). The %C_{org} and silt and clay contents were higher in fluvial compared to marine settings, while δ^{13}C signatures were significantly lower and $CaCO_3$ contents were absent in fluvial settings ($P < 0.001$; Fig. 2). The $^{210}Pb_{ex}$ inventories measured in this study did not differ significantly between fluvial (1040 ± 180 Bq m^{-2}) and marine settings (690 ± 80 Bq m^{-2}; $P > 0.05$, Fig. 3 and Table 2). The larger $^{210}Pb_{ex}$ inventories identified in fluvial settings can likely be attributed to the significantly higher fraction of silt and clay particulates measured in fluvially-situated tidal marsh (50 ± 29%) compared to marine located tidal marsh (19 ± 33%; $P < 0.05$, Fig. 2B), as ^{210}Pb is scavenged by silts and, specially, clays (Arias-Ortiz et al., 2018). This lack of a statistical difference between fluvial and marine geomorphic settings may be a result of the high variability (and interactions) among biotic and abiotic factors driving the deposition of particles across the estuarine systems studied. For example, the coefficient of variation (CV) was 16% for SAR in fluvial settings and 21% for SAR in marine settings (CV = 26% for SAR overall), while the CV of %C_{org} was 98% and 161% for fluvial and marine settings, respectively (CV = 121% for %C_{org} overall). While the inventories of $^{210}Pb_{ex}$ were 1.5-fold higher in tidal marsh situated in fluvial compared to

Table 2
Results of univariate General Linear Models (GLMs) for significant effects of geomorphic setting (marine and fluvial) on soil organic carbon content (%C_{org}), stable carbon isotope values of soil organic carbon (δ^{13}C; ‰), silt and clay content (% < 0.063 mm), calcium carbonate content (%$CaCO_3$) and excess ^{210}Pb inventories ($^{210}Pb_{ex}$, Bq m^{-2}).

Variable	Factor	df	MS	F	P
C_{org} content (%)	Geomorphic setting	1	1439.802	18.657	<0.001
δ^{13}C (‰)	Geomorphic setting	1	983.35	35.881	<0.001
Silt and clay content (%)	Geomorphic setting	1	19,310.862	19.37	<0.001
$CaCO_3$ content (%)	Geomorphic setting	1	18,628.224	64.776	<0.001
$^{210}Pb_{ex}$ (Bq m^{-2})	Geomorphic setting	1	32.263	0.132	0.720

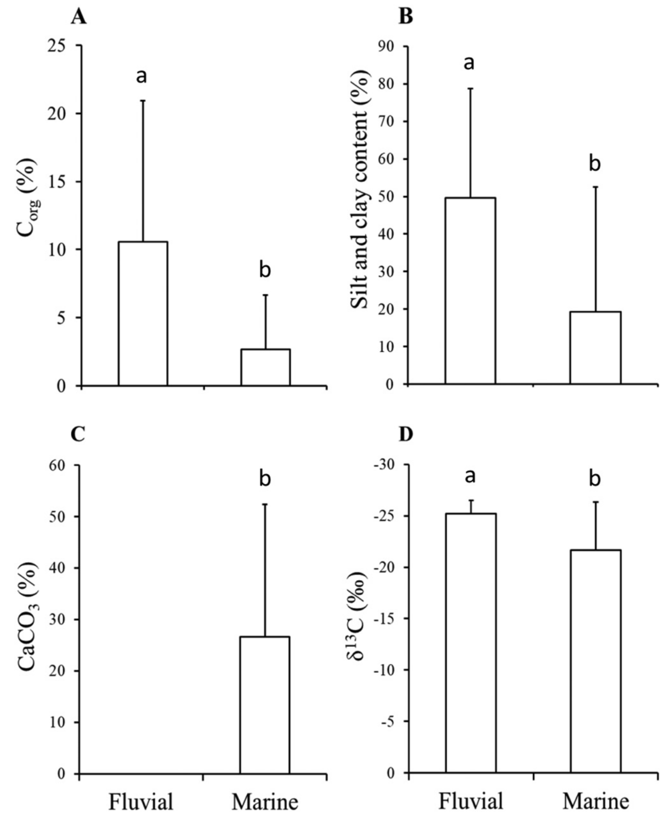

Fig. 2. Significant effects of geomorphic setting (marine tidal deltas and fluvial deltas) on the soil C_{org} content (%C_{org}), silt and clay content (%), calcium carbonate content (%$CaCO_3$), and stable carbon isotope values of soil C_{org} ($\delta^{13}C$, ‰) in temperate Western Australia. Letters (a, b) indicate significant differences ($P < 0.05$ in all cases). Mean (±SD).

marine settings, they were also variable between settings across and within estuaries (CV = 22% for $^{210}Pb_{ex}$ overall; Table 1). For example, the inventories of $^{210}Pb_{ex}$ calculated for both marine and fluvial settings in the Culham Inlet (ranging from 36 to 122 Bq m^{-2}) were 20-fold less than those measured in Oyster Harbour (ranging from 918 to 2538 Bq m^{-2}; Table 1). This heterogeneity of $^{210}Pb_{ex}$ and soil %C_{org} across estuaries and geomorphic settings highlights the need to preferably obtain site-specific baseline blue carbon estimates, rather than relying on national or regional estimates, prior to their inclusion in national carbon inventories or the implementation of blue carbon projects.

Despite the >2-fold higher mean elevation in marine sampling locations (0.25 ± 0.16 m AHD) compared to fluvial sampling locations (0.10 ± 0.09 m AHD), the heterogeneity among SAR and CAR precluded identifying clear trends between fluvial (1.3 ± 0.2 mm yr^{-1} and 39 ± 8 g C_{org} m^{-2} yr^{-1}) and marine settings (0.92 ± 0.08 mm yr^{-1} and 25 ± 2 g C_{org} m^{-2} yr^{-1}; Fig. 3). However, the lack of any clear relationship between soil surface elevation and CAR identified in this study also reflects previous global observations indicating that elevation does not affect CAR in tidal marsh ecosystems (Wang et al., 2020). The SAR measured between geomorphic settings in temperate WA indicate that the higher mean elevation identified in marine sampling locations was not restricting sediment accumulation in these sites, at least compared to the fluvial sampling locations. The absence of $CaCO_3$ in the fluvial sites (Fig. 2C) suggests that soil accumulation is not influenced by $CaCO_3$ inputs. This suggests that C_{org} fluxes are largely dominated by inputs of marine and terrestrial organic particles and in-situ C_{org} production. However, the relatively high $CaCO_3$ content in marine sites (30%; Fig. 2C), which was produced in situ or imported from nearby marine ecosystems owing to the siliciclastic geology of the region (Richardson et al., 2005; Saderne et al., 2019), likely contributed to enhance SAR in marine settings (Saderne et al., 2019).

CAR, SAR, and inventories of $^{210}Pb_{ex}$ in temperate WA's tidal marshes were not correlated to mean annual precipitation or the catchment area of the estuaries studied ($R^2 < 0.10$ in all cases). Previous studies have shown that higher rainfall (both single event storm discharge and persistent annual rainfall) within a catchment area increased the export of dissolved and particulate C_{org} and inorganic particles thereby enhancing CAR in tidal wetlands (Mueller et al., 2016; Sanders et al., 2016; Negandhi et al., 2019; Wang et al., 2020). The lack of correlation between CAR and mean annual rainfall in this study may reflect the relatively small differences in annual precipitation among the estuaries studied (450 mm to 1400 mm) or the confounding effects of other factors interacting at each site (e.g. soil elevation, slope, land-use within the catchment, and groundwater seepage into the marshes; Christiansen et al., 2000; Hayes et al., 2019; Negandhi et al., 2019). While CAR have been shown to vary predictably at global scales (i.e. millennial scale variations due to relative sea-level rise; Rogers et al., 2019), the high variability among and within

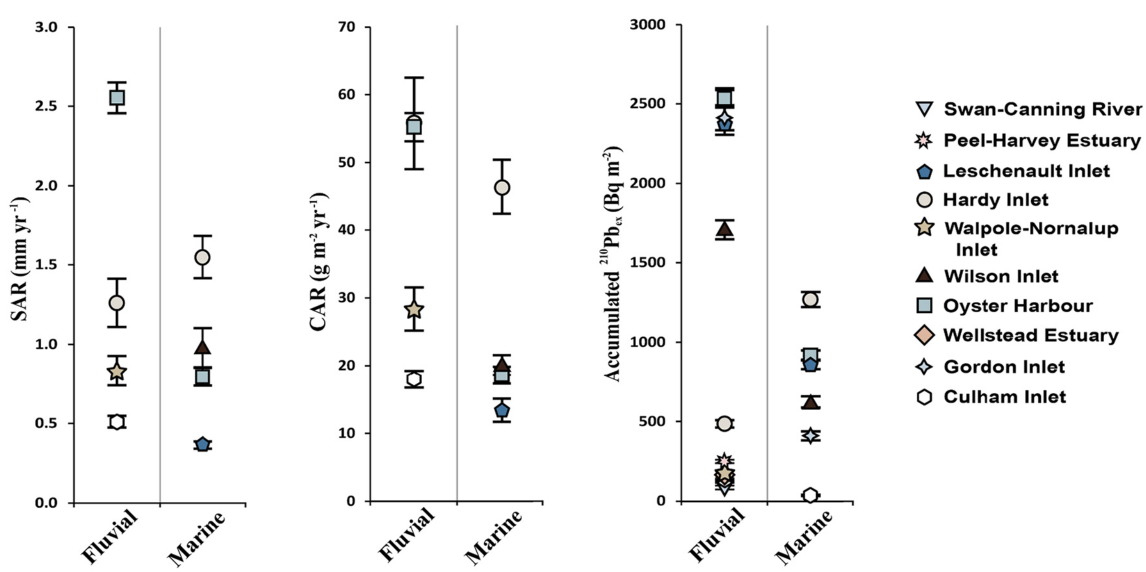

Fig. 3. Sediment accumulation rates (SAR; mm yr^{-1}) soil organic carbon accumulation rates (CAR; g C_{org} m^{-2} yr^{-1}) and accumulated excess ^{210}Pb inventories (Bq m^{-2}) in tidal marsh soils under different geomorphic settings (fluvial and marine) in estuaries across temperate Western Australia. Error bars represent standard deviation.

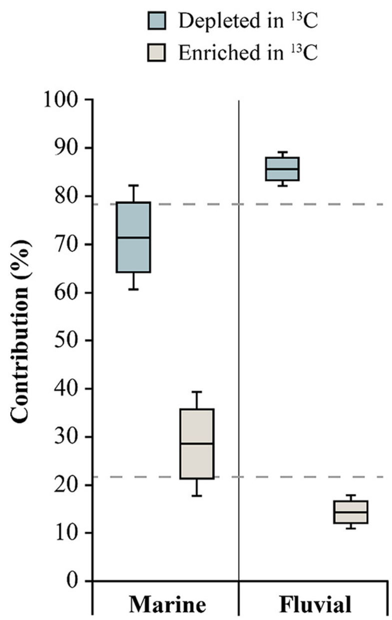

Fig. 4. Isotopic mixing model results showing proportional inputs of organic source material in tidal marsh soils under different geomorphic setting (marine tidal deltas and fluvial deltas) in temperate Western Australia. Boxplots show 25%, 50% and 75% quantiles. Source material = depleted in ^{13}C or enriched in ^{13}C. Dotted lines represent the proportional median input of organic source material across all cores (depleted in $^{13}C = 78.3\%$ and enriched in $^{13}C = 21.7\%$).

estuaries identified in this study indicate that CAR may not vary predictably at regional spatial-scales.

The δ^{13}C signatures measured in temperate WA's tidal marsh soils were used as a proxy to determine the provenance of organic source material. As WA's tidal marsh soils were naturally depleted in δ^{13}C (-24.2 ± 3.2‰ among all tidal marsh; Fig. 2B), they likely reflect higher authochthonous (C3 halophytes) contributions and/or terrestrial detrital carbon contributions, rather than allochthonous marine sources, which typically have less negative δ^{13}C values (Chappuis et al., 2017). Interestingly, marine situated tidal marsh accumulated 14% higher proportions of organic material enriched in ^{13}C compared to their fluvial counterparts (Fig. 4). This likely reflects the enhanced deposition of marine seston, macroalgae and/or seagrass vegetation compared to the fluvial site, owing to the proximity of marine-situated tidal marsh to the coastal environment. It is important to note that owing to the similar δ^{13}C signatures of intertidal halophytes and those from supratidal/terrestrial plant litter of surrounding vegetation, it was not possible to differentiate the proportional contribution of autochthonous C_{org} inputs and allochthonous inputs from adjacent terrestrial ecosystems. The CAR identified between fluvial and marine settings in this study contrast the trends identified in soil C_{org} stocks throughout Australia and globally, where fluvial sites typically have higher soil C_{org} stocks than their marine counterparts (Gorham et al., 2021; Kelleway et al., 2016; Macreadie et al., 2017b; Van De Broek et al., 2016). Specifically, the lack of correlation ($R^2 < 0.20$) between the CAR identified in this study and the 1 m soil C_{org} stocks within the same tidal marsh ecosystems (Gorham et al., 2021), can likely be attributed to the processes (e.g. diagenesis, sea level, climate, geomorphology and particle fluxes) involved in the storage of C_{org} which may differ at decadal to millennial time scales at a particular site. This illustrates that tidal marsh situated in depositional settings attributed as hotspots of soil C_{org} stocks may not be indicative of current hotspots for C_{org} sequestration.

4. Conclusions

This study fills a significant knowledge gap in the carbon sequestration capacity of WA's temperate tidal marsh ecosystems. This research shows that CAR and SAR are low throughout temperate WA relative to regions with higher rates of Holocene relative sea-level rise, illustrating a limited potential for enhanced sequestration among tidal marsh under relatively stable sea-level conditions. We expect CAR and SAR may increase with the current acceleration of sea-level rise (Rogers et al., 2019), though this will be partially dependent upon the response of plant productivity, continued supply of sediments, and availability of lateral accommodation space to enable landward habitat encroachment. Furthermore, this work has illustrated the relatively high variability of C_{org} sequestration among and within estuaries at regional spatial scales. Such variability in CAR may present accounting challenges for the quantification of carbon abatement potential of tidal marsh conservation and/or restoration activities in temperate Australia, and their potential contribution to nationally determined contributions. As such, dedicated research exploring the interactions from biotic and abiotic factors within an estuary may shed more light on the small spatial-scale variability in SAR and CAR across tidal marsh ecosystems.

CRediT authorship contribution statement

C.G. and O.S. conceived the ideas and designed the study; C.G, P.L., J.J.K. and O.S. collected the data; C.G. performed biogeochemical and statistical analyses; P.M. performed radioisotope analyses; C.G. wrote the first draft of the manuscript, and all authors reviewed and edited the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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