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Long-term carbon storage and its recent loss in an estuarine *Posidonia australis* meadow (Albany, Western Australia)

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ABSTRACT

Oyster Harbour, on the south coast of Western Australia, supports 3.6–3.9 km^2 of seagrass meadows, following the loss of approximately 2.8–3.1 km^2 in the 1980s. This small area of prevailing meadows hold significant carbon stores accumulated over the past 3000 years. In this study, we sampled three sediment cores from a *Posidonia australis* meadow and analysed organic matter (OM), organic carbon (OC) and inorganic carbon (IC) contents in bulk sediments, and $\delta^{13}C$ signatures of OM. The OM and OC contents (mean ± SE) in the cores were 9.07 ± 0.36% and 2.24 ± 0.05%, respectively. The mean IC content was 3.16 ± 0.17%. $\delta^{13}C$ signatures of the sedimentary OM ranged from −10.01‰ to −13.28‰. Using a Bayesian isotopic mixing model, it is estimated that 57–67% of the OM in the seagrass sediments was derived from *P. australis* detrital matter. The total carbon (TC) stores in 150 cm-thick seagrass sediments averaged 27.92 kg TC m^{-2} (10.79 kg OC m^{-2} and 17.13 kg IC m^{-2}). Based on radiocarbon dating, the mean sediment accumulation rate was 0.0494 cm yr^{-1}, which led to a long-term TC accumulation rate of 8.92 g TC m^{-2} yr^{-1} (3.45 g OC m^{-2} yr^{-1} and 5.47 g IC m^{-2} yr^{-1}). Based on historical seagrass cover (3.6–6.7 km^2 during the 1960s to 1980s), the estimated TC stores in 150 cm-thick seagrass sediments at Oyster Harbour would have been 101–187 Gg TC. The eutrophication-driven loss of seagrasses during the 1980s resulted in the absence of OC accumulation capacity amounting to 280–310 Mg OC (over 29 years). The loss of seagrass area could also have resulted in the release of 37–41 Gg CO_2, assuming that all of the OC in shallow sediment is remineralised after meadow disturbance. These results exemplify the importance of seagrasses meadows as important carbon sinks and the potential for losses of carbon stores due to ecosystem degradation.

1. Introduction

There is a constant flux of carbon between oceans and the atmosphere through a variety of organic and inorganic carbon forms. The component processes are complex, but the critical intermediaries are the formation and destruction of organic matter (OM) and calcium carbonate (Emerson and Hedges, 2008), with the reversible capture and release of CO_2. Less than 0.5% of the total organic carbon (OC) produced in the oceans enters long-term carbon storage in marine sediments (Hedges and Keil, 1995). Organic matter degrades at varying rates depending on ambient conditions and its inherent biogeochemical characteristics. For instance, the recalcitrant OM buried in anoxic sediments has low rates of remineralisation (Burdige, 2007). Calcium carbonate is less labile and natural coastal settings are often unfavourable for its dissolution resulting in inorganic carbon (IC) being permanently sequestered as carbonates (Smith, 2013; Millero, 2007).

The carbon storage capacities (OC and IC) of seagrass meadows have been recognised since the early 1980s (e.g. Smith, 1981) but interest has only recently been renewed (e.g. Lavery et al., 2013; Fourqurean et al., 2012). Due to their high productivity coupled with low rates of OM remineralisation, seagrass meadows have been recognised as potentially significant Blue Carbon sinks

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(Nellemann et al., 2009). The OC that accumulates in seagrass sediments is derived not only from seagrass production (i.e. recalcitrant tissues of seagrass plants) but from the trapping of other organic particles, since seagrass canopies enhance sedimentation and reduce resuspension (Marbà et al., 2015; Kennedy et al., 2010; Gacia et al., 1999). Seagrass meadows occur in a variety of depositional environments, including estuarine, exposed and sheltered areas (Carruthers et al., 2007). Of the three, estuaries have relatively high amounts of buried OM, either from the deposition of allochthonous OM transported through riparian systems (Cai, 2011; Abril et al., 2002; Bianchi et al., 1999), or from accumulation of autochthonous OM production (Couto et al., 2013).

The recognition of seagrass meadows as intense carbon sinks, and that conserving seagrasses offer potentials for climate change mitigation, has led to interests in evaluating seagrass ecosystem services for their role as carbon sinks (Duarte et al., 2013). This interest has been intensified by policy-making decisions moving towards carbon pricing economies (Lavery et al., 2013). Yet of all the natural carbon sinks on Earth, seagrass meadows rank among the highest in terms of global loss rates (with net decline of global area of 0.9–7% yr^{-1}, Waycott et al., 2009). Consequently, there will be an inevitable loss of all the ecological services they provide, including carbon sequestration (Nellemann et al., 2009).

Posidonia australis is a dominant seagrass species found in many of the estuarine systems throughout sub-tropical and temperate Australia, where it is endemic (Green and Short, 2003). Its meadows are highly productive, with estimates as high as 1.7–2.6 g dry weight (DW) m^{-2} day^{-1} (Marbà and Walker, 1999; Cambridge and Hocking, 1997; Walker and McComb, 1988). Thus, estuaries vegetated with this seagrass species may potentially have relatively high carbon stores compared to other seagrasses (e.g. Couto et al., 2013; Lavery et al., 2013; Flindt et al., 1999). Furthermore, long-term storage has been described for *Posidonia oceanica* meadows (e.g. Serrano et al., 2014, Serrano et al. 2012; Pergent et al., 2012; Mateo et al., 2006) but not for *P. australis*. While there have been studies quantifying the carbon stores in other seagrass meadows (e.g. Lavery et al., 2013; Fourqurean et al., 2012), little is known about the long term carbon accumulation rates and the longevity of these carbon stores. This had been pointed out as a distinct knowledge gap in understanding the carbon cycle in seagrass ecosystems (Mateo et al., 2006).

In this study, we quantified the long-term stores and accumulation rates of sedimentary carbon in a temperate *P. australis* meadow in Oyster Harbour, an estuary in south-western Australia. Eutrophication of the estuary during the 1980s reduced the meadow cover from 6.1–6.7 km^2 to 3.6 km^2 (Bastyan, 1986). Recent studies confirm that this loss of seagrass cover simultaneously led to a reduction of their carbon storage capacity in this area (Marbà et al., 2015). In addition to quantifying the stores and accumulation rates we also characterise the sources of carbon entering the sedimentary organic pool and estimate the loss of carbon storage ecosystem service as a consequence of the seagrass loss within the estuary (i.e. loss of OC sequestration capacity and potential remineralisation of sedimentary stores).

2. Materials and methods

2.1. Study site

Sediment cores ($n = 3$) were collected in 2012 within monospecific meadows of *P. australis* (water depth of 1.5–2.0 m) in Oyster Harbour (Albany, Western Australia, S 34°58′58.0″ E 117°58′29.9″, Fig. 1). This naturally protected embayment has an area of 15.6 km^2, with freshwater inputs supplied mainly by the Kalgan and the King Rivers (Hodgkin and Clark, 1990). The only marine exchange is through a channel at the south of the embayment. It is a marine-dominated estuary with seagrasses recorded to a maximum depth of 5 m. *Posidonia australis* dominates the system and is common to depths of 2.5 m while *Posidonia sinuosa* occurs between 2.5 and 5 m depth (Bastyan and Cambridge, 2008). There is little area of hard substrate in the system and so the dominant algae are free-floating species, such as *Cladophora* or those epiphytic on seagrasses. Sediments are medium-coarse to fine grain, silty sands occurring together with biogenic carbonates (Hodgkin and Clark, 1990).

2.2. Coring and core processing

The sediment cores were sampled randomly within an area of 100 m^2 by manually hammering sharpened aluminium pipes (46.8 mm inner diameter; 180 cm long) into the seafloor. Compression of unconsolidated sediment during coring was inevitable and corrections were applied (i.e. linear regression; Serrano et al., 2012; Glew et al., 2001) to decompress the sediment sequence and obtain the corrected core lengths. These lengths then ranged from 119 cm to 150 cm among the three cores. All analysed variables were plotted against these corrected lengths. After transport to the laboratory, the sediment cores were sub-sampled into 1 cm-wide slices. The sub-samples were oven-dried at 60 °C to constant weight to calculate the sediment dry bulk density (in g DW cm^{-3}). Alternate slices (15–27 samples per core at regular intervals) were ground to fine powder using a mortar and pestle, and further processed for biogeochemical analysis.

2.3. Biogeochemical analysis of Posidonia australis sediments

Ground sub-samples were combusted in a muffle furnace at 550 °C (5 h) to determine the OM content, and then for 950 °C (2 h) to determine the $CaCO_3$ content through loss on ignition (Heiri et al., 2001). The difference between pre-combustion and re-combustion weights provided the proportional weight of the non-$CaCO_3$ mineral fraction. The inorganic carbon (IC) content of the $CaCO_3$ was calculated through stoichiometry using the mass of carbon ($Ar = 12$) and the molecular weight of $CaCO_3$ ($Mr = 100$). Although IC content is directly derived from $CaCO_3$ content, both values were reported to present the proportion of each variable in bulk sediment.

Another set of ground sub-samples (0.5 g) were used for organic carbon (OC) and stable isotope ($\delta^{13}C$ and $\delta^{15}N$) analysis. The sediment samples were acidified (1 M hydrochloric acid) to remove all IC. When effervescence ceased after 12–18 h, the mixture was centrifuged (3400 revolutions min^{-1} for 4.5 min) and pipetted to remove the acidic supernatant. Deionised water (10 ml) was added to wash off residual acid, centrifuged, and the supernatant removed by pipetting. The acidified sample was then oven-dried at 60 °C until constant weight was attained. Then, 9–10 mg of the acidified sample was encapsulated in tin capsules and combusted in a continuous flow isotope ratio mass spectrometer analyser (Delta V Plus: Thermo-Finnigan) at the West Australian Biogeochemistry Centre (The University of Western Australia). The OC contents reported by the analytical facilities were corrected to account for the weight of pre-acidified bulk sediment samples. The sum of OC and IC contents (the latter obtained in the step described earlier) constituted the total sedimentary carbon (TC) content. The $\delta^{13}C$ and $\delta^{15}N$ values (in ‰) were reported relative to the Vienna Pee Dee Belemnite (VPDB) standard and nitrogen from atmospheric air, respectively. Since there are disagreements in reports that acidification of OM will alter $\delta^{15}N$ values (Schlacher and Connolly, 2014; Mazumder et al., 2010; Jaschinski et al., 2008) we ran preliminary analyses to gauge such effects on the samples. $\delta^{15}N$ values of