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Baseline

Variability of sedimentary organic carbon in patchy seagrass landscapes

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ABSTRACT

Seagrass ecosystems, considered among the most efficient carbon sinks worldwide, encompass a wide variety of spatial configurations in the coastal landscape. Here we evaluated the influence of the spatial configuration of seagrass meadows at small scales (metres) on carbon storage in seagrass sediments. We intensively sampled carbon stocks and other geochemical properties ($\delta^{13}C$, particle size, depositional fluxes) across seagrass–sand edges in a *Zostera muelleri* patchy seagrass landscape. Carbon stocks were significantly higher (ca. 20%) inside seagrass patches than at seagrass–sand edges and bare sediments. Deposition was similar among all positions and most of the carbon was from allochthonous sources. Patch level attributes (e.g. edge distance) represent important determinants of the spatial heterogeneity of carbon stocks within seagrass ecosystems. Our findings indicate that carbon stocks of seagrass areas have likely been overestimated by not considering the influence of meadow landscapes, and have important relevance for the design of seagrass carbon stock assessments.

The necessity to reduce CO_2 fluxes to mitigate climate change has generated considerable interest in quantifying the capacity of natural ecosystems to trap and sequester carbon (Mcleod et al., 2011). Most efforts have focussed on quantifying carbon sinks in terrestrial ecosystems, but recently vegetated coastal habitats have been highlighted for their carbon storage potential (Pendleton et al., 2012; Duarte et al., 2013a).

The carbon sequestered by vegetated coastal habitats, referred commonly as "blue carbon", provides long-term organic carbon (C_{org}) storage once it has become bound within sediments. The large amount of C_{org} stored in coastal sediments, combined with their high carbon sequestration rates, highlights the important role that coastal ecosystems play as natural carbon sinks (Macreadie et al., 2014a,b). These ecosystems, particularly mangroves, saltmarshes and seagrasses, have a disproportionately large C_{org} storage potential relative to their global area (Duarte et al., 2005, 2013a; Mcleod et al., 2011).

Seagrasses develop organic-rich soils derived from both autochthonous (produced internally — e.g. seagrass detritus) and allochthonous (of external origin — e.g. sestonic particles) sources (Gacia and Duarte, 2001; Kennedy et al., 2010). Seagrass carbon storage capacity is a result of a high primary productivity, the refractory nature of seagrass tissues and its capacity to trap particles from the water column and incorporate them into the sediment (Hendriks et al., 2008; Kennedy et al., 2010). These facts, in combination with high sedimentation rates and the anaerobic nature of these soils, that promotes slow microbial decomposition rates, provide environments where carbon can be buried and preserved over long time frames, such as the millennial carbon deposits found in temperate seagrass meadows formed by persistent, long-lived species (Mateo et al., 1997, 2006).

The relevance of seagrasses as a potential mitigating agent of CO_2 emissions was already suggested in the last decades (Smith, 1981), although, the paucity of data on the carbon budgets from seagrass ecosystems hindered the inclusion of seagrasses in models of global carbon transfer and global green-house gas abatement schemes (Macreadie et al., 2014a). Over the past five years, however, there has been a major increase in the accuracy of regional and global estimates of carbon stocks and accumulation rates in seagrass ecosystems (Kennedy et al., 2010; Duarte et al., 2010; Fourqurean et al., 2012; Serrano et al., 2012, 2014; Greiner et al., 2013; Lavery et al., 2013).

Seagrass ecosystems encompass a wide variety of species across a range of depositional environments and depths (Carruthers et al., 2007). Species identity as well as abiotic habitat characteristics have been highlighted as factors driving variability of sedimentary carbon stocks of seagrass meadows (Lavery et al., 2013; Serrano et al., 2014). However, our understanding of the factors regulating this variability is still limited (Duarte et al., 2010; Nellemann et al., 2009; Serrano et al., 2014).

Moreover, seagrass meadows present high spatial heterogeneity (Jackson et al., 2006). They can occur either as large, continuous

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meadows or in the form of patches of various shapes and sizes with unvegetated or macroalgal regions interspersed among more homogenous seagrass areas (Robbins and Bell, 1994). Patchiness is an intrinsic feature of most seagrass meadows, especially in shallow and estuarine areas where natural and anthropogenic forcing is severe (Montefalcone et al., 2010). Patchiness increases the amount of edge associated to the habitat (Smith et al., 2008), which constitutes an important transitional gradient from one structural type to another. Habitat edges influence patterns in biological and physical activity by promoting interactions with the surrounding landscape (Puth and Wilson, 2001; Macreadie et al., 2010a,b). In particular for seagrasses, the edge has been defined as a boundary that stops the water flow, increasing turbulence on the edge of the canopy (Granata et al., 2001) and enhancing deposition of particles inside the seagrass meadow (Macreadie et al., 2010a; Zong and Nepf, 2011). Over time, these processes could potentially generate spatial heterogeneity in C_{org} accumulation, both in the seagrass patches and in adjacent bare sediments.

Carbon burial rates on seagrasses can be as much as threefold higher when compared to bare sediments (Duarte et al., 2005), as seagrass canopies promote sedimentation and reduce particle resuspension (Gacia and Duarte, 2001; Gacia et al., 1999). But this is unlikely to be uniform inside such seagrass meadows, where significant differences in burial rates due to the meadow architecture and spatial configuration occurs (Granata et al., 2001; Gruber and Kemp, 2010). Small-scale variability (e.g. one seagrass patch might be denser than another patch) could influence carbon sequestration at the patch level thus affecting carbon stocks estimations at the habitat and landscape scale.

Despite previous works quantifying seagrass carbon sinks, little is known about the within-meadow variability on sediment carbon storage. In this study we selected a patchy seagrass distribution to evaluate the small-scale spatial variability on carbon storage within seagrass ecosystems. We evaluated horizontal spatial variability by quantifying carbon stocks and sources both in seagrass patches and adjacent bare sediments at increasing distances from the seagrass–sand edge. We also evaluated vertical variability by sampling at different depth sections in the sediment. We hypothesized that (1) sediment carbon stocks will be highly variable across seagrass patches, with carbon stocks increasing across the transition from bare sediments to seagrass patch edges and to seagrass patch interiors; and (2) there will be greater contribution of autochthonous (plant-produced) carbon to the carbon stocks within seagrass patches than in bare sediments.

The study was conducted in the middle of the growing season (September 2013), well before the seasonal dieback, on Pelican Banks inside the entrance to Port Curtis Harbour (23°46′57″S; 151°18′0″E). Port Curtis is a macro-tidal estuary in central Queensland (Australia) characterized by the presence of *Zostera muelleri* Irmisch ex Asch. beds in most of its intertidal areas. The selected area for this study represented a patchy landscape characterized by a mosaic of large seagrass patches (diameter about hundreds of metres) interspersed with naturally occurring unvegetated (bare) sediments.

To test for variability in carbon storage, four different locations on the boundary among seagrass patches and bare sediments were selected haphazardly at the same water depth. The seagrass patches selected for the study were determined to be persistent for at least the last 10 years by using satellite imagery (Google Earth, 2013). At each location, cores were taken at 6 different positions along a transect perpendicular to a seagrass-bare sediment edge: at 0.5 m, 10 m and 20 m into seagrass (S0.5, S10 and S20) and at 0.5 m, 10 m and 20 m into bare sediment (B0.5, B10 and B20). Four replicated transects were sampled, resulting in a total of 24 (6 positions × 4 transects) sampling points. Seagrass cover, measured in three replicate 50 × 50 cm quadrates at each seagrass position, was similar among all positions ($p > 0.05$) with an overall mean of 22.5% ± 3.06 SE.

Sediments were collected manually by inserting open-barrel PVC pipes (20 cm length, 5 cm internal diameter) into sediments to a depth of 10 cm, and using a piston to provide suction as cores were withdrawn. Compaction during coring was low (<10%). Once extracted, cores were capped at both ends and transported to the laboratory. In the laboratory, the sediments were extruded, sliced into 10 sections at 0–0.5, 0.5–1, 1–1.5, 1.5–2, 2–3, 3–4, 4–5, 5–6, 6–8, and 8–10 cm intervals, dried at 60 °C and weighed in order to calculate dry bulk density (Howard et al., 2015).

Each sediment section was split into two sub-samples, with grain size particle distribution analysed from the first subsample using a Malvern Mastersizer 2000 laser microgranulometer. Organic matter (OM) was removed from the subsample by addition of hydrogen peroxide 10%, while large organic material was removed by hand. Particle size distribution was expressed as % volume for particle diameters from 0 to 2000 μm. The d_{50} (i.e. the diameter corresponding to the median of particle volumes assuming that all particles are spherical) and skewness (Folk and Ward, 1957) were used as an indicator of the particle size distribution.

The second sub-sample was used for C_{org} elemental and isotopic analysis after being sieved through a 1 mm mesh to remove living plant material and coarse inorganic particles (i.e. carbonate material). Samples were then ground and acidified with HCl 1 M to remove any carbonates that were too small to be sieved. After drying, samples were re-ground and then analysed for carbon elemental and isotopic composition.

The apparent depositional flux (considered as the result of both deposition and resuspension processes) was measured in each position sampled along the transects using sediment traps consisting of cylindrical centrifuge tubes (20.5 ml) with a height versus diameter ratio of 5, with the aperture of the tube positioned at 5 cm above the sediment surface. Sediment traps were removed after 7 days of deployment. These short-term measurements were used only to capture relative spatial differences, and not to elaborate annual budgets. In the laboratory contents of the sediment traps were filtered through pre-combusted (450 °C for 4 h) 25 mm GF/F filters and dried (60 °C for 48 h) to obtain dry weight. Samples were analysed for C_{org} elemental and isotopic composition, after acidification, using the method described above.

Measurements of carbon elemental composition and stable isotope ratios (as a tracer of carbon sources) were performed using a continuous-flow isotope-ratio mass spectrometer MAT253 (Thermo Finnigan) coupled to an elemental analyser EA1108 (Carlo Erba Instruments) through a Conflo III interface (Thermo Finnigan). Carbon isotope ratios are expressed as δ values in parts per thousand (‰) relative to VPDV (Vienna Pee Dee Belemnite) according to standard notation ($\delta^{13}C = [(Rsample / Rstandard) - 1] \times 1000$, where R is the ratio $^{13}C/^{12}C$). Standing carbon stocks per volume unit were calculated using dry bulk density data and C_{org} content and expressed as mg C_{org} cm^{-3}.

Differences in dry bulk density, particle size median diameter (d_{50}), sedimentary C_{org} elemental and isotopic composition, and carbon stocks were analysed using two-way Analysis of Variance (ANOVA) with position along the transects and depth section as fixed factors. The apparent depositional flux and the carbon elemental and isotopic composition of the material collected in the sediment traps were compared using a one-way ANOVA with position along the transects as a fixed factor. Where a significant ($p < 0.05$) difference occurred, post hoc Tukey's HSD tests were used to distinguish differences among groups. When necessary, data were fourth root transformed to meet ANOVA assumptions. Non-transformed values (means ± SE) are shown in figures and tables.

Dry bulk density of sediments was similar across all the positions along the transects and depth sections (Table 1) with an overall mean of 1.57 ± 0.08 g cm^{-3}. The median diameter of sediment particles (d_{50}) was similar among all positions along the transects and depth sections (Table 1), ranging from 103 μm to 120 μm, while skewness was positive (overall mean 0.83 ± 0.01) indicating that sediments can be characterized as fine sands.