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Structural equation modelling reveals factors regulating surface sediment organic carbon content and CO_2 efflux in a subtropical mangrove

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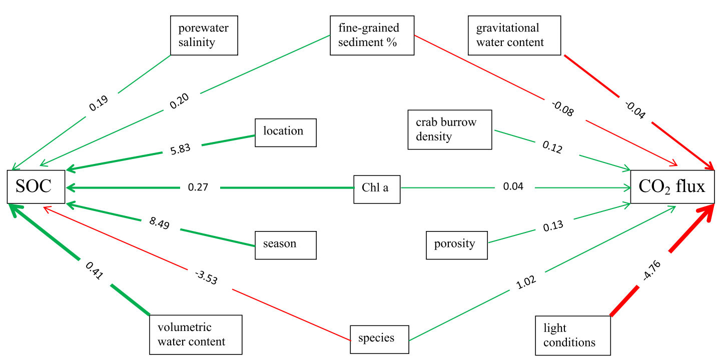
HIGHLIGHTS

- We explored controls on mangrove sediment organic carbon and CO_2 flux in one model.
- Light, edaphic and biotic factors combined drive sediment CO_2 flux.
- Spatio-temporal, edaphic and biotic factors combined drive sediment organic carbon.
- Sediment water content and grain size are essential to blue carbon management.
- Chlorophyll a is a positive driver of both sediment organic carbon and CO_2 flux.

GRAPHICAL ABSTRACT



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ABSTRACT

Mangroves are blue carbon ecosystems that sequester significant carbon but release CO_2, and to a lesser extent CH_4, from the sediment through oxidation of organic carbon or from overlying water when flooded. Previous studies, e.g. Leopold et al. (2015), have investigated sediment organic carbon (SOC) content and CO_2 flux separately, but could not provide a holistic perspective for both components of blue carbon. Based on field data from a mangrove in southeast Queensland, Australia, we used a structural equation model to elucidate (1) the biotic and abiotic drivers of surface SOC (10 cm) and sediment CO_2 flux; (2) the effect of SOC on sediment CO_2 flux; and (3) the covariation among the environmental drivers assessed. Sediment water content, the percentage of fine-grained sediment (<63 μm), surface sediment chlorophyll and light condition collectively drive sediment CO_2 flux, explaining 41% of their variation. Sediment water content, the percentage of fine sediment, season, landform setting, mangrove species, sediment salinity and chlorophyll collectively drive surface SOC, explaining 93% of its variance. Sediment water content and the percentage of fine sediment have a negative impact on sediment CO_2 flux but a positive effect on surface SOC content, while sediment chlorophyll is a positive driver of both. Surface SOC was significantly higher in *Avicennia marina* (2994 ± 186 g m^{-2}, mean ± SD) than in *Rhizophora stylosa* (2383 ± 209 g m^{-2}). SOC was significantly higher in winter (2771 ± 192 g m^{-2}) than in summer (2599 ± 211 g m^{-2}). SOC significantly increased from creek-side (865 ± 89 g m^{-2}) through mid (3298 ± 137 g m^{-2}) to landward (3933 ± 138 g m^{-2}) locations. Sediment salinity was a positive driver of SOC. Sediment CO_2 flux

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without the influence of biogenic structures (crab burrows, aerial roots) averaged 15.4 mmol m^{-2} d^{-1} in *A. marina* stands under dark conditions, lower than the global average dark flux (61 mmol m^{-2} d^{-1}) for mangroves.

1. Introduction

Mangroves are intertidal ecosystems with high carbon (C) sequestration capacity (Bouillon et al., 2008) as well as C stock in sediment (Adame et al., 2013; Brown et al., 2016; Donato et al., 2011; Friess et al., 2015). Mangrove sediment biogeochemistry is complex and variable, and responds to both biotic and abiotic drivers. Mangrove organic material such as leaf litter, if not exported, enters the sediment and, along with roots are decomposed by microbes (e.g. bacteria) (Kristensen et al., 2008a). CO_2 is the main gas product of sediment OC oxidation as methanogenesis is considered to be a minor process in marine sediments (Penha-Lopes et al., 2010).

Carbon stocks in mangroves consist of C of above- and belowground vegetation, as well as sediment C; the latter is the focus of this study. Sediment organic C (SOC) stock in mangroves has been shown to be regulated by different environmental factors in different studies (Alongi, 2014). For example, SOC stock was found to vary with sediment salinity, and-nutrient content (e.g. N and P) in a Mexican mangrove (Adame et al., 2013). SOC stock can be widely different among mangrove species – a comparison among *Laguncularia racemosa*, *Rhizophora mangle* and *Conocarpus erectus* resulted in a large range (23–190 kg m^{-2}); and seasons and sediment types were proposed to be the most important drivers for SOC stock on Carmen Island, Mexico (Cerón-Bretón et al., 2014). It was also reported that SOC stock changes along the transect from the seaward, through interior, to landward sites (Kauffman et al., 2011). Sediment microphytobenthos are also considered to be a significant source of C in mangrove sediments, second to C fixed from the air by the trees (Alongi, 2014).

In addition to the factors that modulate SOC stock, biogenic structures (such as crab burrows and aerial roots) and light conditions are the external drivers of sediment CO_2 flux. Although biogenic structures are directly related to the microphytobenthos, they also promote sediment CO_2 flux via other processes, e.g. increasing the area of sediment and air/water interfaces by epibenthic burrows (Lee, 2008). Likewise, light conditions are directly related to the microphytobenthos but primarily affect CO_2 assimilation during photosynthetic processes. Further, OC content in sediment and bulk density, and thus SOC, account for variations in sediment CO_2 flux (Chen et al., 2010). Pneumatophores and animal burrows can promote sediment CO_2 emission in *Sonneratia alba* and *Avicennia marina* forests (Kristensen et al., 2008b). Sediment CO_2 flux under light conditions may be generally low compared to the dark flux, due to CO_2 uptake by the microphytobenthos during photosynthesis (Bouillon et al., 2008). Sediment CO_2 flux was also shown to vary along the sea-land gradient and with sediment properties (Chen et al., 2010) and mangrove species, as well as chlorophyll a (Chl a) (Leopold et al., 2013) and seasons (Chen et al., 2012) in mangroves.

Despite numerous studies examining the factors that independently influence SOC stock and CO_2 flux, the relationships among SOC stock, sediment CO_2 flux and their drivers have not been analysed in one comprehensive model. It is important to explore the relationships in a single analysis because identifying the relative weight of drivers of both SOC stock and sediment CO_2 flux would provide insights into effective blue C management (McLeod et al., 2011). SOC stock is not only a response variable dependent on sediment physico-chemical properties, landform settings, seasons and species, but also a potential predictor for sediment CO_2 flux. Soil CO_2 flux measured by the chamber technique accounts for CO_2 from the soil surface (Alongi, 2014), and thus surface SOC is utilised as the specific predictor for sediment CO_2 flux measured in our study. It is also of interest directly as well, as to what environmental variables relate to surface SOC. For sediment CO_2 flux, in addition to the same influential factors that regulate SOC stock, the drivers may also include sediment temperature, light conditions and biogenic structures (Kristensen and Alongi, 2006). Additionally, some factors exert influences on each other, this redundancy may be reflected in an overall model. Structural equation modelling is a statistical method capable of resolving this type of problem: (1) when the indirect effects of one predictor influence a second predictor, which in turn influences the response variable; and (2) there exists two or more response variables which can interact with each other (Quinn and Keough, 2002).

In this study, based on data collected from a subtropical mangrove forest in southeast Queensland, Australia, structural equation modelling was used to evaluate (1) factors regulating sediment CO_2 flux, including surface SOC, sediment physico-chemical properties, landform settings, seasons, species, the density of biogenic structures and light conditions; (2) factors modulating surface SOC, including sediment physico-chemical properties, landform settings, seasons and species; and (3) possible correlations among the influential factors.

2. Materials and methods

2.1. Conceptual model

Based on the prior knowledge on factors influencing SOC stock and CO_2 flux, a conceptual model was established (Fig. 1). From reported studies, the common factors affecting both SOC stock and CO_2 flux in mangroves include, but not limited to, sediment particle size, gravitational/volumetric water content, sediment porosity, Chl a, seasons, landform settings, species and porewater salinity. Sediment CO_2 flux is also affected by SOC stock and potentially by an array of other factors, i.e. sediment temperature, the densities of pneumatophores and burrows, as well as light conditions (dark or light). Sediments were categorized into gravel, sand, silt and clay particle size classes according to the Udden scale. The aggregated proportion of silt and clay was used to consider the influence of silt and clay particles.

2.2. Sampling site

The sampling site is located in a mangrove forest, along Tallebudgera Creek, southeast Queensland, Australia (Fig. 2). The forest is dominated by *A. marina* and *Rhizophora stylosa*. According to climate records from the nearest weather station at Coolangatta 8 km away from the sampling site, average annual rainfall is 1507.5 mm and average temperature is 24.7 °C (http://www.bom.gov.au/). The climate at the sampling site generally comprises a cool dry winter and hot wet summer. Average temperature is 21.9 °C in winter between May and September, but 25.3 °C in summer (October–April). The mangroves experience diurnal tides. According to tidal records from the nearest tidal gauge (Gold Coast Operations Base) 15 km from the sampling site, heights of high tides range from 0.9–1.86 m in summer and 0.94–1.92 m in winter, while heights of low tides range from 0–0.62 m in summer and 0–0.65 m in winter.

2.3. Sampling campaign

Sediment CO_2 flux measurements were conducted in the cool (August 2015) and warm seasons (January 2016) at three locations along

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