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Mangrove vegetation enhances soil carbon storage primarily through *in situ* inputs rather than increasing allochthonous sediments

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ABSTRACT

The role of soil carbon (C) in coastal wetlands as a net sink is related to the relative abundance of autochthonous *versus* allochthonous C. We aimed to investigate soil C sources and the pathways by which mangrove vegetation enhances soil C accumulation. We sampled soil to 1 m depth in seven oceanic mangrove forests and an adjacent un-vegetated mudflat at Dongzhai Bay, China. Stable C isotope technique was used to separate autochthonous and allochthonous C sources. Autochthonous C accounted for 27–97% of soil C stock in the top meter. Soil C density was 1.1–3.6 times higher in mangroves than in the mudflat. Among the increased soil C in mangroves relative to mudflat, autochthonous C accounted for 65–100% of the increments. The results suggest that mangrove vegetation enhances soil C storage primarily through *in situ* inputs, therefore the substantial soil C stocks commonly found in mangroves play an important role in sequestering atmospheric CO_2.

1. Introduction

Coastal wetlands (especially mangroves, tidal salt marshes and seagrasses) have been placed at the forefront of scientific and policy interest due to their large capacity to store carbon (C) (Mcleod et al., 2011; Siikamäki et al., 2012; Lu et al., 2016). The C stored in coastal ecosystems has been specifically termed as "blue carbon" (Nellemann et al., 2009). Mangroves, for example, on average contain 3–4 times the C density typically found in boreal, temperate, or upland tropical forests (Donato et al., 2011). Soil plays a key role in mangrove C stock because soil C comprises 49–98% of C in mangroves (Donato et al., 2011; Wang et al., 2013; Liu et al., 2014). However, the role of soil C stocks in coastal wetlands as a net sink depends to a large extent on autochthonous rather than allochthonous C (Saintilan et al., 2013), because autochthonous C is photosynthesized *in situ* by plants of these wetlands whereas allochthonous C is transferred from other ecosystems. It remains unclear whether the soil C in coastal vegetated wetlands derives primarily from *in situ* plant inputs or from allochthonous material sedimentation.

Vegetated coastal wetlands have been commonly found to hold more soil C than adjacent un-vegetated mudflats (Duarte et al., 2005; Wang et al., 2013; Lunstrum and Chen, 2014). Coastal wetland vegetation enhances soil C accumulation through two pathways. Firstly, plant aboveground litter (leaves, propagules and twigs) and fine root turnover provide significant inputs of organic C to soil (Middleton and McKee, 2001; Liu et al., 2018). Secondly, plants in coastal wetlands enhance in trapping suspended materials from tidal waters (Kristensen et al., 2008; Gacia and Duarte, 2001). Plants influence sedimentation by capturing suspended matter (deposition directly on the plant surface) and reducing turbulent energy with stems and dense pneumatophore, which facilitates the settling of suspended particles (Leonard and Croft, 2006; Mudd et al., 2010). Therefore, coastal wetland vegetation contributes to soil C accumulation by increasing both autochthonous and allochthonous C. However, what remains unexplored is the relative importance of the two pathways by which coastal wetland vegetation increases soil C storage, which has important implications for the role of coastal wetland C stocks in offsetting the atmospheric CO_2 enrichment.

Stable isotope signatures have been used to separate the autochthonous and allochthonous sources of soil C in mangrove wetlands (Bouillon et al., 2008). Mangrove tissues and terrestrially derived organic matter are characterized by depleted ^{13}C while suspended organic matter in marine water is more enriched in ^{13}C (Graham et al., 2001; Bouillon et al., 2003). By comparing the isotopic signature ($\delta^{13}C$) of mangrove soils to those of mangrove tissues and marine suspended materials, some studies made qualitative conclusions on the origin of mangrove soil C (Graham et al., 2001; Prasad and Ramanathan, 2009; Saintilan et al., 2013). By applying the $\delta^{13}C$ values of mangrove soil and

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potential organic matter sources to multi-source mixing models, the relative contributions of potential sources to mangrove soil C were quantitatively determined (Kennedy et al., 2004; Stringer et al., 2016). However, a great uncertainty existed in previous studies in determining the sources of mangrove soil C due to the varying $\delta^{13}C$ of the allochthonous source. In determining the $\delta^{13}C$ value of allochthonous source, some studies (*e.g.* Stringer et al., 2016) used the $\delta^{13}C$ of marine materials reported in other studies, however, the composition of marine organic matter and its $\delta^{13}C$ vary in a wide range spatially and temporally (Bouillon and Dehairs, 2000; Bouillon et al., 2008). Some studies determined the $\delta^{13}C$ of allochthonous C source by measuring the $\delta^{13}C$ of contemporary suspended organic matter (Kennedy et al., 2004; Bao et al., 2013), however, the allochthonous C in mangrove soils results from long-term deposition of suspended materials within a history of decades to centuries and thus may differ vastly from contemporary suspended organic matter. Mudflat soils adjacent to vegetated ecosystems actually represent a good proxy of allochthonous C source (Middelburg et al., 1997), because the accretion of mudflat soil results from the sedimentation of suspended matter in tidal waters and has a similar sedimentation history as the soil profile in adjacent vegetated systems. However, mudflat soil C has rarely been considered as a proxy of allochthonous C source in previous studies.

In this study, stable C isotope signatures of mangrove plants and mudflat soils were used as the proxy of autochthonous and allochthonous C signature respectively in a two-source mixing model to separate the relative contributions of autochthonous (from mangrove plants) and allochthonous (from suspended materials) C sources to mangrove soil C. Further, we compared soil total C densities and allochthonous C densities between mangroves and the adjacent bare mudflat to determine to what extent mangrove vegetation enhanced soil C storage and whether the increased soil C in mangroves relative to the adjacent mudflat was mainly due to enhanced allochthonous material sedimentation or plant *in situ* inputs. The conceptual model separating pathways by which mangrove vegetation increases soil C storage is demonstrated in Fig. 1. Briefly, the increment of soil total C in mangroves relative to the adjacent mudflat is considered as the bulk contribution by mangrove vegetation. Since soil autochthonous C derives from plant *in situ* inputs, the increment of allochthonous soil C in mangroves relative to the adjacent mudflat is considered as the contribution of vegetation by enhancing allochthonous C sedimentation.

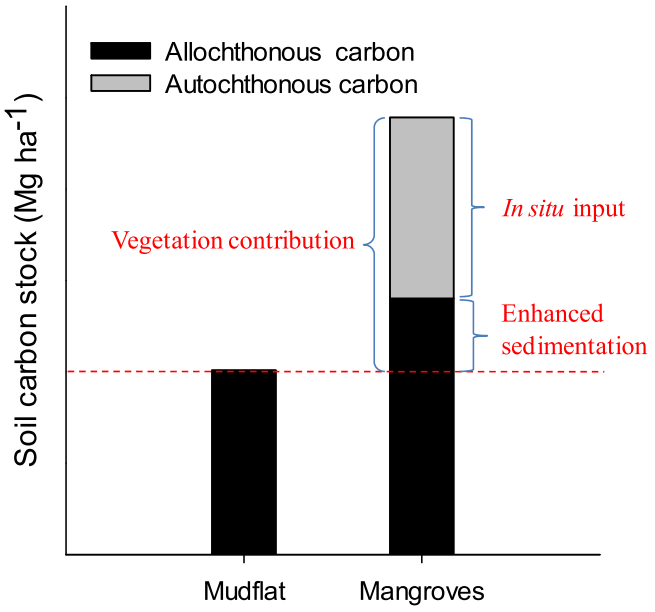

Fig. 1. Conceptual model of separating the pathways by which coastal wetland vegetation contributes to soil C stock.

2. Materials and methods

2.1. Study site

The study was carried out at Dongzhai Harbor National Natural Reserve (N 19°55′, E 110°36′), Hainan Island, China. The reserve covers an area of 3337 ha, and holds one of the most extensive mangrove forests which had the most mangrove species (25 in total including nine introduced species) in China. Mangrove forests in the reserve comprise mainly of naturally occurring mono-specific stands of *Avicennia marina*, *Bruguiera sexangula*, *Ceriops tagal*, *Rhizophora stylosa* and *Kandelia obovata*, and mix-species communities. The study area is characterized by a tropical monsoon climate. The mean annual air temperature is 23.5 °C, with a maximum of 28.4 °C in July and a minimum of 17.1 °C in January. The mean annual rainfall is 1676 mm, with a rainy season between May and October. The tides are irregularly semi-diurnal, with an average range of about 0.89 m. More information about the site can be found in Xiong et al. (2017).

2.2. Soil sampling and plant tissue collection

In October 2015 and October 2016, we sampled soil cores in seven mangrove forests and an adjacent non-vegetated mudflat within oceanic (not influenced by rivers) geomorphic settings at Dongzhai Bay. The forests included *A. marina*, *R. stylosa*, *C. tagal* and *B. sexangula* mono-specific stands. For each species (except *B. sexangula*), a seaward fringe forest and a landward forest hundreds of meters away from the fringe were selected for sampling. *B. sexangula* can only be found at the landward side but not the fringe side within the oceanic geomorphic setting. Three to four plots (10 × 10 m) were set up for soil sampling in each forest. Three mudflat plots were set up 10 m away from the fringe of mangrove forests. In each plot, two soil cores were randomly taken with a steel corer of 5 cm in diameter and 1 m in depth during low tide. A semi-opened corer was used in order not to compress soil cores. Each soil core was separated into five segments (0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm and 80–100 cm). Two core segments of the same soil depth from each plot were pooled as a composite sample for subsequent analyses.

Leaf litter and fine roots of *A. marina*, *B. sexangula*, *C. tagal* and *R. stylosa* were collected from their mono-specific stands for the measurement of stable C isotope composition. Leaf litter was collected with litter traps in April and October, and homogenized for measurement. Fine roots < 0.5 mm in diameter, which turn over most frequently (Xiong et al., 2017), were collected in April and October and homogenized for analysis.

2.3. Soil and plant tissue analyses

Soil and plant tissue samples were dried in the air before analysis. Subsamples of soil were dried in an oven at 105 °C to measure the moisture content. Soil bulk density was measured as the dry weight of soil sample divided by its volume (calculated from the corer). Air-dried soil samples and plant tissues were ground and passed through 0.15 mm mesh for measurements of C concentration and stable C isotope composition. Soil C concentration was measured with an elemental analyzer (Elementar vario MAX CNS, Germany). Our unpublished data suggest that inorganic C was negligible (< 10%) in the soils of the studied area. C density was calculated as soil C concentration multiplied by soil bulk density. Stable C isotope composition of soil and plant tissues, $\delta^{13}C$, was measured with an isotope ratio mass spectrometer (Thermo Fisher Delta V, USA).

2.4. Calculation of autochthonous and allochthonous sources of soil C in mangroves

The relative contributions of autochthonous and allochthonous