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Top-meter soil organic carbon stocks and sources in restored mangrove forests of different ages

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ABSTRACT

Knowledge of the changes in the soil organic carbon (OC) stock and its sources with forest age is crucial to understanding the carbon processes and carbon sequestration benefits associated with mangrove restoration. The present study compared the soil OC contents and stocks among three restored *Kandelia obovata* mangrove forests with different ages (12, 24 and 48 years) in South China. The contributions of mangrove and allochthonous suspended particulate organic matter (SPOM) in tidal water to soil OC were also estimated. The results showed increases in soil OC content and density with forest age, and the OC stocks in the top meter of soil were 13.0 ± 0.5 kg C m^{-2}, 15.1 ± 0.7 kg C m^{-2} and 17.0 ± 0.9 kg C m^{-2} at the 12-year site, 24-year site and 48-year site, respectively. We also found a higher soil labile OC content at the 48-year site. The higher soil OC content was accompanied by more ^{13}C-depleted OC in the older forests, and the significantly negative relationship between soil OC contents and $\delta^{13}C$ values indicated that the increase in soil OC content relied on the input of ^{13}C-depleted mangrove organic matter. Isotope mixing calculations showed that the soil OC was dominated by SPOM at the 12-year site but was dominated by both mangrove-derived OC and SPOM at the 48-year site. Moreover, the findings also suggested that the effect of mangrove restoration on the soil OC content and stock was more substantial in the upper soil layers.

1. Introduction

Although mangroves occupy a limited area compared to terrestrial forests, they have been recognized as highly productive and ecologically important in global carbon cycles and sequestration (Chmura et al., 2003; Dittmar et al., 2006; Alongi, 2014). Mangrove forests account for > 10% of the global terrestrial carbon exports to near-shore environments and as much as 15% of the total carbon accumulated in modern marine sediments (Jennerjahn and Ittekkot, 2002; Dittmar et al., 2006). Recently, quantitative studies of carbon stock have also focused on mangrove forests and highlighted the valuable role played by mangrove forests in carbon stocks on both regional and global scales (Donato et al., 2011; Wang et al., 2013; Jardine and Siikamäki, 2014). The carbon buried in mangrove soils has a long-life span because anoxic conditions in the soil limit the decomposition of organic carbon (OC) (Armentano and Menges, 1986; Alongi, 2009) and contribute to a substantial belowground OC stock. The average global carbon stock was ~720 t C ha^{-1} in mangrove soils, which was greater than that in other ecosystems, such as subtropical tidal marshes, tropical seagrass beds, and tropical peat swamp forests (Alongi, 2014).

However, under the pressures of human development, massive losses of mangrove forests and habitat degradations have occurred in recent decades, and mangrove restorations have been performed around the world to compensate for the loss of mangroves (Das et al., 1997; Field, 1998). Most of the restorations have sought to achieve ‘persistent vegetative cover’ as the basic goal, and studies on nursery techniques and site selection have received the most attention, while functional restoration and ecosystem restoration have been less considered (Lewis, 2000; Ye et al., 2006). Under the goal of ecosystem restoration, detailed monitoring efforts following mangrove restorations are essential, and the performance of basic ecological processes and system dynamics, including the mangrove growth, productivity, benthos, and ecosystem carbon cycle and sequestration, are important items to consider in addition to species composition and the plant and soil structures (Field, 1998; Osland et al., 2012). Some recent studies have shown that mangrove restoration promotes the diversity of the macro-benthos and that the faunal community structures change with forest age, with *Metaplax* spp., Littorinidae, and Assimineidae being more representative of the younger forests and grapsid crabs, ocypodid crabs, and Neritidae and Ellobiidae species being more abundant in

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mature or older forests (Macintosh et al., 2002; Chen et al., 2007, 2011). However, to date, measurements of ecological processes and dynamics in restored mangrove ecosystems have been rare (Field, 1998; Bayraktarov et al., 2016).

Mangrove forests can retain allochthonous OC from marine or riverine inputs in their soils, while autochthonous primary producers, including mangrove and algal materials, also provide high OC inputs to the soils (Twilley et al., 1992; Jennerjahn and Ittekkot, 2002; Bouillon et al., 2003; Kristensen et al., 2008). Previous studies have demonstrated that mangrove restorations increase the underground soil carbon contents and stocks (Ren et al., 2010; Osland et al., 2012; Marchand, 2017), while the increases were limited within the surface soil even 20 years after the restoration (Osland et al., 2012). In this study, we further examined the contribution of mangrove-derived OC to the soil OC stock along a chronosequence following mangrove restoration in the Jiulong River Estuary (JRE), China. The soil profiles of organic matter and the soil OC stock in mangrove forests with different ages were compared, and the contribution of mangrove to the soil OC stock was examined at each site via isotopic analysis. The JRE mangrove forests have been reported to be highly productive, with litter fall production (7.7–15.7 $t\,ha^{-1}\,yr^{-1}$, Ye et al., 2013; Chen et al., 2016) as high as that in tropical mangroves, e.g. 2.2–16.4 $t\,ha^{-1}\,yr^{-1}$ in the 0–10° region, as summarized by Bouillon et al. (2008). Therefore, substantial mangrove-derived carbon is available for retention within the soil in the JRE mangrove. We thus hypothesized that mangrove restoration enhances the soil carbon stock and that the contribution of mangrove-derived carbon to the soil carbon increases with forest age. We also hypothesized that the effect of mangrove restoration on the soil OC content and stock is more relevant in the surface layers and decreases with soil depth.

2. Material and methods

2.1. Study area

The subtropical JRE, with an area of 106 km^2 and a total drainage area of 14,745 km^2, receives approximately $1.48 \times 10^{10}\,m^3$ of runoff annually, (Zheng et al., 2011), and ~74% of the annual runoff occurs in the wet season from April to September (Chen et al., 2012). The mean annual temperature is 20.9 °C, and the tides are semi-diurnal, with an average range of 4 m (Alongi et al., 2005). The majority of the primary mangrove forests in this area have been cleared because of aquaculture activity and sea wall construction. Mono-species restoration of *Kandelia obovata* Sheue, Liu & Yong sp. has been performed since the 1960s in the undisturbed non-vegetated flats located on the periphery of sea walls to protect the shoreline and compensate for mangrove loss.

In the present study, sampling was performed in June 2010 on the south bank of the JRE (Fig. 1) in three *K. obovata* forests planted in 1962 (48-year site, K48), 1986 (24-year site, K24) and 1998 (12-year site, K12) near Caoputou Village (24°24′N, 117°55′E). The total study area extended ~600 m along the coast, and the three forests were subject to comparable hydrological conditions. The mangrove soils are mainly composed of silt and clay, and the salinities adjacent to the mangroves range from 12 to 26 (Alongi et al., 2005). The three forests, all located in the high intertidal zone (Alongi et al., 2005), were ~40 m wide from the land-edge to the sea-edge, and similar forest structures (dominated by *K. obovata* with occasional *Aegiceras corniculatum* found under the canopy), chest height diameters and numbers of buttressed trees were observed in these forests. The mangrove forests in this study area were adjacent to non-vegetated mudflats at their seaward fringe, and only scattered *Cyperus malaccensis* Lam. var. *brevifolius* Bocklr. individuals were observed on the mudflat.

2.2. Plant and soil sampling

Three soil cores were collected from the interior zone of each mangrove site. The cores, each 3 m apart, were placed over clear soil surfaces between trees. PVC tubes (inner diameter: 70 mm) with metal cutters along their bottom edges (to cut through the soil and fibers and thus minimize the compaction) were manually inserted into the soils by gently twisting the tube to a depth of 100 cm. The sampling depth was set to 1 m because a minimum depth of 1 m is standard and has been applied in numerous studies for soil OC stock quantification (Howard et al., 2014; Wang et al., 2013; Sitoe et al., 2014; Marchand, 2017), although greater soil depth is recommended. A previous study found high C contents throughout the top meter of the soil profile, with a decrease below 1 m (Donato et al., 2011). Moreover, Alongi et al. (2005) found that the mangrove-associated silt-clays were limited to the upper 85 cm in a high intertidal mangrove adjacent to our study sites. The soil cores were sliced into subsections at 10-cm intervals in the laboratory. When core compaction occurred, the compaction ratio was used to correct the depth interval (Howard et al., 2014). Each of these subsections was weighed and then sliced into two halves, with one half oven-dried at 60 °C to determine the water content, and the soil bulk density (BD) was determined as a simple dry weight to volume ratio. After removing visible benthic animals, plant residues and stones (> 2 mm), the other half was air dried for subsequent analysis.

Similar to previous studies (Kuramoto and Minagawa, 2001; Fry and Smith, 2002; Bouillon et al., 2003; Kennedy et al., 2004), mangrove leaves were used to represent the mangrove carbon source in this study because the leaf fall accounts for the majority of litter fall production in these mangrove sites (Ye et al., 2013) and because mangrove leaves have a potentially high turnover rate (Chen et al., 2008; Li and Ye, 2014). At each site, 5 senescent mangrove leaves (with a yellowish color) were collected from different trees by gently shaking branches

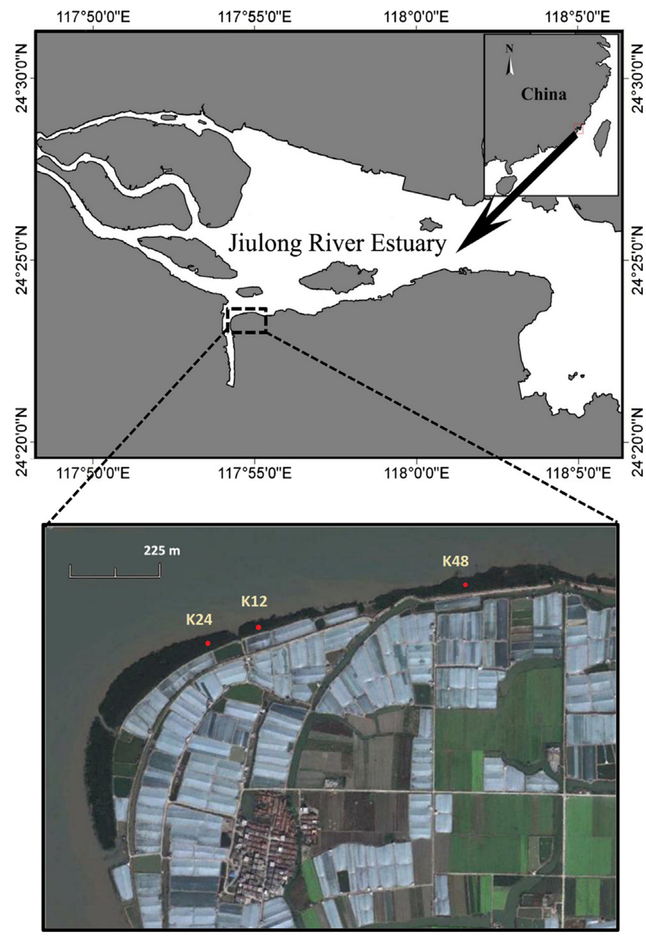

Fig. 1. Map of the Jiulong River Estuary, China, and the locations of the three restored mangrove sites. K12: 12-year site; K24: 24-year site; K48: 48-year site.