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The role of blue carbon stocks becomes more labile with mangrove development

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A R T I C L E I N F O

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A B S T R A C T

Soil labile organic carbon (LOC) is a crucial component in carbon cycling in coastal wetlands and serves as an important indicator of SOC. Despite this, little is known about the stabilization of SOC and its LOC during mangrove development. The objective of our study was to quantify SOC and LOC in the soil at depths ranging from 0 to 100 cm across four sites, including a mudflat and three mangrove sites of varying ages (15-, 45-, and 80-yr old) were selected in Yingluo Bay, China. The concentration of SOC, POC (particulate organic carbon), DOC (dissolved organic carbon), MBC (microbial biomass carbon), and $KMnO_4$-C (potassium permanganate-oxidizable carbon) were measured. The CMI (soil carbon management index) was also calculated to precisely and directly reflect the dynamic changes of soil carbon pools. Mangrove natural expansion showed a significant positive effect on both SOC and LOC. The concentration of $KMnO_4$-C in the top 50 cm of soil layer showed a significant increase in three different mangrove forest sites. The POC, DOC and MBC were also significantly increased in response to mangrove development. The 80-yr old mangrove site had the highest SOC concentrations, LOC concentrations, soil carbon lability Index (LI) and CMI among all sites. These findings suggested that the development of mangroves increases soil organic carbon fractions through vegetation production and enhances long-term carbon sequestration rates by expanding soil labile carbon pools. As a management option, promoting the natural expansion of mangroves can maximize the sequestration potential of soil organic carbon.

1. Introduction

The role of soil organic carbon (SOC) in sustaining soil quality, vegetation production, and environmental quality is crucial (Lal, 2004; Miles and Kapos, 2008). Keep it stabilization is a natural cost-effective and eco-friendly way to combat climate change and other adverse impacts (Simard et al., 2019; Keuper et al., 2020). Blue carbon refers to carbon stored and sequestered in coastal ecosystems (particularly in coastal vegetated habitats such as mangroves, salt marshes and seagrass meadows). These ecosystems are highly efficient at capturing and storing carbon dioxide (CO_2) from the atmosphere to the sediments, which helps mitigate climate change by reducing greenhouse gas concentrations (Nelleman *et al.*, 2009). Despite occupying only 0.5% of the world's coastal area, mangroves contribute 10–15% of the total carbon and play a crucial role in coastal soil carbon flux. (24 Tg C yr^{-1}) (Alongi, 2014; Jennerjahn, 2020; Ouyang and Lee, 2020). Mangroves are highly productive and have a significant capacity for storing carbon, while their soil can potentially store over 90% of the carbon (Donato et al., 2011; Hapsari et al., 2020), due to their capability to accumulate and preserve carbon within anoxic conditions caused by frequent tidal inundation.

While SOC accumulation has been recognized as a key factor in this regard, studies have also highlighted the importance of analyzing the

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dynamics of these specific carbon fractions in different regions. The dynamics of labile organic carbon (LOC), including POC, $KMnO_4$-C, DOC, and MBC, is crucial in assessing the impact of mangrove afforestation and natural expansion on climate change mitigation (Feng et al., 2019a; Feng et al., 2019b). Although the proportion of LOC within the total SOC pool may be relatively low, these labile fractions directly contribute to soil biogeochemical processes, making them significant components in the carbon cycling of ecosystems. SOC stocks are regulated by the equilibrium between carbon inputs and outputs from the soil. Vegetation biomass can influence both carbon input and output fluxes from ecosystems. (Tamooh et al., 2008; Cormier et al., 2015; Arnaud et al., 2021). Previous studies indicate that mangrove artificial afforestation and natural expansion can increase SOC sequestration by simultaneously decreasing carbon loss due to erosion and decomposition (Yu et al., 2020, 2021). Many studies have examined the changes in soil LOC following mangrove plantation. Wu et al. (2020) found that plantations of exotic species exhibited lower $KMnO_4$-C/SOC and MBC/SOC ratios compared to native species. For instance, in a 12-yr-old mangrove forest, the exotic species *Sonneratia apetala* showed greater stability in SOC pools than the native species *Kandelia obovata*. Cui et al. (2021) observed that the SOC increased with time in planted mangroves of different ages (1-, 5-, 10-, 15-yr- mangrove stands), while $KMnO_4$-C and DOC displayed an opposite trend. Furthermore, Zhang et al. (2021) and Yin et al. (2023) reported a positive correlation between landward distance and both LOC/SOC ratio, suggesting that newly expanded mangrove exhibited lower stability in SOC pools. The sources of SOC inputs from plant or root biomass to soil are mostly comprised of labile fractions (Yang et al., 2009; Sheng et al., 2015). Utilization of LOC by microorganisms could stimulate the decomposition of SOC, greenhouse gas emissions, resulting in a decrease in the stability of the SOC pools because LOC inputs are more prone to rapid decomposition, potentially leading to a decrease in the long-term storage of C in the soil. (Osland et al., 2020; Yin et al., 2023). Recent studies obtained different results for LOC with mangrove forest ages or locations, including mangrove forest age, relative position, soil depth, and vegetation biomass (Gress et al., 2017; Walcker et al., 2018). Although LOC are sensitive to environmental changes and are important for assessing the potential carbon equestration, knowledge on mangrove natural expansion concerning LOC is poor.

Although carbon sequestration is an important ecosystem service of mangrove, the accumulation of SOC and LOC is a time-dependent process (Carnell et al., 2022). Therefore, it is crucial to accurately evaluate the community development and its impact on the stability of carbon pools (Santos-Andrade et al., 2021). Typically, young or growing forests sequester more atmospheric CO_2 in their living biomass than mature forests (Casal-Porras et al., 2022), and the net carbon sequestration follows a predictable pattern based on the forest's age (Adame et al., 2018a; Adame et al., 2018b), while the effect of mangrove age on carbon storage capacity and stability have not fully explored (Walcker et al., 2018; Kauffman et al., 2020). Our study involved the investigation of SOC and LOC in three mangrove forests of different ages (15-yr, 45-yr, and 80-yr) and mudflat to test the following two hypotheses: (1) natural expansion of mangroves results in a significant increase in SOC, but it may become more labile in the 0–50 cm soil layers; (2) Long-term natural mangrove forests will lead to significant enhancements in LOC sequestration. The information is vital in evaluating the effectiveness of

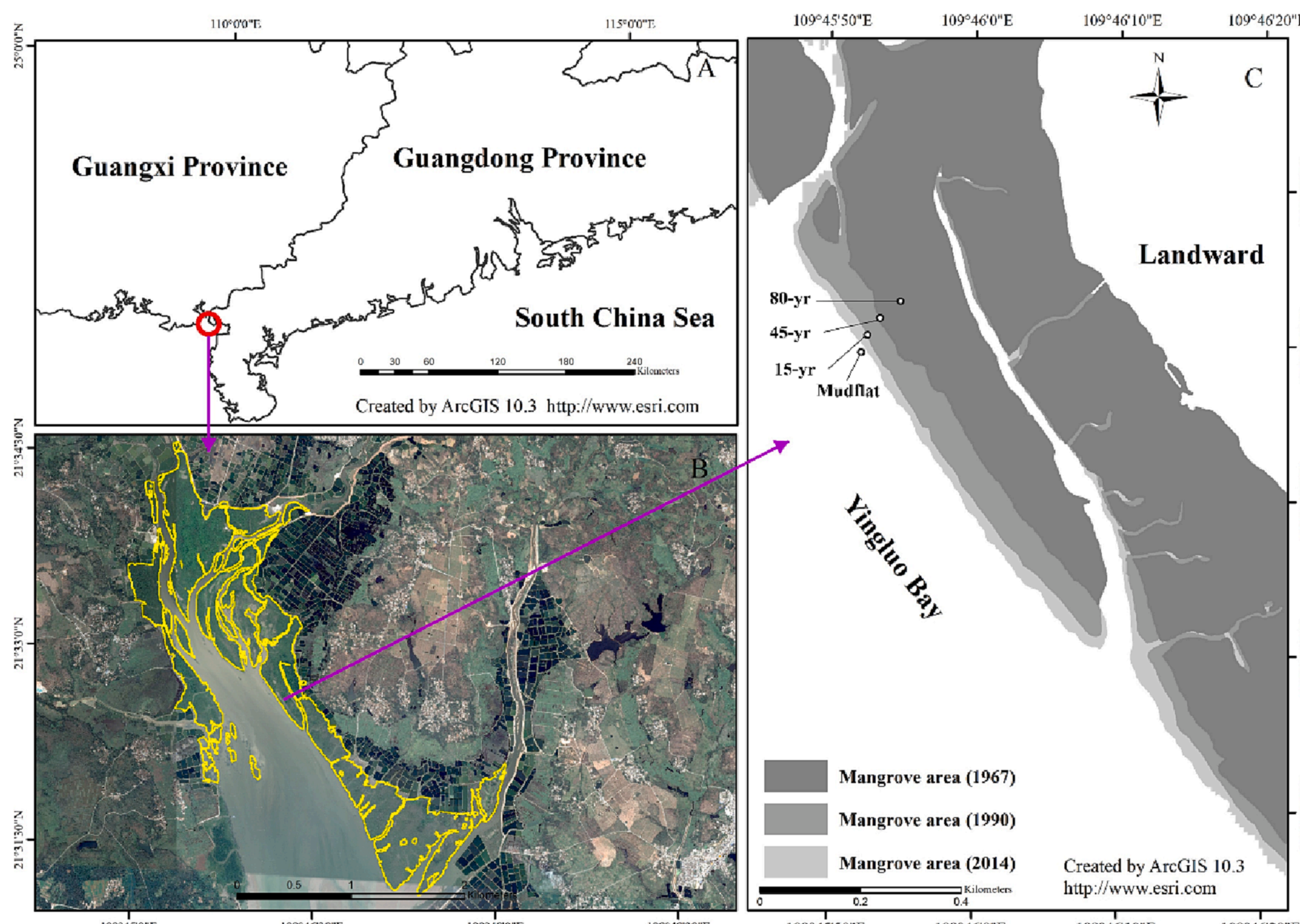

Fig. 1. Study site in Yingluo Bay, China.

protection and plantation programs in China's coastal regions.

2. Methods and materials

2.1. Study site and methods

The study site is situated on the east coast of Yingluo Bay (Fig. 1A) in Zhanjiang Mangrove Nature Reserve, China (E: 109°37′-109°47′, N: 21° 28′-21°37′). The region comprises more than 742 ha that are relatively undisturbed by human activities mangrove forests (Cui et al., 2018). The mangroves grow on a mudflat (Yu et al., 2021) and experience a subtropical climate with average air temperature fluctuations and rainfall ranging from 1400 to 1900 mm per year. The primary rainfall season is from late March to early September, and the tides are mixed irregular diurnal with a mean tidal range of 2.5 m, and mangroves are the dominant species in this region (Zhang et al.,2021).

In this study, we employed involved analyzing satellite images to assess Yingluo Bay and map the distribution and age of mangrove forests. Specifically, we utilized three satellite images: KH-4B (dated 17 December 1967), Landsat TM5 (dated 11 October 2000), and ZY-3 (dated 2 January 2014), which were obtained from various sources. To generate the distribution map of mangrove age, we utilized ArcGIS 10.3 software. Boundary information was extracted from the three remote sensing images by interpreting the mangroves and their spatial expansion. Essentially, a map was created to showcase the evolution of the coastline over time, along with the distribution of mangrove forests (Fig. 1).

The mapping process involved layering the most recent 2014 map (Fig. 1B) over the 2000 map and repeating the same stepwise procedure, going back to the oldest available image from 1967. Only the parts of the map that remained consistent across all previous steps were retained in each iteration. This process ultimately resulted in a final map that represents the "theoretical ages" of the mangrove forests.The ages of the 15-yr and 45-yr mangrove stands were determined based on the map, while the position of the 80-yr mangrove stands was determined using information from literature and local data.

2.2. Sampling and processing

Similar to our previous studies (Yu et al., 2021), Mangrove communities consisting are typically found along coastlines in a parallel distribution. By using remote sensing techniques to determine the ages of mangroves, different stages of mangrove development can be identified based on their structural and biological characteristics (as depicted in Fig. 1C). Within each plot, measurements and calculations were taken of tree density, height and stem diameter at breast height, AGB (above-ground biomass), BGB (below-ground biomass), TFB (total biomass), and collected litterfall and fine-root of the plots was calculated. The litterfall and fine-root (included live and dead) samples could be dried using an oven set at 60 °C, and the dried samples represents the biomass.

In May 2014, soil samples were collected from each plot using a 5.0 cm diameter auger, and separated into seven layers (0–100 cm) based on depth. After removing plant debris and roots, the samples were divided into two parts. The first part, fresh soil samples stored at 4 °C for analysis of DOC and MBC. The second part of each sample was air-dried at room temperature and used for analysis any other soil properities. Furthermore, another soil core was collected from each plot using stainless steel cylinders for the purpose of soil bulk density (BD) analysis.

2.3. Soil analysis and data calculation

The Mastersizer 2000 particle-size analyzer was used to analyze soil particle-size distributions. Soil pH and salinity were measured by extracting the samples with distilled water at a water-to-soil ratio of 5:1 for salinity and 2.5:1 for pH, and analyzed using a multiple parameter water analyzer. SOC concentration was quantified using the $K_2Cr_2O_7$ wet oxidation method. In order to reduce the effect of chloride ions on the combustion results, silver sulfate (about 0.1 g Ag_2SO_4) was added before sulfuric acid (H_2SO_4) (Yu et al., 2021). while the soil total nitrogen (TN) concentration was determined using the Kjeltec 2300 unit. To determine the DOC concentration, fresh soil was mixed with deionized water at a ratio of 1:5 (w/v), and the DOC concentrations was measured using an automated Shimadzu TOC-VCPH Analyzer (Japan). (Ghani et al., 2003). The $KMnO_4$-C concentration was measured using $KMnO_4$ solutions were added to 1.0 g soil samples to construct standard curves, assuming that the oxidation of 0.75 mmol/L (9.0 mg) of carbon consumed 1.0 mmol/L of $KMnO_4$. (Blair et al., 1995; Yin et al., 2023).

To measure POC, 20 g of air-dried soil were mixed with 70 ml of $Na_4P_2O_7$ (5 g/L) and shaken on a centrifuge for 18 h. The resulting soil suspension was poured over a 53-μm sieve and dried in an oven at 60 °C for 48 h, and ground to determine the carbon concentration (Cambardella and Elliott, 1992; Six et al., 2002). The MBC concentration was measured using the fumigation-extraction method on 50 g of treated soil samples, extracted MBC concentration was calculated as (fumigated SOC - non fumigated SOC)/0.38(Vance et al., 1987).

CMI is a reliable measure of changes in SOC dynamics (Blair et al., 1995), and the CMI values was determined for three age categories of mangrove forests using the mudflat as follows:

$$CMI = CPI \times LI \times 100\%;$$

$$CPI = Three\ sample\ plots\ SOCC / mudflat\ SOCC \times 100\%;$$

$$LI = Three\ sample\ plots\ KCC / mudflat\ KCC \times 100\%;$$

$$L = KCC / (SOCC - KCC) \times 100\%;$$

L: Labile carbon pool index, %; Labile carbon pool index, %; CPI: Carbon pool index, %; CMI: Carbon pool management index, %; SOCC: SOC concentration, g kg^{-1}; KCC: $KMnO_4$-C concentration, g kg^{-1}.

2.4. Statistical analysis

SPSS 19.0 software was utilized to analyze the data. The impact of natural expansion on soil BD, SOC concentrations, stocks, and LOC at each soil layer was assessed using one-way ANOVA. Two-way ANOVA was employed to evaluate variations in SOC concentrations and stocks, as well as LOC, with mangrove expansion and soil layers as fixed factors. The least significant difference test was used for mean comparisons at a significance level of $p < 0.05$.

3. Results

3.1. Vegetation and environmental factors

Study sites comprise of mixed mangrove forests, including 15-yr-old mangrove dominated by *A. marina* and *A. corniculatum*, 45-yr-old mangrove consisting of *A. corniculatum*, *A. marina*, and *K. obovata*, 80-yr-old mangrove composed of *A. marina*, *A. corniculatum*, and *R. stylosa*. The TFB of 80-yr was 289.9 ± 18.33 Mg ha^{-1} significantly higher than those of 45-yr and 15-yr (Table 1). TFRB and LB (litterfall biomass) exhibited a similar pattern to TFB. The TFRB (Table 1) of the 80-yr oldwas significantly greater than that of the 15-yr and 45-yr old ($p < 0.05$). However, the increases in LFRB (live fine-root biomass) and DFRB (dead fine-root biomass) accounted for only 3.69% and 4.60% of the TFB (total fine-root biomass) increment, respectively.

Total N concentration increased the proportion of 23% in 80-yr than mudflat (Fig. 2A). Soil bulk density decreased from the mudflat to the mature forest, respectively (Fig. 2B). The 80-yr old mangrove showed the lowest mean soil pH values (Fig. 2D, 4.89 ± 0.62, $p < 0.05$) of the 0–100 cm and the highest salinity values (7.11 ± 1.07 ppt, $p < 0.05$). Soil texture (Fig. 2E-G) was predominated by silt (Fig. 2F) in mangroves,

Table 1
Characteristics of vegetation in mangrove stands of varying ages. Distinct lowercase letters denote a significant difference at $p < 0.05$ among forests of different ages. Values represent the mean ± standard deviation for a sample size of n = 3.

Biomass component	15-yr old	45-yr old	80-yr old
AGB (Mg ha^{-1})	$29.64^c \pm 5.16$	$84.17^b \pm 11.59$	$205.33^a \pm 13.56$
BGB (Mg ha^{-1})	$21.34^b \pm 3.67$	$34.40^b \pm 5.75$	$84.57^a \pm 4.84$
TFB (Mg ha^{-1})	$50.98^b \pm 8.82$	$116.56^b \pm 17.32$	$289.9^a \pm 18.33$
LB (Mg ha^{-1})	N/A	0.69 ± 0.07	1.01 ± 0.22
LFRB (Mg ha^{-1})	$2.35^b \pm 0.12$	$3.37^{ab} \pm 0.46$	$3.93^a \pm 0.79$
DFRB (Mg ha^{-1})	$0.03^b \pm 0.09$	$2.7^b \pm 0.13$	$9.11^a \pm 0.52$
TFRB (Mg ha^{-1})	$2.65^b \pm 0.07$	$5.07^b \pm 0.59$	$13.04^a \pm 1.31$

and the sand content (Fig. 2G) was significantly higher and silt/clay (Fig. 2E-F) content was lower in mudflat than in mangroves ($p < 0.01$).

3.2. Change in SOC concentration and SOC stocks

SOC concentration increased with forest age (Fig. 3), The mudflat had the lowest mean value of 13.58 ± 2.91 g kg^{-1} ($p < 0.01$), while the 80-year-old forest had the highest mean value of 37.58 ± 5.73 g kg^{-1} ($p < 0.01$). At all sites, the highest total SOC stockswere observed in the top 50 cm soil layer (53.82 ± 7.40 Mg ha^{-1}, 72.09 ± 3.57 Mg ha^{-1}, 111.28 ± 4.21 Mg ha^{-1} and 121.78 ± 4.21 Mg ha^{-1} for mudflat, 15-, 45-, 80-yr old stands, respectively, $p < 0.05$).

3.3. Proportions of LOC fractions to SOC

After the conversion of mudflat into mangrove, the LOC concentrations were all significantly increased ($p < 0.05$, Fig. 4). The average maximum POC (21.28 ± 3.60 g kg^{-1}), $KMnO_4$-C (2.30 ± 0.72 g kg^{-1}) and MBC (2.46 ± 0.76 g kg^{-1}) concentrations all occurred in the 80-yr, while the highest DOC concentration (166.75 ± 36.37 mg kg^{-1}) was found in the 45-yr ($p < 0.05$).

POC had the highest proportion among the LOC (Fig. 4A), the proportion was approximately 55% in mangroves, and the percentage of POC (27%) concentrations at the mudflat were relatively lower than in the mangroves ($p < 0.01$), corresponding to their higher silt–clay content. The difference in POC concentration at the depth of 0–40 cm between the 45-yr and 80-yr were not significant. The concentration of $KMnO_4$-C for 0–100 cm layer in 80-yr old were 2.8, 3.15 and 8.52 times higher than those of 45-yr, 15-yr and mudflat. MBC and DOC concentrations in the mudflat were only 12.01–29.52% and 31.10–64.14% of those found in the mangroves, respectively.

At all sites, there was a decrease in the proportion of LOC to SOC with increasing soil depth (Fig. 3A). As a general trend, the proportions of POC, $KMnO_4$-C, DOC and MBC to SOC increased in the order of mudflat < 15-yr < 45-yr < 80-yr, and the concentrations of labile soil carbon pools at mangrove forest increased in the order: DOC < MBC < $KMnO_4$-C < POC (Fig. 5).

LOC fractions were positively related to SOC, TN, and salinity, while they were negatively related to pH and bulk density (Fig. 2). A limited correlation was observed between soil LOC and BD, while a significant association was found between LOC and TN (Table 2).

3.4. Carbon management index

Significant variations were observed among natural mangrove stands of different ages and mudflats in each soil layer for CMI, CPI, and LI values (refer to Table 3). The progression of CMI changes among the three natural mangrove stands and mudflat increased in the following sequence: mudflat < 15-yr < 45-yr < 80-yr, with values ranging from 100 to 1330.88 in the 0—100 cm soil layers.

4. Discussion

4.1. Effect of mangrove development on SOC

The allocation of SOC storage could be affected by forest age and soil depth (Lunstrum and Chen, 2014). In our study, it was shown that the SOC concentration and stocks tended to rise with forest age (Fig. 3A&B), and with the topsoil layer (0–10 cm) exhibiting the highest value. These variations can reasonably be attributed to differing levels of biomass (include vegetation, fine-root, litterfall etc.) returned to the soil (Charles et al., 2020; Arnaud et al., 2021; Rovai et al., 2021; Meng et al., 2022), due to that the fine-root biomass and litterfall is the primary sources of SOC in 0–10 cm soil (Liu et al., 2017), consisting 75% and 95% of the accumulated soil organic materials (Lawrence and Zedler, 2013). In our study, the 80-yr sites had the greater fine-root and vegetation biomass amounts with the largest SOC stocks, while the 15-yr sites had the lowest biomass and SOC stocks (Fig. 3), which was in agreement with our first hypothesis. Therefore, it is suggested that mature mangrove forest has a more conservative carbon-use strategy than young mangrove forest. This finding can be attributed to the fact that as mangrove forests mature, the biomass of the vegetation increases, resulting in greater production of mangrove litterfall. Previous studies have indicated that fine roots of mangrove trees are the primary contributors to SOC accumulation (Liu et al., 2017; Zhang et al., 2021). The higher belowground fine-root biomass in mature mangrove forests with the increases of primary production, leading to a greater accumulation of SOC (Tian et al., 2019; Ouyang and Lee, 2020).

4.2. Effect of mangrove development on LOC

Our second hypothesis posited that the age of a forest significantly impacts the concentration of soil LOC (Cui et al., 2021). This aligns with our observations that the LOC varied among different mangrove forest age treatments and soil depths, that the natural expansion of mangroves not only increases SOC but also leads to higher levels of LOC (Fig. 3) Numerous other studies had demonstrated how the quantity of SOC determines the LOC in mangrove soils (Yin et al., 2023). Firstly, the biomass inputs from fine-root and litterfall biomass may directly contribute to the LOC as the forest ages increase (refer to Table 1 and Fig. 4). Secondly, the greater biomass in mature mangrove forests may lead to increased microbial activity, resulting in a greater conversion of organic matter from litterfall and fine roots into more labile forms of SOC (Liu et al., 2017; Ahmed et al., 2021).

The CMI values serve as a valuable tool for evaluating shifts in soil system dynamics (Deere et al., 2018). Variations in CMI values observed across different soil management techniques can be attributed to changes in the quality of organic matter, which can impact the lability of carbon and its susceptibility to $KMnO_4$ oxidation (Tirol-Padre and Ladha, 2004). The CMI values serve as an indicator of whether an ecosystem is deteriorating or recovering (Blair et al., 1995). Our study revealed that the CMI and LI values for the mudflat indicated degradation, while natural expansion of the mangrove forest result in an increase in $KMnO_4$-C as a percentage of SOC. Generally, 80-yr mangrove stands had the highest CMI and LI values in each soil layer, indicating more soil labile carbon fractions, leading to higher CMI and LI values. Futhermore, with the increase in age of the mangrove forest, there was a corresponding increase of $KMnO_4$-C as a percentage of total SOC, positively contributed to the CMI and LI values. These indices explain why mangrove natural expansion not only increases SOC, but also leads to greater soil LOC (Zhang *et al.*, 2009).

The SOC is primarily influenced by the rate of vegetation growth and decomposition (Xiong et al., 2017). POC refers to the decomposition of plant debris and dead fine roots that have a rapid turnover rates, aligning with the properties of SOC concentrations (Feng et al., 2019a; Feng et al., 2019b). Thus, the POC values were considerably lower in the mudflat compared to the three mangrove forest sites (Fig. 4A) and the

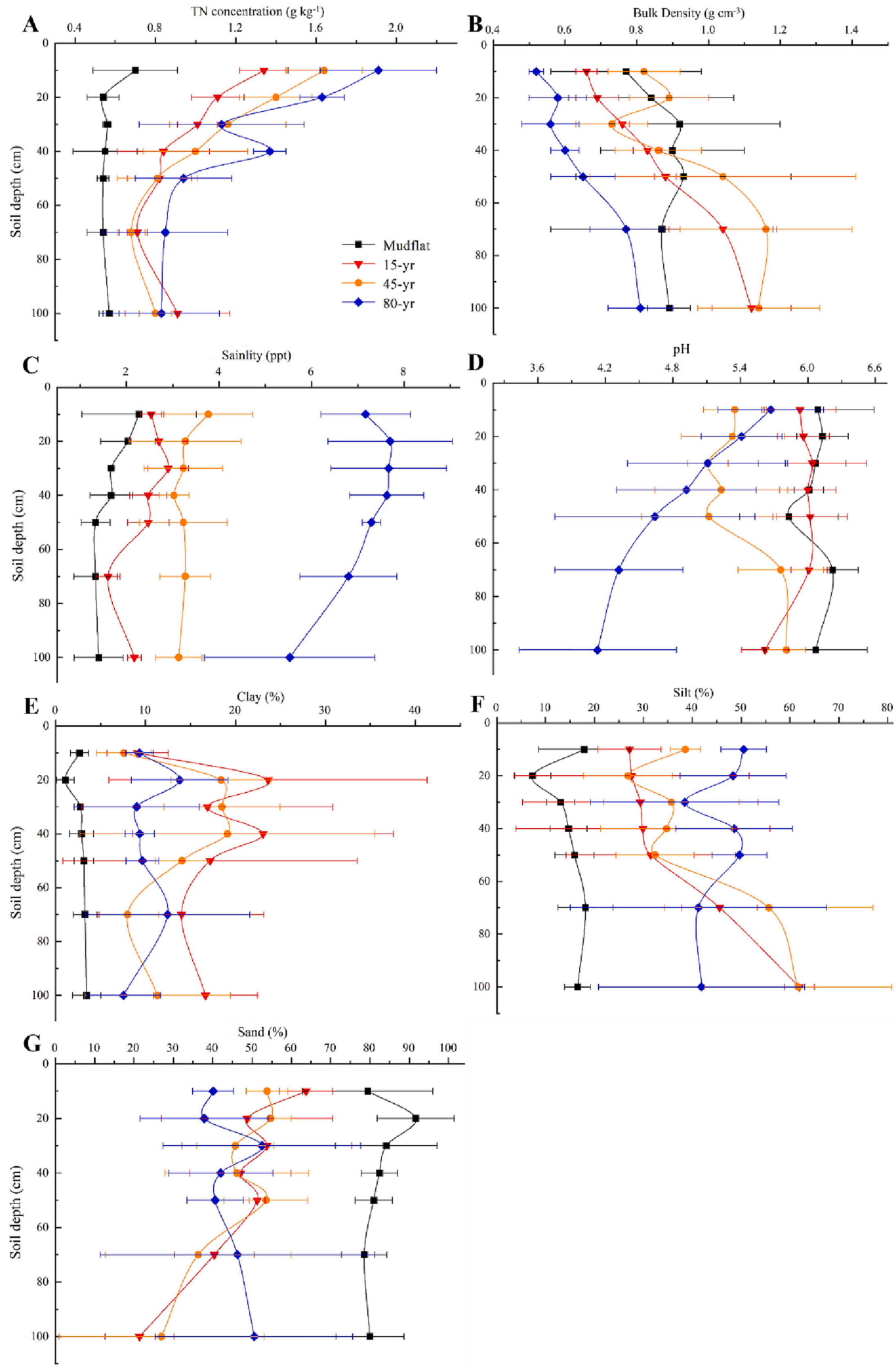

Fig. 2. Vertical distribution of (A)TN concentration; (B)Bulk density; (C)Salinity; (D)pH; (E)Clay; (F)Silt and; (G) Sand in the 0–10, 10–20, 20–30, 30–40, 40–50, 50–70, and 70–100 cm soil layers under different mangrove forest age sites. The values mean ± SD error (n = 3).

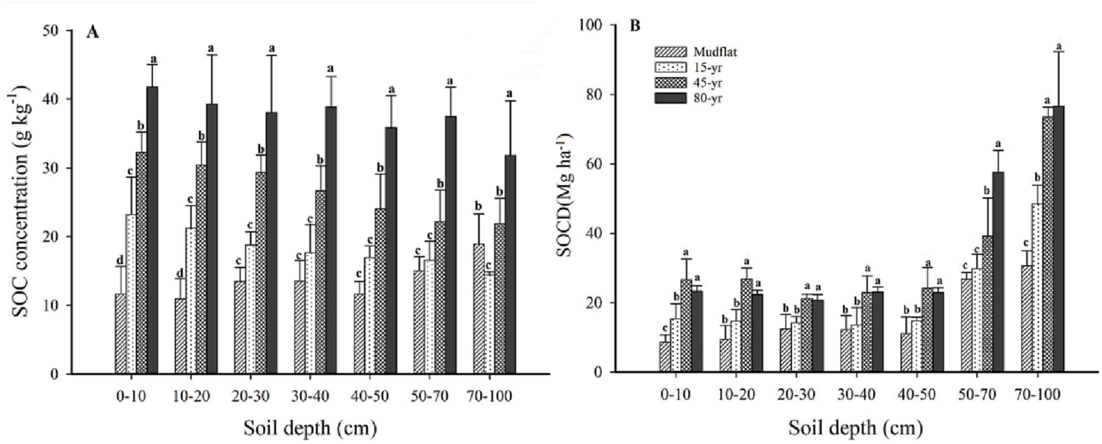

Fig. 3. (A) SOC concentration and (B) SOC stocks (SOCD) for different age categories of mangrove forests are presented. Different lowercase letters indicate significant differences among zones ($p < 0.05$).

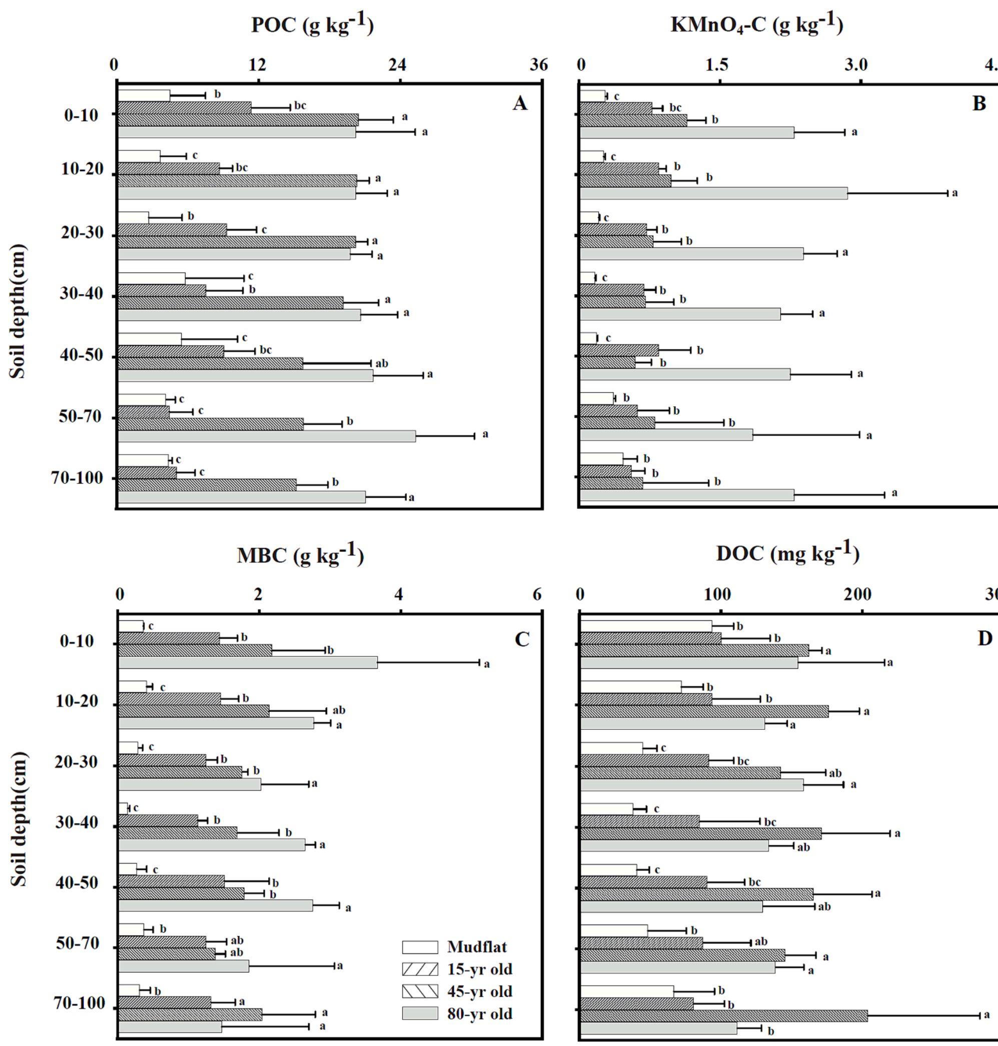

Fig. 4. (A) POC concentration; (B) $KMnO_4$-C concentration; (C) MBC concentration) and (D) DOC concentration in the 0–10, 10–20, 20–30, 30–40, 40–50, 50–70 and 70–100 cm soil layers under different age mangrove. Different lowercase letters in the same soil layer indicate a significant difference at $p < 0.05$ among the mangrove forest age. The values mean ± SD error (n = 3).

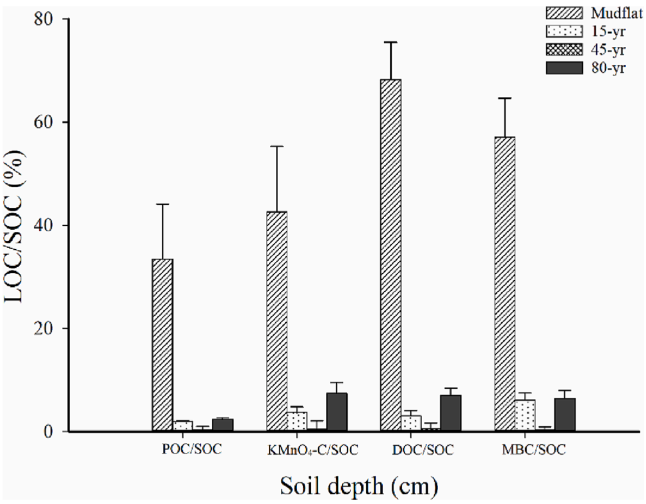

Fig. 5. The average ratio of LOC accounting for SOC in different mangrove forest age. The values mean ± SD error (n = 3).

Table 2
Pearson's correlation coefficients relating LOC fractions and environmental factors.

LOC	SOC	TN	pH	Salinity	Bulk Density
POC	0.785**	0.690**	−0.736**	0.622**	−0.349*
MBC	0.747**	0.731**	−0.460**	0.727**	−0.340*
DOC	0.535**	0.355*	−0.385*	0.218*	−0.119
$KMnO_4$-C	0.699**	0.768**	−0.622**	0.834**	−0.483**

* Significance at $p < 0.05$; ** Significance at $p < 0.01$.

80-yr mangrove forest exhibited the highest levels of POC owing to its higher biomass (AGB, BGB, fine-root and litterfall). MBC and DOC are produced by the decomposition of SOC, which is mainly facilitated by soil microorganisms (Li et al., 2021). Although they consitute only a small fraction of SOC, MBC and DOC are often regarded as crucial indicators of soil nutrient cycling. In our study, MBC accounted an average of 7.10–7.78% of SOC, while DOC accounted for an average of 0.31–0.46% of SOC (Davies et al., 2017; Jilkova *et al.*, 2020). Mangrove forest natural expansion onto the mudflat resulted in a significant increase in MBC and DOC, as shown in Fig. 4C and 4D. These findings suggest that the expansion of mangrove forests had a positive impact on the activity of microorganisms, likely due to the provision of an available source of carbon substrate (Yu et al., 2020).

4.3. Effects of environmental factors on LOC

Soil TN is a crucial environmental factor that can limit vegetation growth, thus, the availability of soil TN played great role in carbon cycling in mangrove soils (Mckee and Rooth, 2008). The soil TN is significantly related to the source of POC, with a correlation coefficient of 0.690 ($p < 0.01$). In our study, during the natural expansion process of a mangrove forest, from mudflat to 80-yr mangrove stands, DOC, KMnO4-C, MBC and POC has increased by 63.19%, 415.64%, 631.03%, and 535.17%, respectively. As mangroves naturally expand, the vegetation biomass and the amount of plant return material increased. leading to an increase in soil TN, which in turn alleviates microbial nitrogen restriction and promotes the growth of LOC and vegetation biomass (Laanbroek et al., 2018; Huang et al., 2022).

Soil salinity is correlated with tidal frequency and the age of mangrove (Wu et al., 2020). Higher tidal frequency and age increase soil salinity. As soil salinity increases, microbial activity is inhibited, and SOC in soil is less likely to be decomposed by microorganisms, resulting in better accumulation (Wang et al., 2019). Ha et al. (2018) found that under higher salinity accelerated the decomposition rate of litterfall, but weakened soil decomposition, hindering the formation of CO_2 and CH_4, and resulting in SOC accumulation.

Soil BD was found to be negatively correlated with $KMnO_4$-C ($p < 0.01$, $R^2 = 0.483$), POC ($p < 0.05$, $R^2 = 0.349$), and MBC ($p < 0.05$, $R^2 = 0.340$), and this relationship partly explained the variability of LOC (Table 2). Previous research has shown that soils with lower BD tend to store more SOC due to greater mobilization of SOC along the pores within the soil structure (Ola et al., 2018). Lower soil BD typically contain higher levels of POC and macro-aggregates, leading to increased soil microbial activity and improved fine root growth. On the other hand, more compacted soils may hinder the process of carbon mineralization (Castillo et al., 2017; Wang et al., 2021). Soils have lower BD, higher SOC, larger fine-root biomass, and greater soil porosity typically have higher LOC fractions. This is exemplified by comparing the soils of the 80-yr old mangrove forest with those of other sites, as the former had lower BD value and higher LOC fractions. In addition to these factors, soil pH is also a key environmental factor that can influence the distribution of microorganisms involved in carbon cycling in the soil (Huang et al., 2022). Soil pH is a crucial factor in numerous chemical processes that occur in the soil. This is particularly important for mangroves, which are periodically inundated and play a significant role in redox and sorption processe (Adame et al., 2018a; Adame et al., 2018b; Sasmito et al., 2020), which may be responsible for the significant negative correlation of pH with MBC and POC.

Table 3
The CMI changes across different soil layers for three age categories of mangrove forests are presented. The values represent the mean ± SD for a sample size of n = 3. Lowercase letters within the same soil layer indicate a significant difference at $p < 0.05$ among the different forest ages. The abbreviations CPI and LI stand for carbon pool index and lability index, respectively.

Index	Layers (cm)	Mudflat	15-yr old	45-yr old	80-yr old
CMI	0–10	100^{c}	284.60^{bc} ± 56.21	414.06^{b} ± 48.12	852.16^{a} ± 255.18
	10–20	100^{b}	336.37^{b} ± 24.15	388.36^{b} ± 119.53	1246.3^{a} ± 647.17
	20–30	100^{c}	338.44^{bc} ± 52.86	372.52^{b} ± 161.45	1163.62^{a} ± 195.38
	30–40	100^{b}	416.78^{b} ± 81.45	436.28^{b} ± 210.47	1330.88^{a} ± 301.53
	40–50	100^{b}	473.90^{b} ± 205.55	326.22^{b} ± 101.77	1260.30^{a} ± 423.87
	50–70	100^{a}	161.79^{a} ± 81.70	233.09^{a} ± 134.74	497.50^{a} ± 310.40
	70–100	100^{b}	120.02^{b} ± 10.66	207.68^{ab} ± 176.06	519.91^{a} ± 193.72
CPI	0–10	1.00^{d}	2.47^{c} ± 0.56	3.63^{b} ± 0.14	4.75^{a} ± 0.47
	10–20	1.00^{c}	2.39^{bc} ± 0.35	3.84^{ab} ± 0.58	4.53^{a} ± 1.61
	20–30	1.00^{c}	2.51^{b} ± 0.47	4.27^{a} ± 0.97	4.90^{a} ± 0.95
	30–40	1.00^{c}	2.84^{bc} ± 1.00	4.02^{ab} ± 1.21	5.39^{a} ± 1.72
	40–50	1.00^{c}	2.41^{bc} ± 1.02	3.72^{ab} ± 2.01	5.32^{a} ± 1.28
	50–70	1.00^{b}	2.08^{b} ± 0.67	2.53^{ab} ± 1.05	4.46^{a} ± 1.76
	70–100	1.00^{b}	1.92^{ab} ± 0.35	2.89^{ab} ± 1.25	3.60^{a} ± 1.73
LI	0–10	1.00^{b}	1.20^{ab} ± 0.40	1.14^{ab} ± 0.13	1.84^{a} ± 0.69
	10–20	1.00^{a}	1.43^{a} ± 0.27	1.00^{a} ± 0.19	3.47^{a} ± 2.21
	20–30	1.00^{b}	1.36^{b} ± 0.14	0.89^{b} ± 0.39	2.46^{a} ± 0.80
	30–40	1.00^{b}	1.59^{ab} ± 0.54	1.24^{ab} ± 0.81	2.73^{a} ± 1.35
	40–50	1.00^{b}	1.97^{a} ± 0.39	0.97^{b} ± 0.37	2.36^{a} ± 0.43
	50–70	1.00^{a}	0.75^{a} ± 0.14	1.20^{a} ± 0.41	1.11^{a} ± 0.40
	70–100	1.00^{a}	0.64^{a} ± 0.11	1.21^{a} ± 0.85	1.80^{a} ± 1.11

5. Conclusion

Our study clearly demonstrates that mangrove development significantly increases the concentrations and stocks of SOC, as well as the LOC such as POC, $KMnO_4$-C, MBC, DOC, LI and CMI, when compared to the mudflat in Yingluo Bay. We found that the 80-yr old mature mangrove forest had the greatest carbon benefits among the three forests, attributed to its high biomass and fine-root inputs. However, although the development of mangroves increased SOC, it also resulted in greater amounts of soil LOC fractions in mangroves. However, it has been pointed out that the method we used to measure the TOC and LOC has some defects, such as that the wet oxidation could oxidize some refractory DOC that is not readily available to microorganisms (Jiao et al., 2021). Therefore, future studies using alternative methods can provide more robust results. Protecting mature mangroves, with their high labile SOC fractions, is important for managing SOC accumulation in natural mangroves. Promoting the natural expansion of mangroves can be considered a viable option for enhancing carbon sequestration and mitigating the impacts of climate change, thereby contributing to climate change mitigation efforts and supporting sustainable coastal management.

CRediT authorship contribution statement

Chenxi Yu: Methodology, Data curation, Formal analysis, Writing – review & editing. **Jianxiang Feng:** Writing – review & editing. **Weizhong Yue:** Writing – review & editing. **Long Wei:** Writing – review & editing. **Yu Ma:** Writing – review & editing. **Xiaofang Huang:** Writing – review & editing. **Juan Ling:** Writing – review & editing. **Junde Dong:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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