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Research Paper

Variation and influences of soil organic carbon stocks after mangrove restoration in Qinglan Bay, Hainan: intertidal gradient, soil depth, and physicochemical properties*

Zhanjun QUAN[1, #], Xiongjie GU[1, #], Tianyang LI[1], Quanwei LI[2], Jianming DENG[3], Shuguo LÜ[4], Yanpeng ZHU[1, 4], Lihui AN[1], Feifei WANG[1, **]

[1] *State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing 100012, China*

[2] *Anhui Research Academy of Ecological and Environmental Sciences, Hefei 230088, China*

[3] *College of Ecology, Lanzhou University, Lanzhou 730000, China*

[4] *Hainan Research Academy of Environmental Sciences, Hainan 570100, China*

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Abstract To protect mangrove ecosystems and mitigate area decline, effective restoration and conservation have been implemented. Quantifying how intertidal positions and variations in soil depth jointly affect the spatial heterogeneity of soil carbon pools in restored mangrove areas is essential for mangrove ecosystem restoration. Despite restoration efforts, a systematic evaluation of soil organic carbon storage (SOCS) is still lacking in Qinglan Bay. Thus, 3-year-old artificially restored mangroves were selected, and 30-year-old natural mangroves with similar physical and geographic conditions were chosen as control. The study indicates that driven by the synergistic effects of surface and subsurface root distribution, shallow sedimentary characteristics, and tidal hydrodynamics, SOCS within the (0–30)-cm soil layer did not exhibit significant vertical differentiation. Consequently, a relatively homogenized distribution pattern emerged within this depth range. Notably, during the early stages of mangrove ecosystem restoration, soil organic carbon accumulation was first observed in the low intertidal zone. This finding suggests that low-intertidal soils warrant intensive monitoring as key indicators during the initial phases of restoration. Moreover, soil salinity positively correlated with SOCS and initially increasing. As mangroves mature, the degree of soil acidification, salinity, and the content of fine soil particles increase. The results contribute to further elucidating the mechanisms underlying mangrove carbon sequestration and provide a scientific basis for the protection of carbon sink resources, thereby establishing SOCS as a key indicator for evaluating the effectiveness of artificial mangrove restoration.

Keyword: mangrove; soil organic carbon; soil organic carbon storage (SOCS); carbon storage; intertidal zone; coastal restoration

1 INTRODUCTION

Mangrove ecosystems are coastal wetlands consisting of woody vegetation that occur in tropical and subtropical intertidal zones (Ellison et al., 2020; Kauffman et al., 2020; Yang et al., 2024). Mangroves are anaerobic due to periodic inundation by seawater, which causes slow decomposition and better fixation of organic carbon from both terrestrial and marine sources (Alongi, 2020; Maxwell et al., 2024). The sources of organic carbon storage in mangrove ecosystems included both vegetation and soil stocks, with soil organic carbon (SOC) constituting the dominant portion (Alongi, 2020; Kauffman et al., 2020). For instance,

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** Corresponding author: wangfeifei826@126.com

# Zhanjun QUAN and Xiongjie GU contributed equally to this work and should be regarded as co-first authors.

the total carbon stock of mangrove ecosystem in Leizhou Peninsula reached 962.96±119.22 Gg, with 81.30% sequestered in soil and others in vegetation (Liao et al., 2025). However, the mangrove ecosystems have been seriously damaged, owing to the threat of natural factors and human activities (Shi et al., 2021). It was estimated that 20%–35% of global mangrove area has been lost (Polidoro et al., 2010; Carugati et al., 2018). Research in northwestern Madagascar comparing intact and deforested mangrove plots found that deforestation disturbed the upper 40 cm of soil, leading to a significant loss of carbon, and the carbon loss rate 4.5 times higher than the sequestration rate of intact soil (Arias-Ortiz et al., 2021). To protect mangrove ecosystems and mitigate the decline in mangrove area, various restoration measures have been implemented worldwide, including China (Friess et al., 2019; Ellison et al., 2020; Li et al., 2022; Song et al., 2023; Zeng et al., 2024). Therefore, discussing the response of SOC and soil organic carbon storage (SOCS) to the restoration projects after their implementation is of great significance for mangrove restoration management.

Mangroves enhance the capacity to capture carbon within sediments and effectively promote carbon sequestration and storage through ecological restoration (Veenstra et al., 2021; Morris et al., 2023). In northeastern Brazil, soil carbon in mangroves 3 and 7 years post-planting exhibited a significant upward trend compared to degraded areas, confirming the key role of mangrove vegetation in driving carbon capture (Jimenez et al., 2021). Similar to this finding, the particulate organic carbon (POC) content in restored mangroves at Qi'ao Mangrove Wetland Park, China, was also significantly higher than that in the mudflats (Huang et al., 2025). Further research indicates that, in terms of vertical distribution, carbon in recovering areas is primarily concentrated in the surface soil layer (Eid and Shaltout, 2016). The distribution and sequestration of SOC in mangrove ecosystems are jointly regulated by multiple factors, including climate (Bouillon et al., 2008), topography (Bouillon et al., 2008), and anthropogenic activities (Ruiz et al., 2024). Mangroves are mainly distributed in intertidal wetland between mean sea level and the highest astronomical tide (Alongi, 2008; Rogers et al., 2019). The periodic rise and fall of tides define the core spatial boundaries of the intertidal zone (from high to low tidal level), and its dynamic rhythmic of inundation and exposure influencing the distribution and growth of mangroves (Kirwan and Megonigal, 2013; Liu et al., 2024a). Based on a systematic analysis of field measurements globally, Song et al. found that mangrove reforestation (replanting in formerly occupied areas) possessed a higher carbon storage potential, which is partly attributed to the fact that most reforestation sites benefit from more suitable intertidal positioning (Song et al., 2023). Research indicates that tides further influence the content and distribution characteristics of organic carbon by altering factors such as the physicochemical properties of soils in different intertidal zones (Yuan et al., 2017; Dicen et al., 2019; Ma et al., 2020). Currently, variations in the content of mangrove SOC across different intertidal zones have been preliminarily identified. However, the relationship between SOCS distribution patterns and intertidal positioning remains to be elucidated. Clarifying the influence of intertidal positioning on mangrove SOCS is of significant importance for ecosystem restoration.

Qinglan Port Mangrove Nature Reserve located in Wenchang City, Hainan Province, has been recognized as one of the largest mangrove habitats in China (Guo et al., 2014). It covers an area of approximately 1 223.3 hm^2, with a maximum tide level of 2.38 m, a minimum tide level of 0.01 m, and a maximum tidal range of 2.07 m (Guo et al., 2014). Due to anthropogenic activities, the mangrove area in Qinglan Bay significantly declined (Jia et al., 2022). As of 2020, mangrove restoration projects have been implemented within the reserve to support the large-scale ecological recovery of the mangrove ecosystem (Sun et al., 2023). Despite restoration efforts, a systematic evaluation of SOCS is still lacking, particularly regarding the comprehensive studies on the depth variation of SOCS and its distribution patterns across various intertidal zones. Thus, this study investigates the Qinglan Bay restoration site to: 1) quantify the differences in SOCS between different intertidal positions and different depth layers of the soil, thereby analyze the spatial distribution pattern of SOCS during the initial stage of mangrove planting; 2) examine the correlations between soil physicochemical properties and SOCS to analyze how local soil conditions relate to carbon distribution. The study aims to clarify how intertidal positions and variations in soil depth jointly affect the spatial heterogeneity of soil carbon pools in

restored mangrove areas. The findings are expected to provide a scientific basis for monitoring and evaluating the effectiveness of artificial mangrove restoration, and support research on the conservation of mangrove carbon sink resources.

2 MATERIAL AND METHOD

2.1 Sampling site

Given the ecological importance and demonstrated recovery effects of the Qinglan mangroves (19°22′N–19°35′N, 110°40′E–110°48′E), this nature reserve was selected as the study area (Fig.1a). After three years of restoration, the root systems of artificially restored mangroves reached a preliminary stage of growth. Therefore, 3-year-old artificially restored mangroves were selected for investigating the characteristics of organic carbon accumulation in the early stages of mangrove restoration in September 2023. Moreover, 30-year-old natural mangroves with similar physical and geographic conditions were also selected as a control area for analyzing and comparing the process of organic carbon accumulation (Fig.1b). Within each area, three intertidal zones were set, including the high intertidal zone, the middle intertidal zone and the low intertidal zone (Fig.1c & d).

2.2 Sample collection

In September 2023, the mangroves with good growth status were selected at each sampling site. After removing the topsoil, (0–30)-cm (0–15, 15–30 cm) soil column samples were taken with soil drill. Three parallel samples were collected at each sampling point, for a total of 36 soil samples. They were bagged and sealed immediately after collection and sent to the laboratory for cryogenic storage.

2.3 Sample detection

After the collected soil samples were dried and screened, the soil physical and chemical indexes of SOC, pH, salinity, soil bulk density (SBD) and soil particle density were determined. SOC was determined by oxidation method (NY/T1121.6-2006). The soil pH was measured by potentiometrically (NY/T 1377-2007). The soil salinity was analyzed using the mass method (NY/T 1121.16-2006). SBD was determined by ring knife method (NY/T1121.4-2006). The soil particle sizes were measured by densitometer method (NY/T1121.3-2006) and divided into clay (<0.002 mm), silt (0.002–0.02 mm), and sand (0.02–2.0 mm). SOCS was obtained using the following formula (Kauffman et al., 2011; Hu et al., 2024):

$$\mathrm{SOCS} = \sum_{i}^{n} \mathrm{SOC}_i \times \mathrm{SBD}_i \times d_i \times 0.1,$$

where SOC_i refers to SOC of the i^{th} soil layer, SBD_i refers to SBD of the i^{th} soil layer, and d_i refers to the thickness of the i^{th} soil layer.

2.4 Statistical analysis

One-way ANOVA analysis and LSD or Tukey test was used to analyze the significant differences

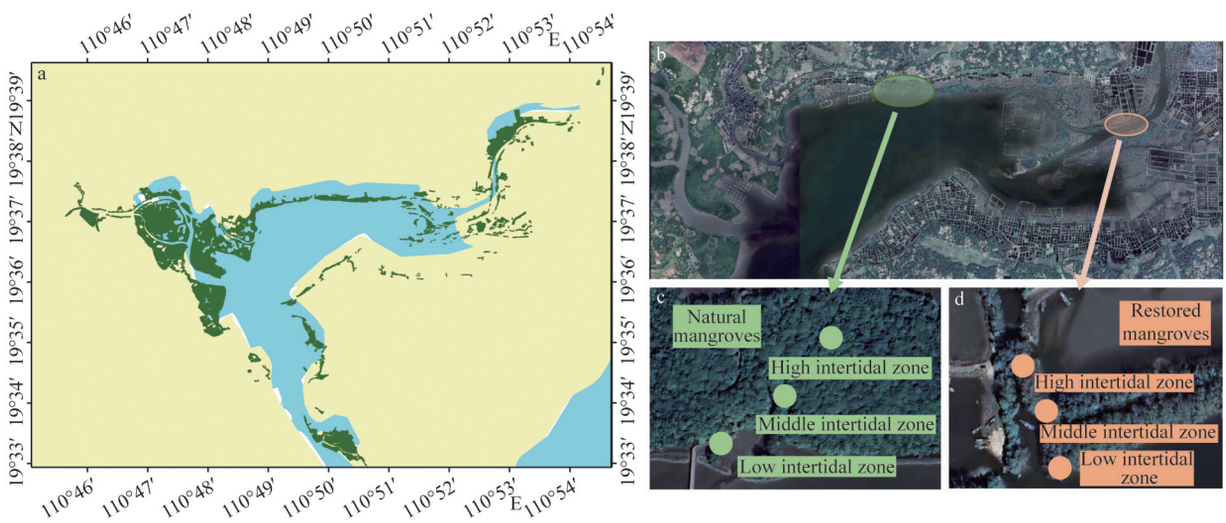


Fig.1 Study area and distribution of sampling points

a. the location of the mangrove study area in Qinglan Bay, Hainan Province, China; b. the study area of the natural mangroves (green mark) and artificially restored mangroves (brown mark); c. the sample plot sites in the natural mangroves (30-year-old); d. the sample plot sites in the artificially restored mangroves (3-year-old). The mangrove distribution data were derived from Liao et al. (2021).

between natural and artificial restoration mangroves at different intertidal zones by using SPSS 27.0 (SPSS Inc., USA). Pearson correlation analysis was used to obtain the soil physical and chemical properties correlation with SOC and SOCS. ArcGIS 10.1 (ESRI, Redlands, USA) was used to draw the schematic diagram of the study area and the distribution map of sampling sites. The OriginPro 2021 and 2024b (Origin Lab Corporation, USA) was used to plot the distribution characteristics and correlation results.

3 RESULT

3.1 Comparison of vertical soil physicochemical properties between restored mangroves and natural mangroves

The longitudinal depth comparison chart systematically compares the variation characteristics of SOC content, SBD, SOCS, and several other soil physicochemical properties between natural mangroves and artificially restored mangroves in the (0–15)- and (15–30)-cm soil layers. The results indicate that the trends of major soil physicochemical properties between natural and restored mangroves are generally consistent across both the (0–15)- and (15–30)-cm layers, and no significant differences were observed between the two soil layers. In both layers, natural mangroves consistently exhibited higher SOC content and SOCS, while restored mangroves showed higher SBD and pH, with salinity generally slightly lower than in natural mangroves, and the soil physicochemical properties of mangroves did not exhibit significant vertical differentiation (Fig.2).

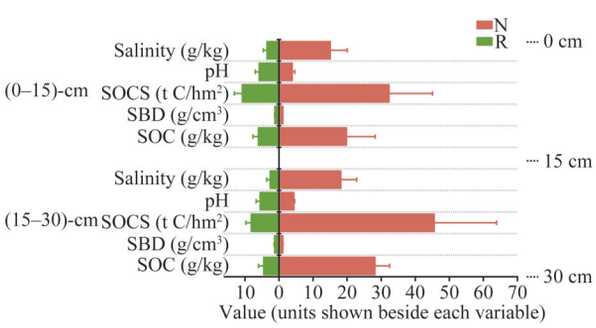


Fig.2 Comparison of vertical soil physicochemical properties (0–15 cm and 15–30 cm) between natural mangroves and artificially restored mangroves

SOC: soil organic carbon; SOCS: soil organic carbon stock; SBD: soil bulk density; N represents natural mangroves; R represents artificially restored mangroves. Bars extending to the left and right represent artificially restored and natural mangroves, respectively. The direction is used only for visual comparison; all values are positive.

3.2 Comparative analysis of SOCS across different intertidal positions

3.2.1 Distribution of SOC across different intertidal positions

In the (0–15)-cm soil layer, the average SOC content in natural mangrove soils was 28.14±12.20 g/kg, while that in artificially restored mangroves was 4.49±1.51 g/kg. In the (15–30)-cm layer, the SOC content was 19.79±8.48 g/kg for natural mangroves and 6.04±1.59 g/kg for restored mangroves. For the entire (0–30)-cm profile, the SOC content was 23.96±10.12 g/kg in natural mangroves and 5.27±1.54 g/kg in restored mangroves (Fig.3b).

Under different intertidal positions, the SOC content in the (0–15)-cm layer of natural mangroves showed a significant decreasing trend from high to low tidal positions. In contrast, the SOC content in the (0–15)-cm layer of restored mangroves exhibited a gradual increase from high to low intertidal positions. In the (15–30)-cm layer, both natural and restored mangroves maintained clear tidal zonation in SOC content ($P<0.05$, Fig.3a). In the (0–30)-cm layer, SOC content in natural mangroves also decreased gradually from high to low tidal positions, with the high position being significantly higher than the middle and low positions ($P<0.05$). For restored mangroves, SOC increased from high to low tidal positions; although significant differences existed between tidal positions ($P<0.05$), the magnitude of change was notably smaller than in natural mangroves (Fig.3c).

3.2.2 Distribution of SBD across different intertidal positions

In the (0–15)-cm layer, SBD of restored mangroves (1.26±0.20 g/cm^3) was significantly higher than that of natural mangroves (1.10±0.07 g/cm^3) ($P<0.05$). In the (15–30)-cm layer, the SBD of restored mangroves (1.20±0.09 g/cm^3) remained generally higher than that of natural mangroves (1.10±0.04 g/cm^3). For the (0–30)-cm layer, the SBD of restored mangroves (1.23±0.15 g/cm^3) was significantly higher than that of natural mangroves (1.10±0.05 g/cm^3) (Fig.4b).

In the (0–15)-cm layer, the SBD of natural mangroves showed a significant increasing trend from high to low intertidal positions, whereas restored mangroves displayed the opposite trend, with SBD significantly decreasing from high to low

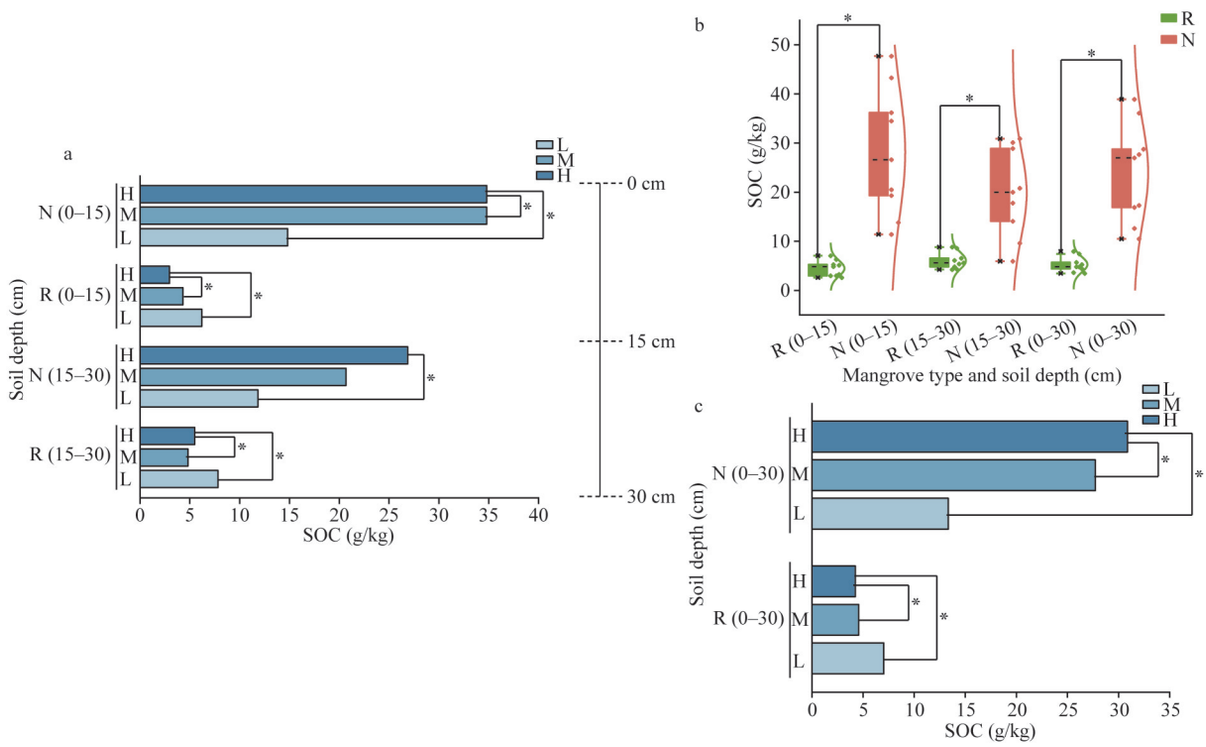


Fig.3 Distribution patterns of SOC content across different soil depths and intertidal positions in natural and artificially restored mangroves

a. distribution of SOC content at different intertidal positions in the (0–15)- and (15–30)-cm soil layers; b. distribution of SOC content across different soil depth layers; c. distribution of SOC content at different tidal positions in the (0–30)-cm soil layer. L: low intertidal positions; M: middle intertidal positions; H: high intertidal positions; N: natural mangroves; R: artificially restored mangroves; *: highly statistically significant differences (P<0.05).

intertidal positions. In the (15–30)-cm layer, the intertidal gradient effect on SBD remained significant for both natural and restored mangroves (P<0.05, Fig.4a). In the (0–30)-cm layer, significant differences (P<0.05) were observed in SBD between natural and restored mangroves across different intertidal positions. For natural mangroves, SBD increased significantly from high to low intertidal positions. Conversely, for restored mangroves, SBD decreased significantly from high to low intertidal positions (Fig.4c).

3.2.3 Distribution of SOCS across different intertidal positions

In the (0–15)-cm layer, the average SOCS of natural mangroves was 45.56±18.32 t C/hm^2, significantly higher than that of restored mangroves (8.14±1.59 t C/hm^2) (P<0.05). In the (15–30)-cm layer, the average SOCS of natural mangroves (32.30±12.79 t C/hm^2) was also significantly higher than that of restored mangroves (10.76±2.35 t C/hm^2) (P<0.05). In the (0–30)-cm layer, the average SOCS of natural mangroves (78.06±28.48 t C/hm^2) was significantly higher than that of restored mangroves (19.01±3.72 t C/hm^2) (P<0.05, Fig.5b).

SOCS exhibited different intertidal variation trends between natural and restored mangroves across soil depths. In the (0–15)-cm layer of natural mangroves, carbon stock was higher at high and middle intertidal positions than at the low position. In the (15–30)-cm layer, carbon stock at the high position was also higher than at the low position. For restored mangroves, in both the (0–15)-cm and (15–30)-cm layers, carbon stock at the high position was lower than at the low position, though the difference was relatively small (Fig.5a).

In the (0–30)-cm layer, as the tidal position increased (from low to high), the carbon stock of natural mangroves showed a significant increasing trend, with the high position being significantly higher than the middle and low positions (P<0.05). In contrast, SOCS of restored mangroves gradually decreased from low to high tidal positions, exhibiting a distribution trend opposite to that of natural mangroves (Fig.5c).

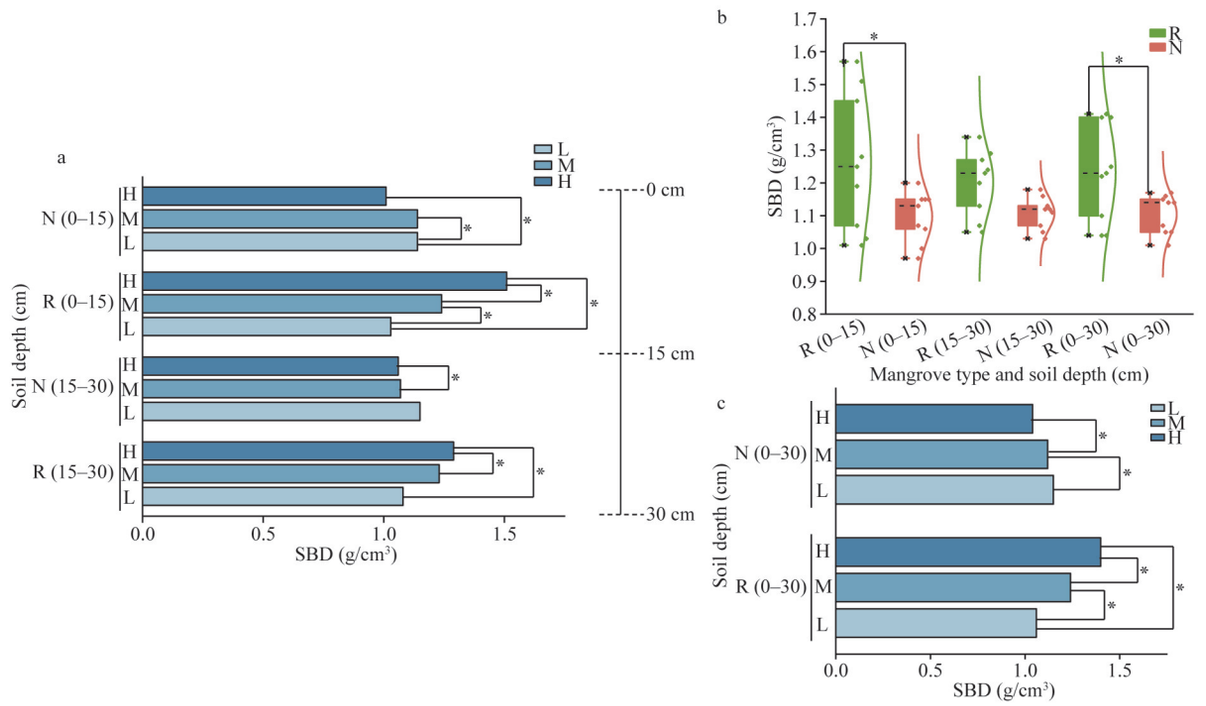


Fig.4 Distribution patterns of SBD across different soil depths and tidal positions in natural and artificially restored mangroves

a. distribution of SBD at different tidal positions in the (0–15)- and (15–30)-cm soil layers; b. distribution of SBD across different soil depth layers; c. distribution of SBD at different tidal positions in the (0–30)-cm soil layer. L: low intertidal positions; M: middle intertidal positions; H: high intertidal positions; N: natural mangroves; R: artificially restored mangroves. *: highly statistically significant differences (P<0.05).

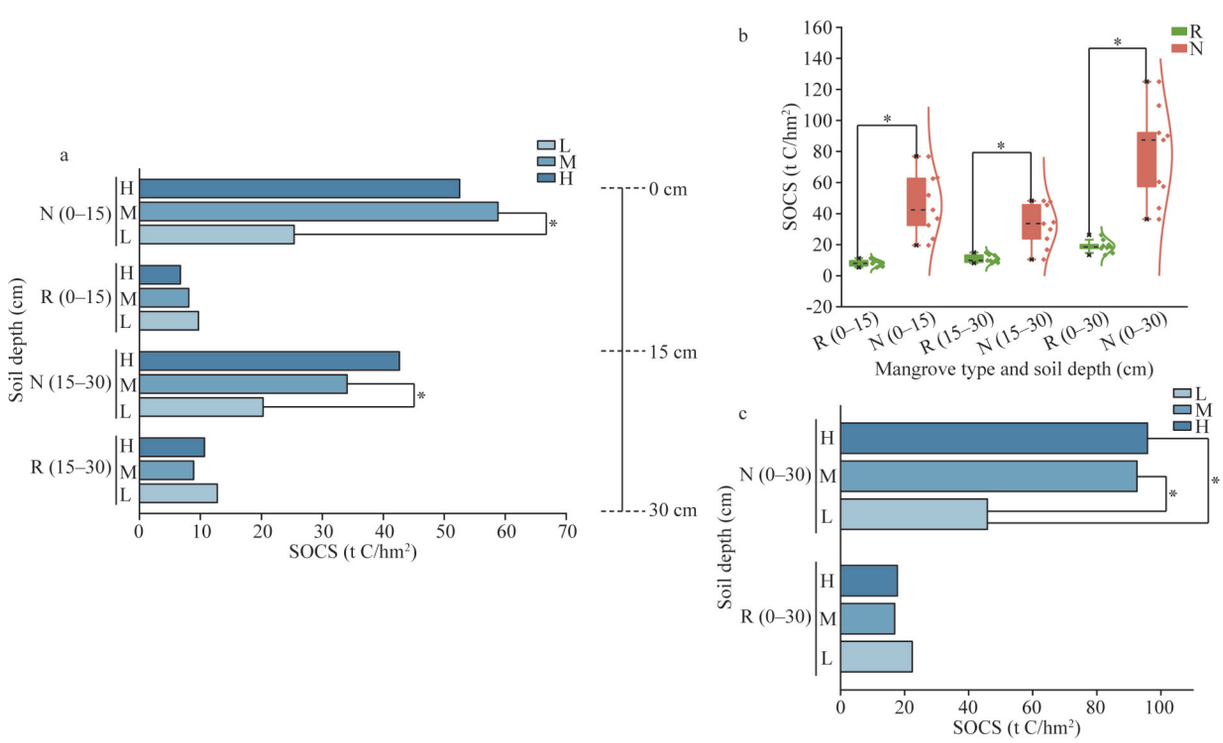


Fig.5 Distribution patterns of SOCS across different soil depths and tidal positions in natural and artificially restored mangroves

a. distribution of SOCS at different tidal positions in the (0–15)-cm and (15–30)-cm soil layers; b. distribution of SOCS across different soil depth layers; c. distribution of SOCS at different tidal positions in the (0–30)-cm soil layer. L: low intertidal positions; M: middle intertidal positions; H: high intertidal positions; N: natural mangroves; R: artificially restored mangroves; *: highly statistically significant differences (P<0.05).

3.3 Correlation analysis of soil physicochemical factors affecting SOCS

3.3.1 Comparative analysis of pH across different intertidal positions

Soil pH in restored mangroves was significantly higher than in natural mangroves, and this difference remained stable across all soil layers (Fig.6b). In the (0–15)-cm layer, soil pH in restored mangroves was mainly neutral to slightly acidic (5.52±1.20), while natural mangrove soil pH (4.35±0.70) was noticeably lower, being weakly acidic. In the (15–30)-cm layer, restored mangroves still maintained a relatively high soil pH (5.81±1.18), whereas the acidic characteristic of natural mangrove soil (3.84±0.80) became more pronounced. For the (0–30)-cm layer, soil pH in restored mangroves (5.67±1.23) was overall higher than in natural mangroves (4.10±0.73).

In both soil layers ((0–15)- and (15–30)-cm), soil pH in natural and restored mangroves followed the same trend. In natural mangroves, for surface soil (0–15 cm), pH across the intertidal zone was highest at the low position, followed by the middle position, and lowest at the high position, with significant differences between the low position and the middle positions (P<0.05). In the (15–30)-cm layer, pH values were generally lower than in the surface layer, but the gradient characteristic with tidal position persisted. In restored mangroves, soil pH also showed a decreasing trend with increasing tidal elevation. In both the (0–15)- and (15–30)-cm layers, the order was low position>middle position>high position, with significant differences between different tidal positions (P<0.05, Fig.6a). In the (0–30)-cm layer, soil pH in both natural and restored mangroves exhibited a decreasing trend with increasing tidal elevation. In natural mangroves, soil pH was highest at the low position, followed by the middle position, and lowest at the high position, with significant differences between tidal positions (P<0.05, Fig.6c).

3.3.2 Comparative analysis of salinity across different intertidal positions

Across different soil depths ((0–15)-, (15–30)-, and (0–30)-cm), soil salinity in natural mangroves (18.15±4.63, 15.03±4.97, 16.59±5.20 g/kg) was significantly higher than in restored mangroves (2.56±1.06, 3.53±1.03, 3.0±1.19 g/kg) (P<0.05, Fig.7b).

In natural mangroves, soil salinity increased with

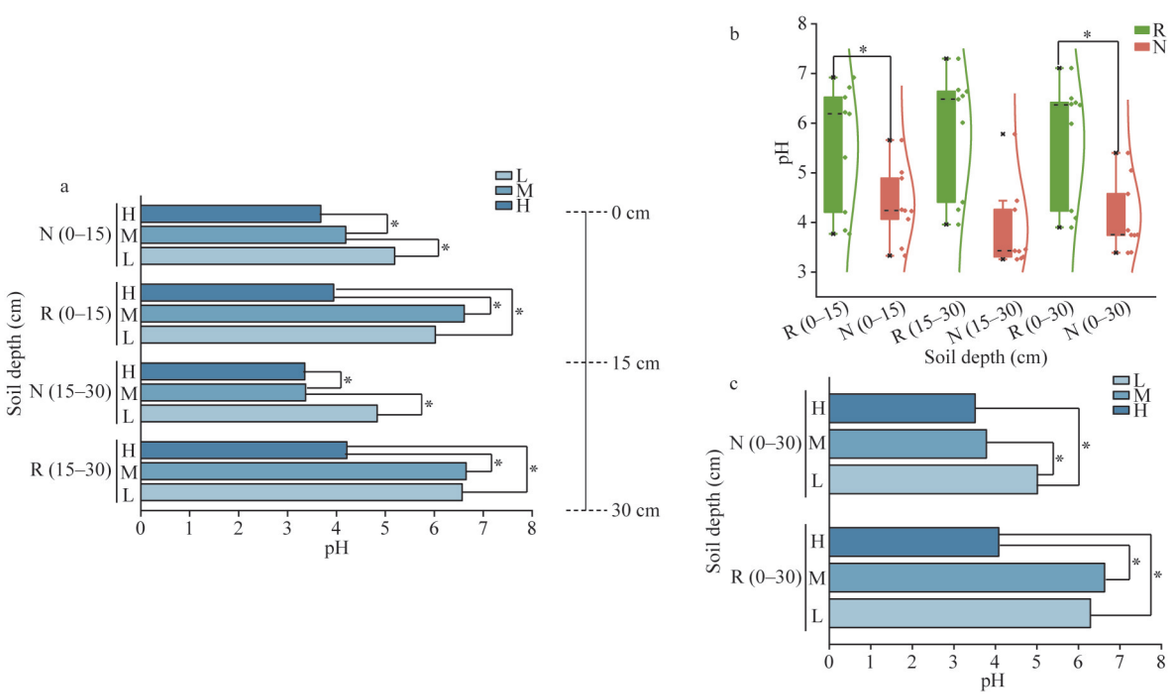


Fig.6 Distribution patterns of soil pH across different soil depths and tidal positions in natural and artificially restored mangroves

a. distribution of soil pH at different tidal positions in the (0–15)- and (15–30)-cm soil layers; b. distribution of soil pH across different soil depth layers; c. distribution of soil pH at different tidal positions in the (0–30)-cm soil layer. L: low intertidal positions; M: middle intertidal positions; H: high intertidal positions; N: natural mangroves; R: artificially restored mangroves; *: highly statistically significant differences (P<0.05).

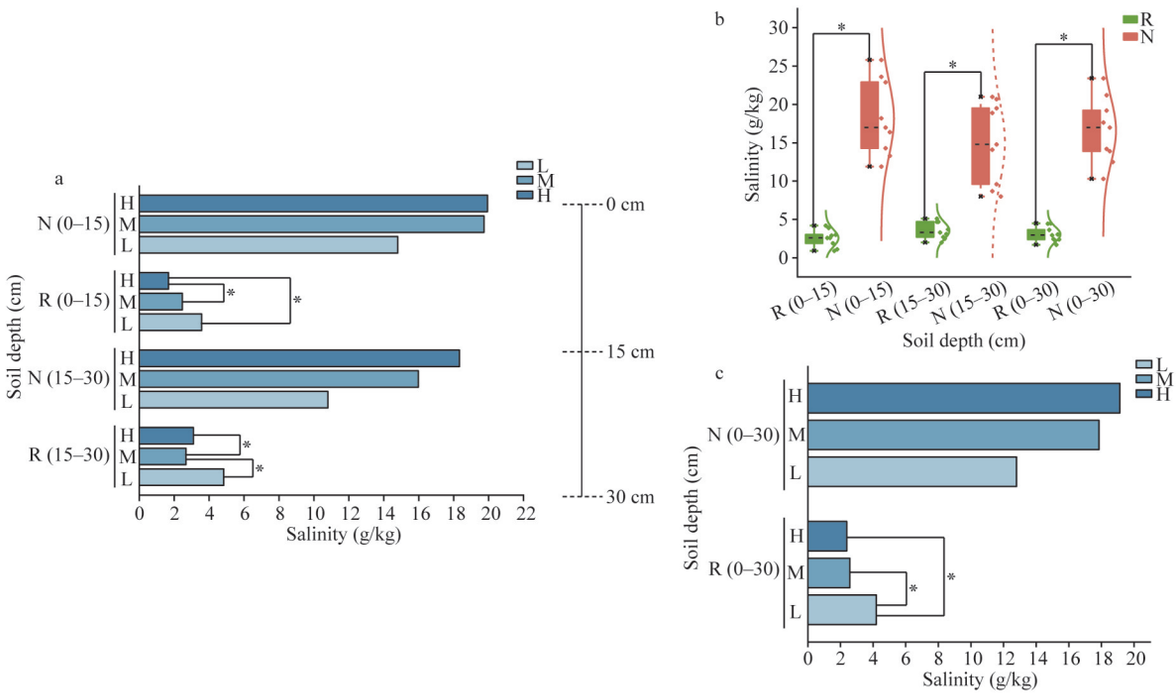


Fig.7 Distribution patterns of soil salinity across different soil depths and tidal positions in natural and artificially restored mangroves

a. distribution of soil salinity at different tidal positions in the (0–15)- and (15–30)-cm soil layers; b. distribution of soil salinity across different soil depth layers; c. distribution of soil salinity at different tidal positions in the (0–30)-cm soil layer. L: low intertidal positions; M: middle intertidal positions; H: high intertidal positions; N: natural mangroves; R: artificially restored mangroves; *: highly statistically significant differences (P<0.05).

rising tidal elevation in both the (0–15)- and (15–30)-cm layers, showing the highest values at the high position, followed by the middle, and the lowest at the low position. Conversely, in restored mangroves, soil salinity in both the (0–15)- and (15–30)-cm layers was greater at the low position than at the high position, exhibiting a characteristic decrease with increasing tidal elevation (Fig.7a). In the (0–30)-cm layer, soil salinity in natural mangroves was highest at the high position, followed by the middle, and lowest at the low position, overall showing a clear increasing trend with rising tidal elevation (Fig.7c).

3.3.3 Comparative analysis of soil particle content across different intertidal positions

The results showed that the distribution pattern of soil particle in both restored and natural mangroves varied distinctly with intertidal position across the (0–15)-, (15–30)-, and (0–30)-cm layers (Table 1). The soil types in the (0–15)-, (15–30)-, and (0–30)-cm layers for both natural and restored mangroves were essentially loamy sand (Fig.8a). In the (0–15)-cm layer and (15–30)-cm layer, in natural mangroves, clay+silt content increased with rising tidal level, with significantly higher values at high and mid-tidal positions than at low intertidal positions, whereas sand content showed an overall decreasing trend with increasing tidal level, with lower sand content at high tide than at low tide (P< 0.05). The artificially restored mangroves also exhibited significant tidal differentiation, with clay+ silt contents at middle- and low-tidal zones being significantly higher than at high-tidal zones (P< 0.05) in both soil layers, while sand contents at mid- and low-tidal zones were significantly lower than at high-tidal zones (P<0.05, Fig.8b & c).

Considering the integrated (0–30)-cm soil layer, fine particle (clay+silt) content in natural mangroves increased gradually from low to high tidal zones, with the highest values at high tide and the lowest at low tide, and significant differences between high and low tidal zones (P<0.05, Fig.8d). Whereas sand content showed an opposite increasing trend from low to high tide (P<0.05, Fig.8e). In artificially restored mangroves, the distribution of fine particles exhibited a tidal pattern opposite to that of natural mangroves, with significantly higher clay+silt contents at low and mid-tidal zones than at the high-tidal zone (P<0.05), while sand content was significantly lower than at high-tidal zone (P<0.05,

Table 1 The percentage of soil particle distribution across different soil depths and intertidal positions in natural and restored mangroves

Soil layer (cm)	Mangrove type	Intertidal position	Clay (%)	Silt (%)	Sand (%)	Soil type
0–15	Restored	L	9.50	13.68	76.82	Loamy sand
		M	9.69	12.59	77.72	Loamy sand
		H	1.89	1.00	97.11	Loamy sand
	Natural	L	5.61	6.45	87.94	Loamy sand
		M	7.02	12.56	80.42	Loamy sand
		H	6.69	12.07	81.24	Loamy sand
15–30	Restored	L	9.17	14.04	76.79	Loamy sand
		M	9.13	9.20	81.67	Loamy sand
		H	2.23	2.70	95.07	Loamy sand
	Natural	L	5.01	5.40	89.59	Loamy sand
		M	5.39	9.38	85.23	Loamy sand
		H	7.13	13.28	79.59	Loamy sand
0–30	Restored	L	9.34	13.86	76.80	Loamy sand
		M	9.41	10.90	79.69	Loamy sand
		H	2.06	1.85	96.09	Loamy sand
	Natural	L	5.31	5.92	88.77	Loamy sand
		M	6.21	10.97	82.83	Loamy sand
		H	6.91	12.67	80.41	Loamy sand

Fig.8d & e). This pattern is consistent with the distribution characteristics of soil particle composition observed in the (0–15)- and (15–30)-cm soil layers.

3.4 Correlation between soil physicochemical factors and SOCS

The correlation heatmap of soil physicochemical indicators for restored mangroves reveals the relationships among soil properties in restored mangroves. Soil pH was significantly positively correlated with clay+silt content and significantly negatively correlated with sand content. (Fig.9a).

The correlation heatmap of soil physicochemical indicators for natural mangroves reveals the relationships among soil properties in natural mangrove ecosystems. SOCS showed significant positive correlations with salinity and clay+silt content and significantly negatively correlated with soil pH and sand content. In addition, salinity was significantly positively correlated with clay+silt content, and both were significantly negatively correlated with sand content (Fig.9b).

4 DISCUSSION

4.1 Distribution characteristic of SOCS across soil depth profiles in restored mangroves

Mangroves are recognized as one of the most productive blue carbon ecosystems globally, possessing a high carbon sequestration capacity (Kato et al., 2024; Zhang et al., 2024). The majority of carbon sequestration in mangrove ecosystems occurs in sediments, and the most concentration in the surface and subsurface soil layer (Alongi, 2014; Hong Tinh et al., 2020). Relevant study further indicates that the effect of mangrove restoration on SOCS is more pronounced in the upper soil layers (Chen et al., 2018). Mangrove litter (leaves and twigs) primarily covers the soil surface and, upon further decomposition, accumulates preferentially in the surface layer to form a direct source of carbon input (Eid and Shaltout, 2016; Dewiyanti et al., 2021). Additionally, influenced by soil anaerobic conditions, a portion of the dead roots is stabilized as soil organic matter, serving as a further source of replenishment for surface organic carbon (Chen et al., 2023). Consequently, a vertical distribution pattern characterized by higher organic carbon storage in the surface and subsurface soil was formed.

In the present study, SOCS in (0–15)- and (15–30)-cm soil layers did not show significant differences. This phenomenon can be primarily attributed to: 1) the distribution of mangrove root systems in the surface and subsurface soil (Kauffman et al., 2011; Zhang et al., 2021); 2) the

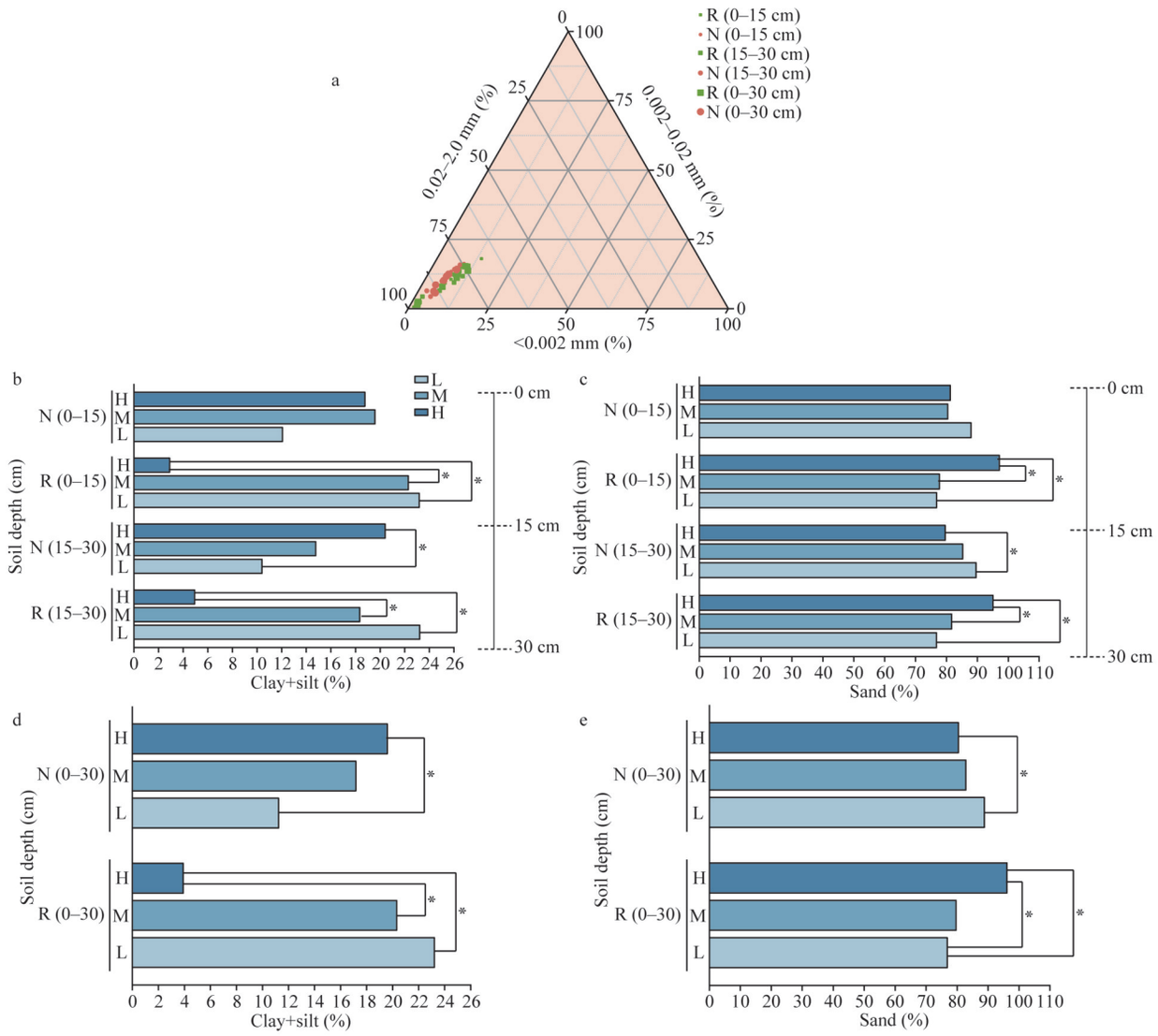


Fig.8 Soil particle composition across different soil depths and tidal positions in natural and artificially restored mangroves

a. soil texture triangle for the (0–30)-cm soil layer, particle-size fractions are expressed as percentages (%), with sand (0.02–2 mm), silt (0.002–0.02 mm), and clay (<0.002 mm) summing to 100%; b. distribution of fine particle (clay+silt) content at different tidal positions in the (0–15)- and (15–30)-cm soil layers; c. distribution of sand content at different tidal positions in the (0–15)- and (15–30)-cm soil layers; d. distribution of fine particle (clay+silt) content at different tidal positions in the (0–30)-cm soil layer; e. distribution of sand content at different tidal positions in the (0–30)-cm soil layer. L: low intertidal positions; M: middle intertidal positions; H: high intertidal positions; N: natural mangroves; R: artificially restored mangroves; *: highly statistically significant differences (P<0.05).

similar hydrological and redox conditions within shallow mangrove sediments (Kristensen et al., 2008); and 3) the tidal-driven redistribution of organic matter (Sanders et al., 2016). The distribution of SOC in the vertical profile remains relatively homogeneous overall in the mangrove forests of Micronesia which is closely associated with the well-developed underground root system of mangroves and their continuous root turnover and decomposition (Kauffman et al., 2011). Relevant study has shown that fine roots in shallow soil layers (typically (0–30)-cm) are a major contributor to organic carbon sequestration in mangroves (Zhang et al., 2021). Therefore, the uniform occur of roots in the soil surface layer further influences the distribution of carbon, mitigating the vertical differentiation of SOC within the (0–30)-cm soil range.

The sediments in mangrove ecosystem are long-term controlled by tidal inundation and hydrodynamic processes (Sanders et al., 2016). The tidal-driven cycle of inundation and drainage promotes material

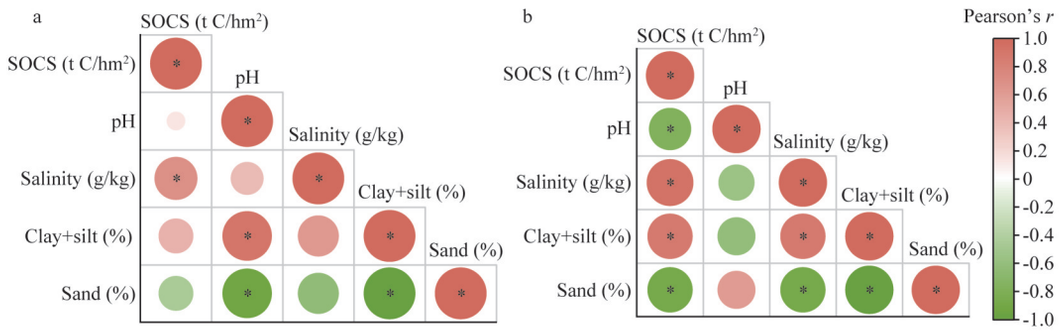


Fig.9 Correlation heatmap between SOCS and soil physicochemical properties

a. correlation heatmap of soil physicochemical properties in artificially restored mangroves; b. correlation heatmap of soil physicochemical properties in natural mangroves. Color bar: dimensionless Pearson correlation coefficient, ranging from -1 to 1, red gradient denotes positive correlation, and green gradient denotes negative correlation. Bubble size reflects absolute correlation magnitude. *: highly statistically significant differences (P<0.05).

exchange between mangroves and adjacent waters, maintains environmental continuity in shallow sediments, and consequently influences carbon dynamics (Kristensen et al., 2008). This process simultaneously enhances biogeochemical coupling between surface and subsurface layers, thereby facilitating efficient interlayer material exchange. Furthermore, high sedimentation and strong hydrodynamics lead to minimal vertical changes in organic carbon density within shallow mangrove sediments (typically (0–30)-cm) (Sanders et al., 2016), with the result that no significant surface enrichment occurs. In summary, driven by the combined effects of surface and subsurface root distribution, shallow sedimentary environmental characteristics, and tidal hydrodynamics, SOCS within the (0–30)-cm layer of the study area did not exhibit significant vertical differentiation. Instead, a relatively homogenized distribution pattern was formed within this depth range.

4.2 Distribution pattern of SOCS across different intertidal positions in restored mangroves

Mangroves are a type of vegetation influenced by tide (Dewiyanti et al., 2021). The periodic rise and fall of tides facilitate the transport of suspended organic matter into mangrove sediments, where this allochthonous carbon is captured by root systems and continuously accumulates as a significant source of soil organic carbon (Lyu et al., 2024). The present study found that the content of organic carbon in both restored and natural mangroves exhibits a significant gradient distribution across high, middle, and low intertidal zones. Similar trends were observed between corresponding groups within the soil depth ranges of (0–15)-, (15–30)-, and (0–30)-cm. Specifically, in 30-year-old natural mangroves, the content increased progressively from the low-tide to the high-tide zone, which is consistent with the results reported by Zou et al. (2023) and Xu et al. (2020). Conversely, 3-year-old restored mangroves displayed an opposite trend, with carbon content decreasing from the low-tide zone to the high-tide zone.

Consistent with the distribution of SOC, the SOCS of restored mangroves exhibited a trend of being higher in the low intertidal zone than in the high intertidal zone across the (0–15)-, (15–30)-, and (0–30)-cm soil layers, though there is no statistical significance was observed. Organic carbon in mangrove soil is primarily derived from the decomposition of mangrove plant litter and root turnover (Doughty et al., 2016; Sun et al., 2019; He et al., 2020). During the three-year restoration period, the plant quantity of artificially restored mangroves was undeveloped and their root system were not mature, which made it difficult to retain organic litter in the high tidal zone under the scouring action of seawater. As a result, it was transported to the low tidal zone to gather (Zhao et al., 2018; Wang et al., 2021; Lin et al., 2024). In addition, the low-tide marginal effect was relatively high, and some organic matter came from water, zooplankton and algae residues. Therefore, compared with the high tidal and middle tidal zones, the low tidal area of artificially restored mangroves had more organic carbon sources, which was more conducive to the sedimentation and accumulation of organic carbon (Yang et al., 2012).

Notably, the restoration periods studied by Zou et al. (2023) (9 years) and Xu et al. (2020) (13 years)

far exceed the three-year restored duration of the present study. This suggests that the duration of mangrove restoration is a critical factor in determining the distribution patterns of SOCS across different intertidal positions. As the mangroves gradually mature, their well-developed root systems can effectively mitigate the flow velocity and weaken the scouring effect of tides (Nizam et al., 2022; Wang et al., 2023). When the scouring force of seawater is weaker, it is difficult for plant litter in high-tide areas to be washed away by tides (Nizam et al., 2022; Wang et al., 2023). These litters further facilitate the storage of organic carbon. Additionally, a flooded environment affects the soil aeration, which in turn restricts the gas exchange between plants and the outside world, resulting in the distribution characteristics of plant biomass that related to the distance from the coast (He et al., 2007; Cui et al., 2022). For example, some studies have found that the quantity of mangrove had a gradually decreasing trend from landward to seaward area (Ye et al., 2010; Lu et al., 2013). Greater biomass means more carbon sources. These influencing factors collectively led to the high tide level of natural mangroves had minimal tidal influence and favorable growth conditions, which retained abundant organic carbon sources and enabled high carbon sequestration efficiency. This phenomenon was verified in our control group and consistent with the findings reported by Dung et al. (2016) and Kauffman et al. (2011).

Above findings indicate that under the influence of tidal dynamics, the spatial distribution of SOCS in mangroves exhibited differences across different intertidal zones and undergo transitions as the mangrove mature. In the early stages of mangrove ecosystem restoration, the accumulation of soil organic carbon was first observed in the low intertidal zone. This implies that the low tidal soil should be intensively monitored in the early stage of restoration. The phenomenon also reflects the carbon sequestration capacity of mangroves will gradually stabilize over the course of restoration. Furthermore, the complex aboveground structure of mangrove vegetation (such as aerial roots, dense plants, etc.) has a strong wave attenuation effect, which was conducive to promoting the deposition and combination of POC in tidal water, thereby improving erosion resistance of soil (Chowdhury et al., 2016; Ezcurra et al., 2016), indicating that mangrove restoration helps control coastal erosion and stabilize shorelines (van Bijsterveldt et al., 2020; Mai et al., 2022).

4.3 Correlation between SOCS and soil physicochemical properties: pH, salinity, and soil particle size

pH is an important index affecting the physical and chemical properties of soil, which mainly influences the dynamic change of organic carbon through chemical and biological processes (Li et al., 2017; Ji et al., 2024). The unique root system of mangrove can promote the precipitation of suspended particles in seawater (Liu et al., 2024b). Coupled with its own metabolism, the system typically contains a lot of plant litters, humus, and other organic matters (Sebastian, 2002; Prasad et al., 2017). As these matters gradually decomposed, they produce a large number of organic acids, leading to a decrease in soil pH (Sebastian, 2002; Wang et al., 2014; Sun et al., 2024; Iqbal et al., 2025). The acidic soil condition in mangrove ecosystems leads to the species and activity of microorganisms in mangrove soil are usually limited (Zhang et al., 2023). As the result, it reduces the decomposition and consumption of soil organic carbon by soil microorganisms (Zhang et al., 2023). However, it is noteworthy that mangrove restoration is a long-term process, and its soil acidification effect remains limited in the short term (Deng, 2019; Jiang et al., 2025). As the duration of restoration increases, the soil pH in mangroves decreases. This pattern is consistent with the findings from the study, the artificially restored mangroves were still in the early stages of their growth cycle, where the correlation between pH and SOCS was relatively weak. In contrast, the 30-year-old nature mangroves showed a significant negative correlation between pH and SOCS.

In the study, SOCS of both natural mangroves and artificially restored mangroves showed a significant positive correlation with soil salinity. As a key environmental factor regulating mangrove growth and development, soil salinity plays an important role in the organic carbon accumulation. Soil salinity can promote mangrove root development, and well-development root in turn can increase soil salinity (Chen et al., 2019). Therefore, the growth of mangroves was better in the salinity range of 2.2–34.5 g/kg than others (Chen et al., 2021). Some studies showed that the salting-out effect could be enhanced by the increasing soil salinity, which regulating plant photosynthetic carbon fixation to influence the return and decomposition of plant residues, thereby affecting the processes of soil carbon input and output. The decomposition rate of organic carbon tends to decrease in a high-salinity environment (Kida et al.,

2017; Wang et al., 2018; Fu et al., 2022). On the other hand, soil salinity influences organic carbon accumulation by affecting microorganism (Wang et al., 2017; Zuo et al., 2023). High salinity can alter microbial metabolism due to increased osmotic pressure, which affects cell function. Moreover, it is able to inhibit microbial enzyme activity. With the increase of salinity, the activities of soil microorganisms would be inhibited and the decomposition rate of roots would be decreased (Ouyang et al., 2017; Li et al., 2024). Thus, as the result of high organic carbon source and low organic carbon decomposition, the storage of organic carbon was promoted in the soil (Kida and Fujitake, 2020; Xue et al., 2020). However, appropriate salinity level has beneficial effect, excessively high salinity conversely causes adverse impacts. A study in a Tianjin coastal wetland showed that when the soil salinity was less than 2.19 dS/m, increasing salinity inhibited microbial activity, thereby reducing the organic carbon decomposition rate and resulting in higher carbon content. When salinity exceeded 6.87 dS/m, further increases negatively impacted mangrove root systems and consequently decreased SOCS (Li et al., 2024).

Soil particle size is an important factor that affecting the content of organic carbon (Bi et al., 2023). Fine particulate matter is more likely to interact with organic carbon, contributed to the stabilization and increase of the carbon storage in mangroves (Kleber et al., 2011; Kida and Fujitake, 2020; Kopittke et al., 2020). Mangroves reduce the hydrodynamic energy of tides through their aerial roots and stems, thereby promoting the capture and deposition of silt and clay (Jimenez et al., 2021). These fine particulate matters were combined with the decomposed organic matter, which were provided by the plant litter and well-developed roots system of mangroves, consequently protecting the content of silt and clay in the soil (Prasad et al., 2017; Sun et al., 2019; Kida and Fujitake, 2020). Moreover, when the sand content was lower and the clay and silt contents were higher in the soil, the soil aggregates formed with organic carbon were relatively stable. This mechanism effectively sequestrates organic carbon within the aggregates, thereby playing a protective role in the storage of organic carbon (Wang, 2023). Furthermore, the clay and silt particles were small and had poor permeability, leading to reduce the decomposition of organic carbon by microorganisms after combining with organic matter (Kleber et al., 2011; Kopittke et al., 2020). However, the sand particles were large and had strong permeability, causing organic carbon to be easily decomposed by microorganisms (Liddle et al., 2020; Yao et al., 2023). Therefore, SOCS was positively related with silt and clay content and negatively correlated with sand content. There was no significant correlation observed, but a consistent trend was identified in the artificially restored mangroves.

5 CONCLUSION

Currently, systematic and comprehensive investigations into the vertical variation of SOCS and their distribution patterns across different intertidal positions in Qinglan Bay mangroves remain limited. This study revealed that the synergistic effects of surface root distribution, shallow sedimentary environmental characteristics, and tidal hydrodynamics contribute to a relatively uniform distribution pattern of SOCS within the (0–30)-cm soil layer. Furthermore, the results indicate that restoration age is a critical factor influencing the spatial distribution of SOCS across intertidal zones. In the early stages of restoration, carbon accumulation occurs primarily in the low-tide zone, significantly driven by soil salinity. As the mangroves mature, the further evolution of organic carbon accumulation and storage patterns is driven by the combined effects of soil acidification, increased salinity, and an elevated proportion of fine-grained particles.

Building on these findings, and acknowledging the limitations in soil sampling depth, monitoring duration, and detection indicators, the present study requires further improvement and in-depth research in the future. Firstly, establishing long-term ecological monitoring mechanisms is essential. This approach is necessary to track the long-term recovery trajectory of mangrove carbon sink functions more effectively. Although this study clarifies the distribution of surface and subsurface SOCS, future research should extend into deeper soil layers to fully resolve vertical profile characteristics. Additionally, further research is needed to resolve the mechanisms governing intertidal SOCS distribution. Future studies should integrate a broader range of variables, including tidal elevation, inundation frequency, and soil porosity, to provide a more holistic assessment. Moreover, further exploration of biogeochemical processes, such as microbial metabolism, is

necessary to regulate carbon cycling. The present study provides reference for constructing an effective carbon sequestration enhancement strategy based on mangrove restoration, and further offer scientific guidance for monitoring during the mangrove restoration.

6 DATA AVAILABILITY STATEMENT

All data generated or analyzed during this study are included in this published article.

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