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Unravelling Soil Carbon Dynamics in *Rhizophora apiculata* Blume Plantations of the Kien Vang Coastal Area, Ca Mau Province, Vietnam

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ABSTRACT

Mangroves are highly productive blue carbon (C) ecosystems with an exceptional capacity to store organic C in soils. Soil organic C storage in these systems is recognized as a key component of the global C cycle and an important natural mechanism for climate change mitigation. Nonetheless, knowledge of how soil C dynamics vary with forest development in mangrove plantations remains limited. To address this gap, the current study quantified changes in soil C stocks along a forest age sequence of Rhizophora apiculata Blume plantations in the Kien Vang coastal area, Ca Mau Province, Vietnam, through systematic field surveys. The results revealed that: (1) Soil C content and stocks significantly increased with the developing forest age. (2) Soil C concentration and storage significantly decreased with increasing of soil depth along forest age. (3) The stocks of total soil organic C (SCs) increased from 94.97 Mg C· ha^{-1}to 224.75 Mg C· ha^{-1}, during forest development. SCs exhibited obvious surface aggregation, with more than 70% of SCs occurring in the soil of 0–40 cm depth, underscoring the pivotal role of surface soils in C sequestration. (4) Based on the random forest regression analysis, soil salinity, total nitrogen, and stand density were identified as the key factors regulating variations in SCs across forest age development, accounting for 15.3%, 13.4%, and 11.8% of the variation, respectively. These findings highlight the vital role of R. apiculata mangrove plantations as effective C sinks and underscore their contribution to global climate change mitigation efforts and sustainable forest management strategies for improved soil health.

Keywords: Mangrove plantations, carbon dynamics, climate change mitigation, forest age gradient, soil organic carbon storage, sustainable forest management

INTRODUCTION

Forest ecosystem biomass and carbon (C) stocks play a dominant role in the global C cycle and serve as critical C reservoirs for mitigating global warming (Justine *et al*., 2017; Zhang *et al*., 2019). This is largely attributed to their high capacity for C sequestration in both vegetation and soil, as well as their interactions with atmospheric processes through storing and sequestrating CO2 (Cuong *et al*., 2025).

Mangrove forests play a crucial role in climate regulation by sequestering and storing significant amounts of CO_2, a key greenhouse gas driving global warming (Atwood *et al*., 2017). Carbon in mangroves is stored in aboveground biomass (stems, branches, leaves, roots) and in the soil (belowground roots and retained sediments) (Pham *et al*., 2017; Nguyen *et al*., 2021). Notably, around 90% of their total C is retained in anaerobic, waterlogged soils, which slow organic matter decomposition and facilitate long-term C storage (Nam *et al*., 2016). Despite occupying only about 0.5% of the world's coastline, mangroves hold an estimated 10–15% of coastal sediment C stocks, underscoring their vital role in reducing greenhouse gas emissions and enhancing climate change adaptation capacity (Kang *et al*., 2025). Beyond C storage, mangrove forests provide vital ecological services, including biodiversity maintenance, nursery habitats for fish and invertebrates, and protection against natural disasters (e.g., typhoons, floods, tsunamis) (Eid & Shaltout, 2016; Cooray *et al*., 2024). Consequently, they are increasingly recognized as a critical component in climate change mitigation strategies and in REDD+ schemes (Tue *et al*., 2014).

The total area of mangrove forests in Vietnam is estimated at approximately 164,701 hectares, with the largest proportion located in the southern region. In particular, Cà Mau Province contains about 63,017 hectares of mangroves (Bao *et al*., 2021). *Rhizophora apiculata* Blume is the most common and dominant species in these planted mangrove forests, valued for its wood, which is used for firewood, charcoal, poles, wood chips, and construction materials (Cuong, 2025b). Beyond its economic uses, *R. apiculata* provides vital ecosystem services by mitigating adverse impacts on the C cycle through C sequestration and storage (Cuong, 2025a). Consequently, accurate information on C stocks in *R. apiculata* plantations is essential. Although previous studies have improved our understanding of the biological and ecological characteristics of *R. apiculata*, including growth traits, allometric models, biomass, primary productivity, and C sequestration at local scales (Nam, 2011; Ha *et al*., 2017; Vinh *et al*., 2019; Bao *et al*., 2021; Cuong, 2025a), most have focused primarily on C stored in plant biomass. However, knowledge of soil C accumulation dynamics in relation to forest age structure, particularly in the Kien Vang coastal area, Ca Mau Province remains limited. Quantifying temporal changes in soil C stocks in *R. apiculata* plantations in this region is therefore essential for improving predictions of C balance responses at both regional and global scales under future climate change scenarios.

In this study, we investigated changes in soil C stocks across five age classes of *R. apiculata* plantations: young (Yu, ~5 years), middle-aged (Ma, ~10 years), pre-mature (Pm, ~15 years), mature (Mu, ~20 years), and post-mature (Pm, ~25 years) in the Kien Vang coastal area, Ca Mau Province. The mainly focuses of the study were to: (i) estimate soil organic C content and stocks across these five stand ages; and (ii) identify the key environmental factors influencing soil C accumulation. The findings will enhance our understanding of mangrove C sequestration, guide forest management strategies to increase C stocks, and provide a scientific foundation for participation in C markets and climate change mitigation programs.

MATERIALS AND METHODS

Study area

The research site is situated in the Kien Vang coastal area, Phan Ngoc Hien Commune, Ca Mau Province, Vietnam (8°39′33″ N, 105°03′54″ E; **Figure 1**). The region has a tropical monsoon climate characterized by two distinct seasons: a rainy season extending from May to November and a dry season from December to April. Mean annual temperature is 26.5 °C, annual rainfall averages 2,390 mm, and mean relative humidity is 85.9%. The soils in the study area belong to the group of permanently saline soils formed on newly deposited, unstable alluvium, with a texture ranging from loam and soft clay to compact clay (Cuong, 2025a, b).

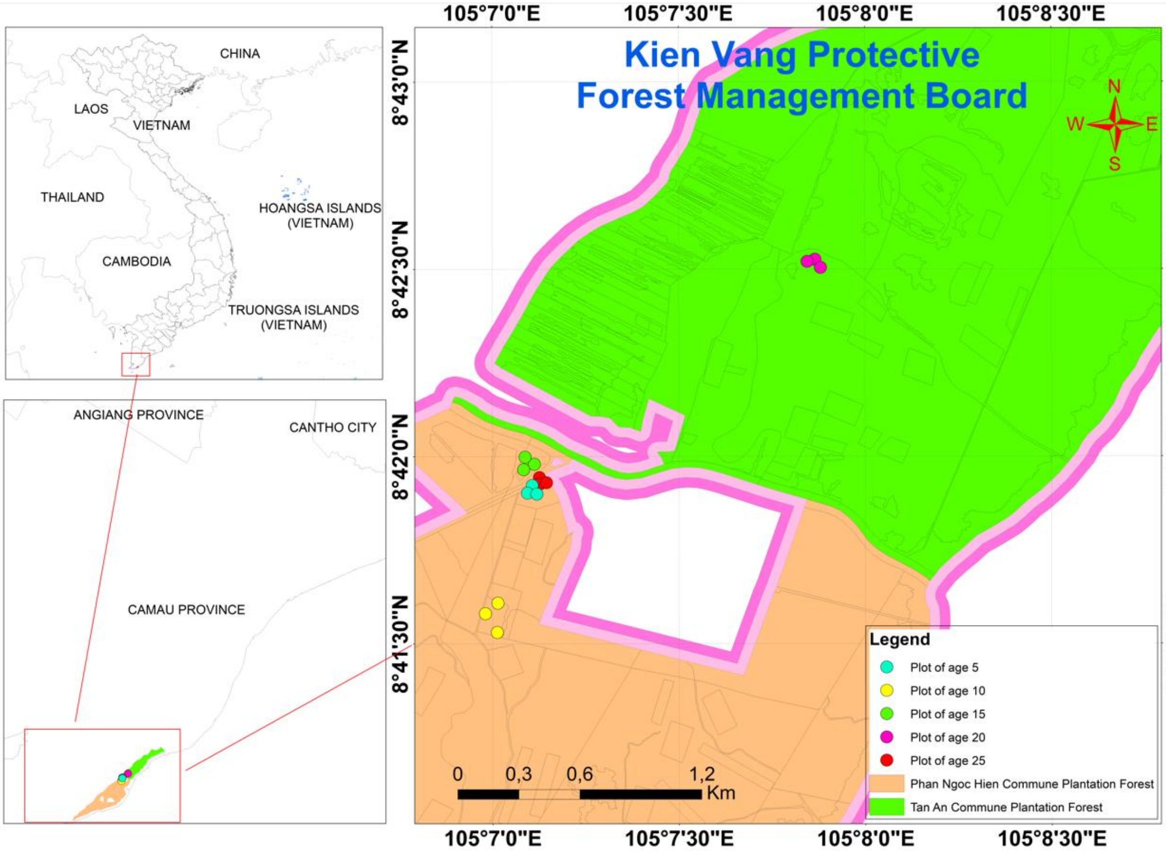

Figure 1. Map revealing the locations of sampling points in the Kien Vang coastal area, Phan Ngoc Hien Commune, Ca Mau Province, Vietnam

The region contains numerous *R. apiculata* plantations of varying ages and densities, along with other woody species such as *Ceriops tagal* (Pers.) C.B.Rob., *Bruguiera parviflora* (Roxb.) Wight, *Avicennia officinalis* L., *Bruguiera sexangula* (Lour.) Poir., & Arn. ex Griff., *Ceriops decandra* (Griff.) W.Theob., and *Avicennia alba* Blume. The study encompassed five *R. apiculata* stands aged 5, 10, 15, 20, and 25 years, corresponding to the age classes Yu, Ma, Pm, Mu, and Pm. All fifteen experimental plantations selected for the study were established on the same soil type and texture, under similar disturbance histories and topographic conditions. No fertilizer was applied to any of the stands prior to planting. The initial planting density was 10,000 trees ha^{-1} (1 m × 1 m), and thinning treatments were applied once, twice, and three times to the 5-, 10-, and 15-year-old plantations, respectively. Five stands of different ages were located within a 10 km radius (Cuong, 2025a, b).

Experimental design and sampling

Three sample plots (20 m × 20 m) were established within each stand, resulting in a total of 15 plots. Field measurements and sampling were conducted from January 1st to February 28th, 2025. In each sample plot, tree diameter at breast height (D, cm) and height (H, m) were measured for each tree using a Haglöf Mantax caliper and a Haglöf Vertex IV hypsometer, with an accuracy of approximately 1%. Canopy closure (C) of the overstory was determined using the Forestry 4.0 Application for hemispherical canopy analysis installed on on a smartphone. In each sample plot, 20 measurement points were taken, and the average value was used to represent the sample plot.

The stand density index (N, trees·ha^{-1}) was calculated according to (Them & Toai, 2024) using:

$$N = \frac{10000}{s} \times n \qquad \text{(Equation 1)}$$

where s is the sample plot area (m²) and n is the number of trees per plot.

The tree volume (V) was estimated following (Them & Toai, 2024):

$$V = g \times H \times F \qquad \text{(Equation 2)}$$

where g (m$^{2\cdot}$ tree^{-1}) is the cross-sectional area of each tree ($g = 0.00007854 \times DBH^2$), DBH and H are the diameter and height of each tree, and F is the tree form factor). The research adopted a value of F = 0.5 for plantation forests (Them & Toai, 2024).
The timber volume per hectare (M, m³·ha^{-1}) was computed using Equation 3 (Them & Toai, 2024):

$$M = \sum V \times \frac{10000}{s} \qquad \text{(Equation 3)}$$

where $\sum$V (m$^{3\cdot}$ sample plot^{-1}) is the total volume of trees in the sample plot and s is the area of the sample plot.

Detailed descriptions of the study site and the methods used to estimate total aboveground biomass, including tree prop roots, stems, branches, and leaves are given in our previous study (Cuong, 2025a) and summarized in **Table 1**.

Table 1. Basic stand characteristics of the research site

Characteristics factors / Forest age (years)	N (trees· ha^{-1})	D (cm)	H (m)	T	G (m$^{2\cdot}$ ha^{-1})	M (m³ ·ha^{-1})	AGB (Mg ·ha^{-1})
5	9498	5.1	6.7	0.7	20.8	81.7	107.24
10	5765	8.3	9.7	0.78	29.0	183.2	201.23
15	3789	10.7	11.6	0.82	32.4	239.7	265.29
20	2742	12.5	13	0.86	34.2	274.2	306.69
25	2188	14.1	14.1	0.89	35.4	297.3	332.86

Note: N, stand density; D, mean diameter at breast height; H, mean height; T, canopy density; G, stand basal area; M, standing timber volume; AGB, total aboveground biomass

Soil measurements and sampling

Soil samples from each standard plot were collected for laboratory analysis of their physical and chemical properties. Sampling followed a five-point S-shaped transect method at three depth intervals: 0–20 cm, 20–40 cm, and 40–60 cm, after removing surface litter. A 6-cm diameter PVC pipe was used to collect samples from each soil profile during low tide. The pipe was carefully inserted into the soil to minimize disturbance to the core surface, rotated, and then withdrawn, following the procedure described by (MacKenzie *et al*., 2016). For each depth, the five subsamples from the same plot were thoroughly mixed to form a composite sample. In total, 45 composite samples were obtained (five stand ages × three replicate plots per age × three soil depths). The collected samples were sealed in zip-lock bags, stored on ice during transport to the laboratory, and refrigerated at 4 °C until further analysis (Hu *et al*., 2022). Before analyzing soil organic C (SOC) and other soil parameters, all soil core samples were carefully cleaned to remove visible plant and animal residues, then freeze-dried. The dried samples were weighed to determine bulk density, ground using a mortar and pestle, and sieved through a 0.15 mm mesh to obtain a fine during transport to the laboratory, and refrigerated at 4 °C until further analysis (Hu *et al*., 2022). Soil organic C (SOC) content was measured using the potassium dichromate oxidation method with external heat application (Nelson &

Sommers, 1982). Total nitrogen (TN) was analyzed following the Vietnam National Standard method (TCVN 6498:1999 – ISO 11261:1995), as applied by (Cuong *et al*., 2022). TN concentration was determined using a modified Kjeldahl method after digestion with a mixture of $C_7H_6O_3$ and H_2SO_4. Soil salinity (Ss) and pH were measured by mixing each soil sample with deionized water at a 1:5 (soil-to-water) ratio and analyzing the mixture using a Thermo Scientific Orion 5-Star Plus pH/ORP/ISE/Cond/DO Portable Meter (Cuong *et al*., 2022). Soil bulk density (BD) weight was determined by first recording the wet mass of each sample, followed by oven-drying at 80 °C to a constant weight was reached. The dry mass of the 100 cm^3 soil samples were calculated after subtracting the mass of the aluminum container. Soil bulk density was then calculated as the ratio of dry mass to the volume of the wet sample.

Calculation of soil organic carbon storage

Soil organic C stocks ($Mg\cdot C\cdot ha^{-1}$) for each depth interval was calculated based on the measured soil organic C (SCs) concentration, bulk density (BD), and the thickness of the sampled layer (Yu *et al*., 2021; Kang *et al*., 2025).

$$SCs_i = SC_i \times BD_i \times d_i \qquad \text{(Equation 4)}$$

where: SCs_i, soil carbon storage in the soil layer i ($Mg\cdot C\cdot ha^{-1}$); i represents the 0–20 cm, 20–40 cm, and 40–60 cm soil layers; SC_i, soil organic carbon concentration of the soil layer i ($g\cdot kg^{-1}$); BD_i, soil bulk density of the soil layer i ($g\cdot cm^{-3}$); and d_i, soil thickness of the soil layer i (cm).

Statistical analyses

All data were processed and analyzed using SPSS version 27.0 (IBM Corp, 2020) and R version 4.2.0 (R Core Team, 2022). A one-way analysis of variance (ANOVA) followed by Fisher's Least Significant Difference (LSD) test ($p < 0.05$) was used to assess differences in soil C content, C storage, and other soil properties across forest ages and soil depths. Prior to statistical analysis, data normality was checked using the Kolmogorov–Smirnov test, and variance homogeneity was verified with Levene's test. Relationships between soil C storage and environmental variables were utilised using the correlation (Pearson) coefficient analyses method. The environmental variables included soil factors (pH, BD, Ss, and TN) and stand factors (N, D, H, G, T, M, and AGB). Statistical analyses were performed in SPSS version 27.0

Random forest (RF) model was used to quantitatively assess the effects of individual indices (Ss, BD, pH, TN, N, D, H, G, T, M, and AGB) on the soil C storage. RF is an ensemble machine-learning method based on decision trees that enhances prediction accuracy and model robustness (Breiman, 2001). RF modeling was performed using the "RandomForest" and "caret" packages. The number of trees (ntree) was fixed at 500, while the mtry parameter was optimized via grid search. The "expand.grid()" function in "caret" package was applied to generate candidate parameter sets, and model performance was evaluated across different mtry values to identify the optimal configuration (Chen *et al*., 2024).

RESULTS

Soil physicochemical parameters in different stand ages

The physicochemical properties of soils in the five stand ages are summarized in **Figure 2**. Soil BD ranged from 0.71 to 0.87 g cm^{-3} across the forest stand ages. At all three soil depths, significantly higher BD values were observed in the Yu and Ma compared to the other three stand ages (Nm, Mu, and Pm) (**Figure 2a**).

The lowest pH value (6.33 ± 0,15) was found in the 0–20 cm layer of the Pm, while the highest pH (6.97 ± 0,07) was observed in the 40–60 cm layer of the Yu. In general, soil pH increased with increasing soil depth, with no significant differences observed among stand ages across all soil layers, except for the Yu (**Figure 2b**).

The highest Ss value (28.02 ± 0,59) was recorded in the 40–60 cm layer at the Yu, whereas the lowest value (18.98 ± 0,86) occurred in the 0-20 layer at the Pm. Overall, Ss exhibited to increase with increasing soil depth (**Figure 2c**).

Soil TN content showed significant variation ($p < 0.05$) among different stand ages across the soil layers of 0–20 cm, 20–40 cm, and 40–60 cm (**Figure 2d)**. The highest TN levels were observed in the Pm compared to Ma, Nm, and Mu across all layers ($p < 0.05$). Furthermore, TN concentrations consistently declined with increasing soil depth regardless of stand age ($p < 0.05$).

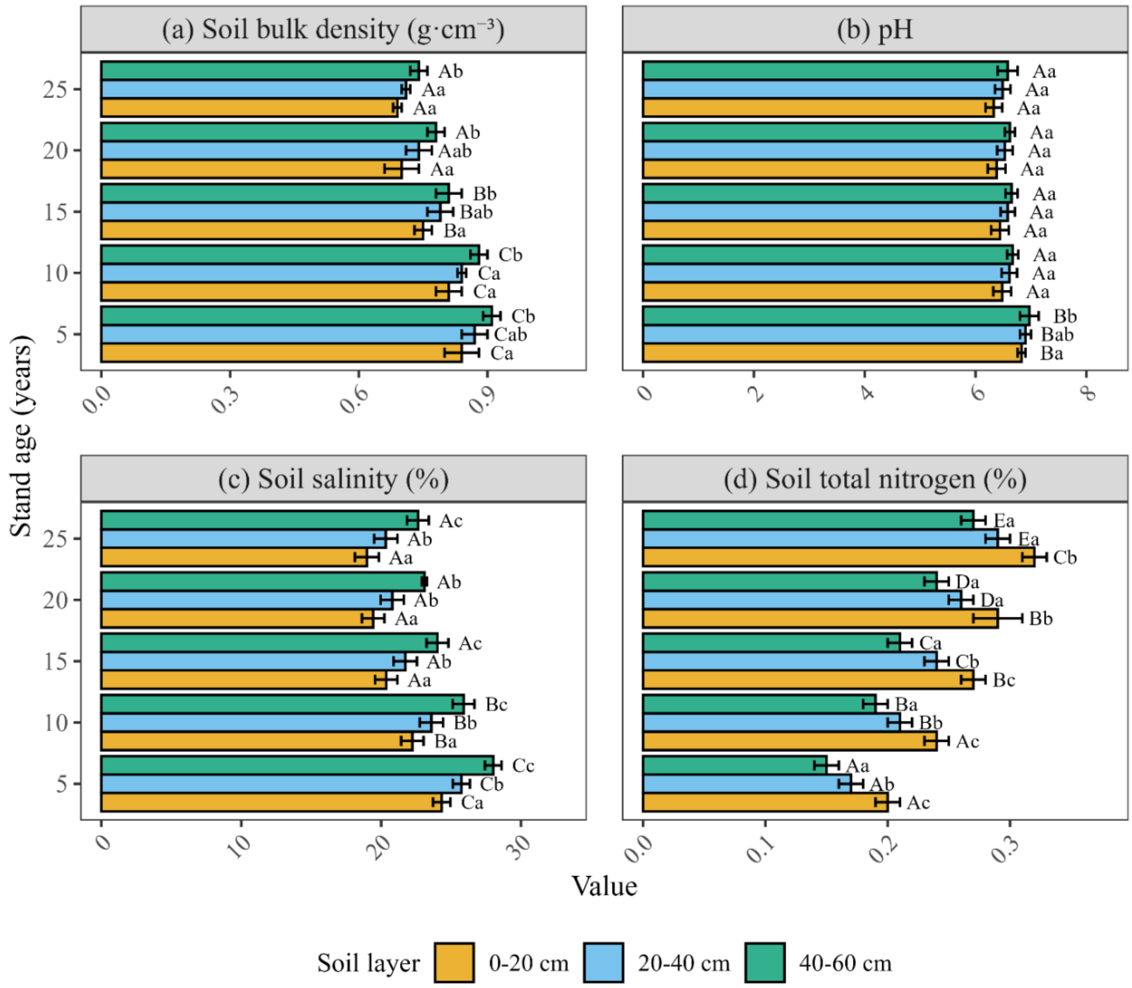

Figure 2. Bar chart with error bars depicting the variation of soil bulk density (a), pH (b), sanility (c), and total nitrogen (d) across soil depths along along forest stand ages. Note: Distinct uppercase letters denote statistically significant differences in soil physicochemical indices among stand ages at the same soil depth, while distinct lowercase letters indicate significant differences in soil physicochemical indices among soil depths within the same stand age.

Soil organic carbon contents in different stand ages

The SOC content in each soil layer (0–20 cm, 20–40 cm, and 40–60 cm) showed significant variations ($p < 0.05$) under different stand ages (**Figure 3a**). In each of these layers, SOC levels were notably higher ($p < 0.05$) in the Pm compared to other age groups (i.e., 0–20, 20–40, and 40–60 cm). Additionally, the contents of SOC showed a significant ($p < 0.05$) decreasing trend with increasing depth of the soil layer under all stand ages.

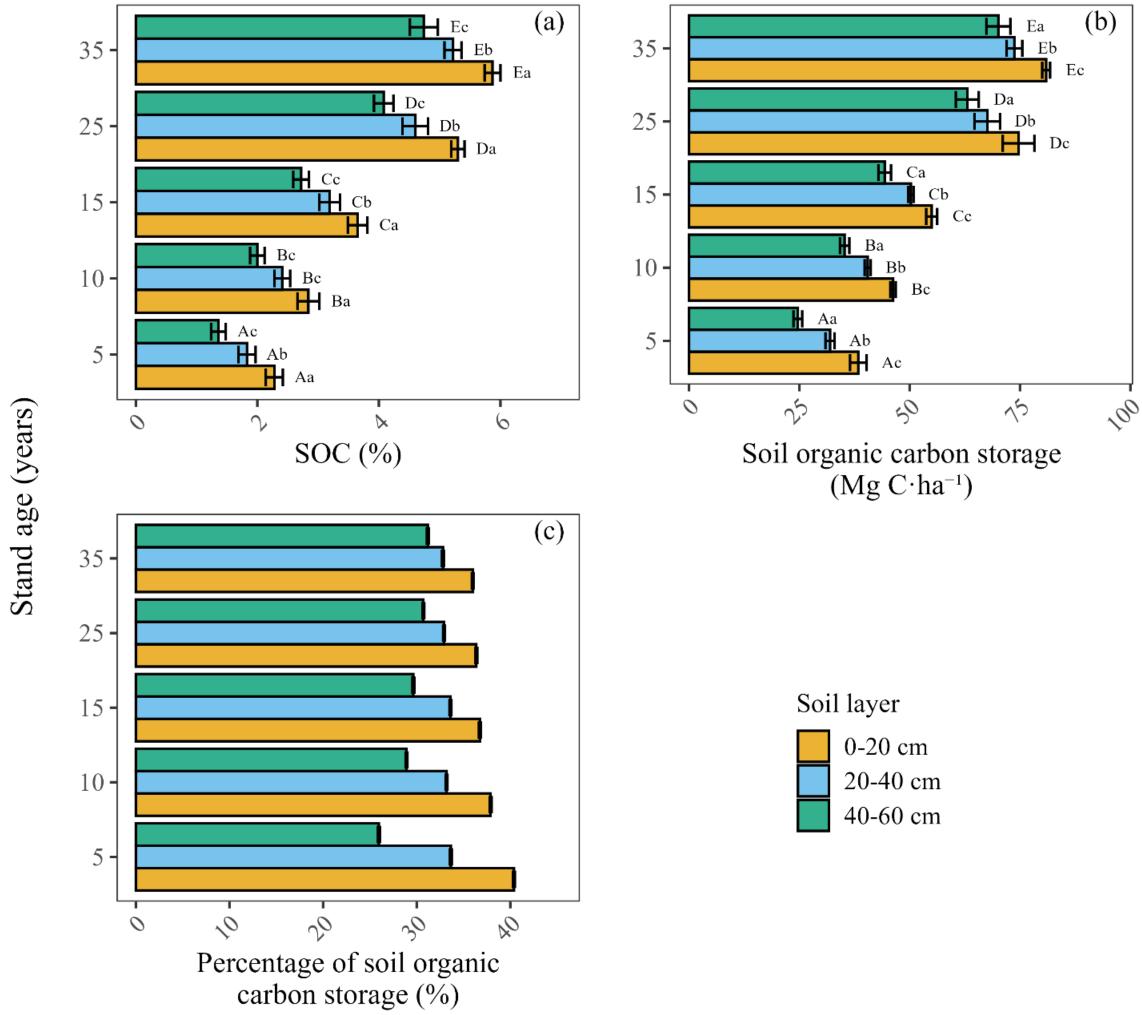

Figure 3. Bar charts with error bars showing the variation in (a) soil organic carbon content, (b) soil organic carbon storage, and (c) the percentage of soil organic carbon storage across soil depths along forest stand ages. Note: Distinct uppercase letters denote statistically significant differences in soil physicochemical indices among stand ages at the same soil depth, while distinct lowercase letters indicate significant differences in soil physicochemical indices among soil depths within the same stand age.

Soil organic carbon stocks in different stand ages

The SCs differed significantly ($p < 0.05$) among soil layers (0–20 cm, 20–40 cm, and 40–60 cm) under different stand ages (**Figure 3b**). The SCs at the 0–20 cm depth ranged from 38.36 ± 1,78 Mg· C· ha^{-1} in the Yu to 80,92 ± 0,80 Mg· C· ha^{-1} in the Pm. In the 20–40 cm soil layer, SCs varied from 31,96 ± 0,94 Mg· C· ha^{-1} in the Yu to 73,73 ± 1,67 Mg· C· ha^{-1} in the Pm. In the 40–60 cm soil layer, SCs varied from 24,66 ± 0,10 Mg· C· ha^{-1} in the Yu to 70,10 ± 2,61 Mg· C· ha^{-1} in the Pm. The total SCs for the 0–60 cm depth ranged from 94.97 ± 2,79 Mg· C· ha^{-1} at the Yu to 224.75 ± 4.41 Mg· C· ha^{-1} at the Pm. Across all depths, mean SCs followed the pattern: Pm > Mu > Nm > Ma > Yu, with the Pm exhibiting significantly higher SCs than the the other stand ages (Mu, Nm, Ma, and Yu).

Overall, for all five stand ages, most of the soil C were concentrated in the upper 0–40 cm soil layer, representing 68.82%–74.02% of total C within the 60 cm soil profile (**Figure 3c**).

Relationships between soil organic carbon storage and environmental factors

Pearson correlation analysis was carried out to assess the relationships between SCs, stand factors (N, D, H, T, G, M, and AGB), and soil properties (pH, BD, Ss, and TN). The results revealed significant positive correlations of SCs with TN, D, H, G, T, M, and AGB, while negative correlations were observed with BD, pH, Ss, and N (**Figure 4**).

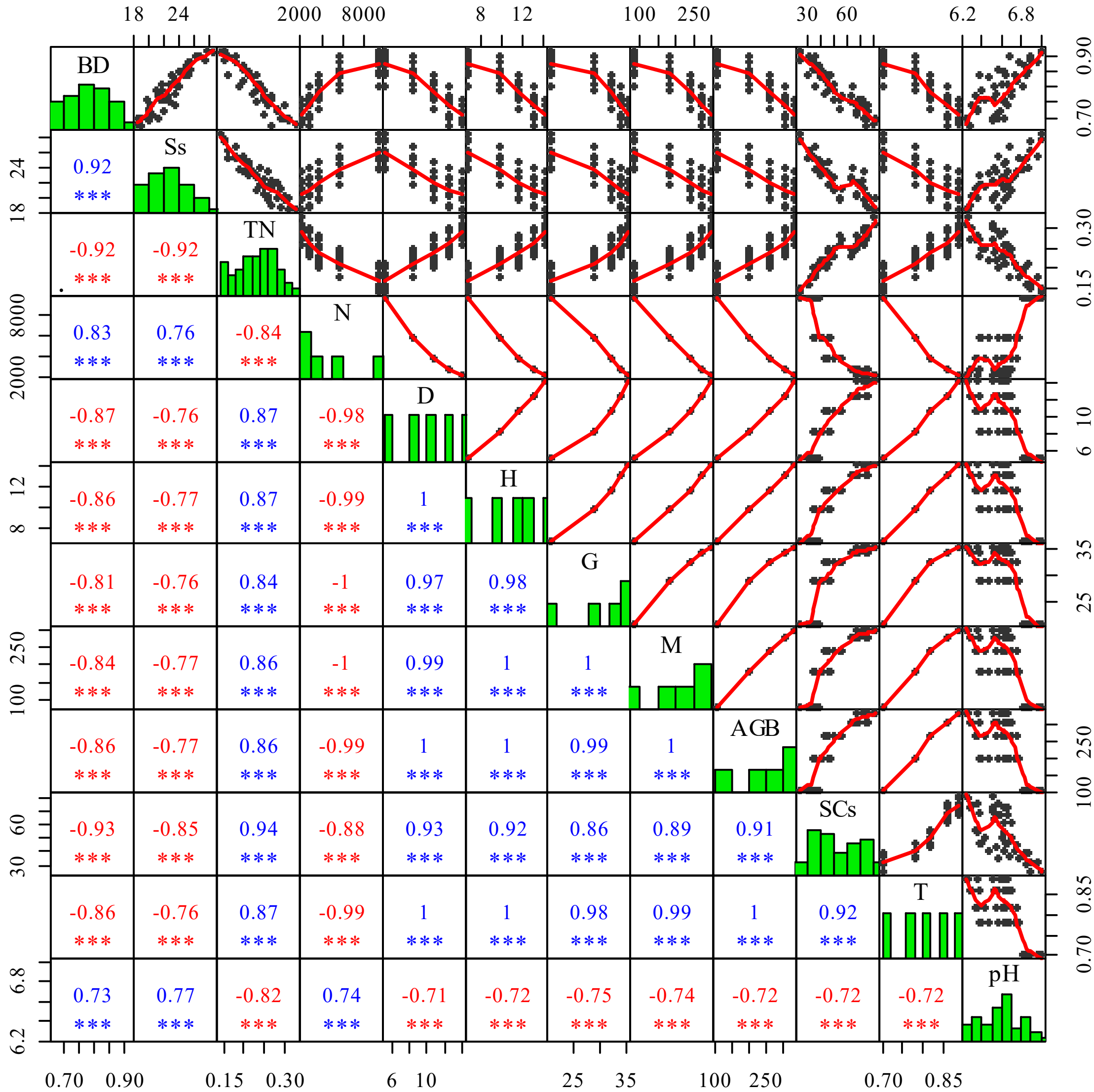

Figure 4. Correlation plot showing the relationships between SCs and environmental parameters. Positive correlations are indicated in blue, negative correlations in red, and the color intensity reflects the strength of each correlation. Note: BD, bulk density; Ss, Soil salinity; TN, soil total nitrogen; N, stand density; D, diameter at breast height; H, height; T, canopy density; G, basal area; M, standing timber volume; AGB, total aboveground biomass; SCs, soil organic carbon storage

Figure 5 presents the relative importance of the independent variables in explaining SCs. Regarding soil properties, Ss and TN exhibit higher explanatory power, amounting to 15.3% and 13.4%, respectively. For stand-related factors, N had the highest explanatory power at

11.8% in explaining SCs. Other variables also contributed appreciably. Soil pH and BD demonstrate explanatory power of 8.7%, and 7.6%, respectively. For stand structure, AGB, G, T, H, D, and M had explanatory power of 7.8%, 7.5%, 7.3%, 6.9%, 6.9%, and 6.8%, respectively. These results suggest that, in addition to Ss, N, and TN, various environmental attributes also play a substantial role in shaping the distribution of SCs

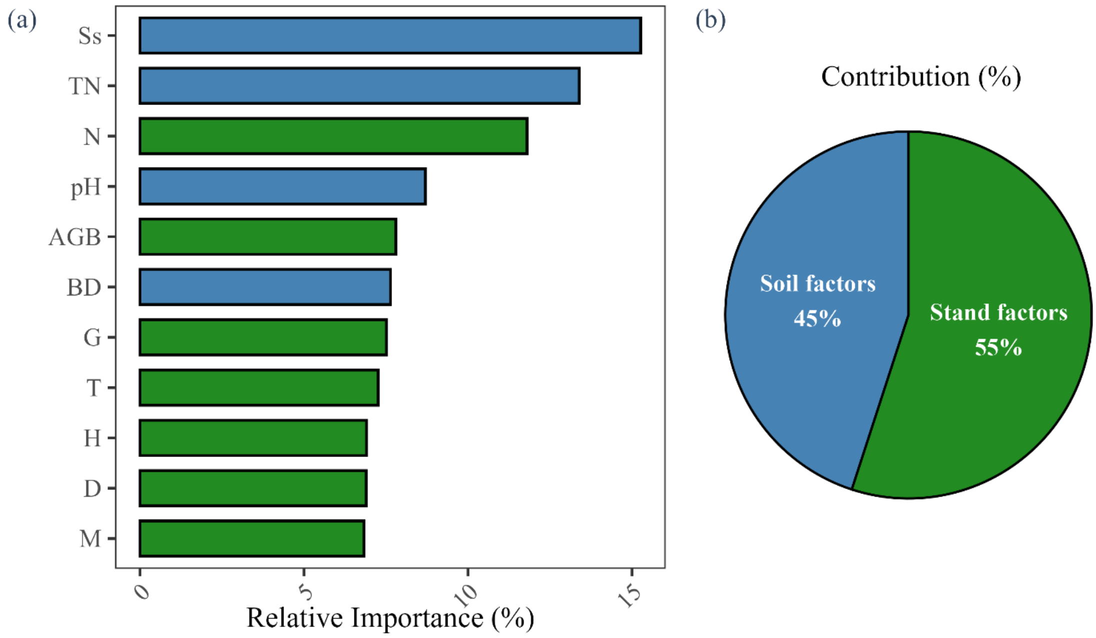

Figure 5. Variable importance analysis based on the Random Forest model. Note: BD, bulk density; Ss, Soil salinity; TN, soil total nitrogen; N, stand density; D, diameter at breast height; H, height; T, canopy density; G, basal area; M, standing timber volume; AGB, total aboveground biomass

DISCUSSION

General characteristics of soil physicochemical features in the study area

The study reveals significant variations in soil physicochemical properties across stand ages and soil depths (**Figures 2a-d**). Soil BD was lower in older stands and surface layers due to greater soil organic matter (SOM) accumulation and reduced anthropogenic disturbance (**Figure 2a**) (Que *et al*., 2010). Elevated SOM increased soil volume without proportionally raising mass, thereby reducing BD, whereas BD increased with depth as SOM declined and compaction intensified (Cuong *et al*., 2022). The soil pH under *R. apiculata* ranged from 6.47 to 6.91, reflecting slightly acidic to near-neutral conditions typical of mangrove soils (**Figure 2b**). Soil pH decreased with stand age, likely due to organic acid release from litter decomposition, but increased with depth as deeper layers were buffered by mineral interactions and less exposed to acidifying processes (Sam & Binh, 2000). Soil salinity decreased with stand age but increased with soil depth (**Figure 2c**), highlighting the role of mature stands in reducing surface salinity through organic matter accumulation and canopy shading, while deeper layers retained more salts due to limited leaching. Similar trends were also reported by (Sam *et al*., 2006). Soil TN content increased with stand age, being lowest in younger and highest in older stands, reflecting progressive litter and root input accumulation, decomposition, and stabilization (**Figure 2d**) (Chau *et al*., 2023; Cuong *et al*., 2025). Soil TN declined with soil depth due to reduced organic matter inputs and greater microbial decomposition, consistent with previous studies emphasizing the dual role of mangroves in generating and retaining organic matter in situ (Song *et al*., 2024).

Soil carbon storage variation with stand age and soil depth

It is well established that soil plays a fundamental role in maintaining the productivity and sustainability of forest ecosystems. The capacity of forest soils to store and transform organic material is largely determined by SOM, which in turn is strongly influenced by forest age and developmental stage (Hanh & Duc, 2017; Hanh *et al*., 2018; Guo *et al*., 2021; Panda *et al*., 2025). The findings of this study revealed that SCs (SOC) was highest in Pm, followed by Mu, Nm, Ma, and lowest in Yu (**Figures 3a-b**). This pattern can be attributed to greater litter input, root biomass, and organic matter accumulation in Pm and Mu compared to the others (Marchand, 2017; Pham *et al*., 2017). In addition, longer afforestation duration has been shown to enhance soil microbial and enzymatic activities, thereby facilitating SOC accumulation (Hanh & Tinh, 2017). Furthermore, soil organic C accumulation is primarily driven by litter inputs, while the higher soil C:N ratio in Pm and Mu slows decomposition, leading to greater stabilization of organic matter (Chau *et al*., 2024). Collectively, these results suggest that older stands have a higher capacity to store SOC, highlighting the key role of stand age in regulating soil C dynamics. Yet, the effects of forest stand age on SCs remain debated (Walcker *et al*., 2018; Song *et al*., 2023), suggesting that stand age may not directly determine soil C stocks but instead exert its influence through interactions with other abiotic and biotic factors (Hanh & Tinh, 2017).

Soil depth is a critical factor regulating the concentration and storage of soil C (Arif *et al*., 2017; Gao *et al*., 2019). Our finding data indicated that C content and storage in the soil of the Pm, Mu, Nm, Ma, and Yu stands decreased considerably with increasing soil depth and was predominantly found in the upper 0–20 cm layer (**Figures 3a-b**). These findings are consistent with the results from previous studies (Eid & Shaltout, 2016; Song *et al*., 2024). The accumulation observed in the surface soils can be attributed to the high concentration of plant residues, animal detritus, and fine roots that foster a nutrient-rich environment conducive to SOM decomposition and stabilization (Adame *et al*., 2014; Arnaud *et al*., 2021). Favorable moisture and aeration conditions in the upper layers further support microbial activity and accelerate the turnover of external inputs (Loi *et al*., 2021). In addition, continuous enrichment from forest litterfall, alluvial deposits, and marine sediments transported by tidal dynamics, coupled with organic matter sulfation and anaerobic soil respiration processes, enhances C retention near the soil surface (Hanh *et al*., 2018). Conversely, our findings (**Figures 2a-c**) revealed that soil BD, pH, and Ss tended to increase with depth, collectively affecting the vertical distribution of C in forest soils. Increased BD led to reduced porosity, hindered root penetration, and limited SOM incorporation, while suboptimal pH levels and elevated Ss inhibited microbial activity and root efficiency, consequently restricting C stabilization compared to the surface horizon, where conditions were more conducive to biological activity and C cycling (Sam *et al*., 2006; Que *et al*., 2010).

Moreover, regarding vertical distribution, approximately 68.81–74.04% of SCs were found within the upper 40 cm across all five stands (**Figure 3c**), suggesting that the surface layer represents a disproportionately significant portion of SCs. This observation underscores the importance of topsoil as a primary C reservoir in the study area, despite its high vulnerability to natural erosion and human-induced disturbances. Consequently, implementing effective plantation management practices is crucial for improving SOC sequestration and sustaining soil productivity.

Effects of environmental variables on soil carbon storage

Various parameters, both biotic and abiotic, influence the amount of C stored in the soil of mangrove forests (Hanh & Tinh, 2017; Guo *et al*., 2024; Panda *et al*., 2025). Based on the random forest regression analysis, we found that the distribution of SCs in the *R. apiculata* plantations was strongly impacted by the soil physicochemical properties and stand structural characteristics. Among the eleven parameters evaluated, Ss, TN, and N emerged as the most critical driving factors influencing SCs (Figure 5). According to previously published results (Huang *et al*., 2017; Xin *et al*., 2014), Ss significantly affects plant growth, SCs, and soil microorganisms, with an inverse trend between soil organic C and Ss. High Ss enhances microbial decomposition, and reduces SOC, while excessive Ss reduces biomass and restricts soil C input. In this study, the soil salinity was moderate (20.66–26.03), and SCs tended to decrease as Ss rose. This finding is consistent with some previous results (Huang *et al*., 2017; Gao *et al*., 2019), although some other studies did not find a clear correlation (Zhao *et al*., 2017), revealing that this relationship may vary depending on soil traits in each region.

Additionally, TN has been identified as another major soil indicator influencing the distribution of SCs in previous studies (**Figure 5**) (Soto-Jimenez *et al*., 2003), as it directly affects plant growth and standing biomass. In this study, we observed a significant positive correlation between SCs and soil TN concentration (**Figure 4**), underscoring the crucial role of soil nutrients in regulating SCs at the local scale (Huang *et al*., 2017). Numerous studies have further demonstrated that nitrogen, as a key limiting nutrient in most ecosystems (Reef et al., 2010), can constrain SOC accumulation (Cuong *et al*., 2025) and thus plays a pivotal role in SOC sequestration through its interactions with SOC (Zaehle *et al*., 2015). The soil C/N ratio is a critical indicator of soil quality, reflecting the balance between SOC and TN and influencing nutrient cycling processes (Dai *et al*., 2019). In this study, we found a strong correlation between the soil C/N ratio and SCs ($r = 0.93$, $p < 0.001$; data not shown), consistent with previous findings (Huang *et al*., 2017). Earlier research has also demonstrated that lower C/N ratios are associated with reduced SOC content in mangrove soils, as elevated nitrogen levels can accelerate organic matter decomposition and consequently decrease SOC storage (Bouillon *et al*., 2003).

Among stand factors, stand density was the most influential factor regulating SCs of *R. apiculata* forests in the study area (**Figure 5**). On the other hand, our results showed that stand density had a significant negative correlation with SCs (**Figure 4**). This suggests that N promoted the accumulation of C in the soil under the canopy of *R. apiculata* plantations. Previous studies have shown that N is an important indicator of forest structure, establishing the spatial structure of the stand (Song *et al*., 2024; Cuong, 2025). Therefore, stand density not only affects the accumulation of litter but also affects soil temperature and moisture as well as microbial activity in the soil, affecting the C cycle (Hai *et al*., 2009). Many studies have acknowledged that the C content in the soil will reach its maximum value at the optimal tree density instead of following a simple correlation with increasing density (Hanh *et al*., 2018).

In addition, other environmental parameters such as soil pH, BD, AGB, G, T, H, D, and M play significant roles in the distribution of SCs across various stand ages (**Figure 4**). Soil pH and BD, as fundamental soil traits, plays a critical role in modulating soil organic matter turnover. The significant negative correlations of SCs with pH and BD identified in the current study are consistent with results of previous findings which also identified a negative relationship between the soil traits (Huang *et al*., 2017; Gao *et al*., 2019). The results indicated that the soil pH and BD strongly influence the variation of microorganisms' community structure and diversity (Tripathi *et al*., 2018), which in turn regulate the process of soil organic C decomposition. Most microorganisms prefer to grow and metabolize at pH values from 6 to 8 (Gao *et al*., 2019). In this pH range, microbial activity is more vigorous, hence contributing to promoting the decomposition of organic C in the soil. Previous studies have reported that microbial activity is typically maximized when soil pH is close to neutral (Xin Kun *et al*., 2014). Furthermore, it also showed that increased biomass in above- and below-ground components serves as the main source of soil C inputs in forest ecosystems, thereby playing a key role in soil C dynamics (Kristensen *et al*., 2008). Consistently, our results demonstrated that plant biomass quantity had a significant effect on soil C stocks. As trees mature, the accumulation of plant biomass increases, with aboveground biomass and litterfall being the main contributors to SOC in surface soils, while belowground root biomass plays a dominant role in SOC accumulation across soil profiles (Hanh & Duc, 2017; Ha *et al*., 2018). Variations in forest canopy structure properties will affect the exchange between soil and aboveground forest biomass, affect soil temperature, soil moisture content, and soil respiration rates, and subsequently affect SCs (Zhang *et al*., 2022).

CONCLUSION

The present study investigated the soil C storage potential and its influencing factors of *R. apiculata* mangrove plantations in the Kien Vang coastal area, Ca Mau Province, Vietnam. The results revealed that the *R. apiculata* mangrove plantation significantly enhanced soil C content and storage, with both increasing notably as forest age advanced. Soil C concentration and stocks significantly decreased with soil depth, showing a clear surface aggregation trend, as more than 70% of soil C stocks were concentrated within the 0–40 cm layer. Among the influencing factors of SCs; Ss, TN, and N were identified as the most significant factors, explaining 15.3%, 13.4%, and 11.8% of the variation, respectively. The results achieved in this study proved that *R. apiculata* mangrove plantations play a significant role in mitigating global climate change by serving as an effective C sink.

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