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Characterizing soil properties and carbon storage potential across diverse wetlands in the Vietnamese Mekong Delta

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ABSTRACT

Wetlands are critical ecosystems that play a vital role in biodiversity conservation, carbon sequestration, and climate regulation. This study investigates soil physicochemical properties and soil organic carbon (SOC) stocks across four wetland types in the Vietnamese Mekong Delta (VMD): mangrove forests, *Melaleuca* forests on clay soil, *Melaleuca* forests on peatland, and flooded grasslands. Results reveal significant variations in soil properties and SOC stocks among these ecosystems. Mangrove forests exhibited neutral pH levels and the highest potassium concentrations, while peatland *Melaleuca* forests had the highest SOC stocks (545.78±91.24 MgC ha^{-1}) and nutrient concentrations, highlighting their significant carbon storage potential. Flooded grasslands and clay soil *Melaleuca* forests demonstrated moderate SOC levels (290.75±105.44 MgC ha^{-1} and 251.85±55.76 MgC ha^{-1}), with acidic soil conditions influencing nutrient availability. SOC content generally decreased with depth, except in mangroves, where no significant variation was observed between soil layers. These findings underscore the importance of wetland conservation and the critical role of peatlands in carbon sequestration. The study provides essential baseline data for wetland management and informs strategies to mitigate carbon loss, protect biodiversity, and strengthen ecosystem resilience against climate change.

Keywords: Mekong Delta, plant communities, soil carbon stock, wetland ecosystem.

INTRODUCTION

Wetland ecosystems encompass a broad range of habitats across terrestrial, coastal, and marine environments. They provide numerous ecosystem services that contribute to human well-being, such as fisheries resources, biodiversity conservation, water supply and purification, climate regulation, flood regulation, coastal protection, recreational opportunities and tourism (Millennium Ecosystem Assessment, 2005; Mitsch et al., 2015). Among their functions, wetland ecosystems play an important role in the global carbon cycle, as significant carbon sinks (Carnell et al., 2018). The anoxic conditions commonly found in wetlands slow decomposition of organic matter, resulting in substantial organic accumulation. As a result, wetlands can contain far greater soil carbon concentrations – sometimes exceeding 40% in contrast to the typical 0.5–2% found in agricultural soils (Nahlik and Fennessy, 2016). Forested freshwater wetlands, estuarine forests, salt marshes, flooded grass, and mangroves are especially important in soil carbon sequestration, often storing carbon for extended periods while maintaining relatively low methane emissions (Malak et al., 2021).

Although wetlands are among the world's most important carbon reservoirs, their area has been rapidly declining due to the pressures of the economic development and climate change (Davidson, 2014; Xu et al., 2024). Climate change manifestations – rising temperature, altered rainfall patterns, changing streamflow, drought, sea levels rise, and saltwater intrusion – adversely affect wetland ecosystems and their plant communities by altering hydrological regimes and soil characteristics (Tran et al., 2015; Dang et al., 2021). Concurrently, socio-economic development activities, including urban development, industrialization, agricultural intensification, and land use/land cover (LULC) changes – have profoundly impacted the management and conservation of wetlands globally and regionally (Akinyemi and Speranza, 2024; Fluet-Chouinard et al., 2023; Nguyen et al., 2022; Zhang and Ke, 2016). In this context, the VMD – the largest wetland region in Vietnam – has experienced significant wetland loss and degradation due to socio-economic pressures and LULC changes (Funkenberg et al., 2014; Nguyen et al., 2016; Nguyen et al., 2020; Nguyen et al., 2022). Over the last three decades (1990–2020), more than 23% of the VMD's wetland area has disappeared, primarily because of aquaculture and agricultural expansion (Nguyen et al., 2022). Beyond their importance in in biodiversity conservation and provision of ecosystem services, wetlands in the VMD act as vital carbon sinks. Hence, the loss of wetland could diminish carbon storage and increase atmospheric carbon concentrations, exacerbating climate change.

Typical wetland ecosystems in the VMD include *Melaleuca* forests (e.g., in front of Tram Chim National Park, U Minh Thuong National Park, Tra Su cajuput forest), mangrove forests (e.g., Mui Ca Mau National Park), and flooded grasslands (e.g., Phu My Grassland Nature Reserve). Numerous studies have documented that these ecosystems – *Melaleuca* forests, mangrove forests, and flooded grasslands – store significant amounts of carbon in both biomass and soil (Bajaj et al., 2024; Nam et al., 2016; Tran et al., 2015; Tue et al., 2014). For instance, *Melaleuca* forests in the VMD (Phu Quoc National Park and U Minh Thuong National Park) contain carbon stocks ranging from 159.36±21.01 MgC ha^{-1} to 784.68±54.72 MgC ha^{-1} (Tran et al., 2015). The carbon storage in mangrove forest fluctuates from 762.0±57.2 MgC ha^{-1} (Tue et al., 2014) to 889±111 MgC ha^{-1} (Nam et al., 2016) while soil carbon stock is 122.27±35.47 MgC ha^{-1} (Lu et al., 2023). However, the capacity for soil carbon storage varies substantially across different wetland community types in the VMD due to their diverse hydrological conditions, soil properties, and plant communities. Comprehensive and consistent assessments of soil organic carbon (SOC) stocks in these distinct wetland ecosystems are still lacking. Therefore, studying SOC accumulation in a range of wetland community types is crucial for understanding their carbon sequestration potential. The findings will provide a critical scientific foundation for developing strategies to manage and conserve soil carbon stocks in VMD wetlands, thereby supporting the long-term conservation and sustainable management of these valuable ecosystems.

MATERIALS AND METHOD

Study sites

The study sites are in the VMD in the South of Vietnam. VMD has a mostly flat terrain with an average elevation of 0.7–1.2 m. This area is in the tropical monsoon climate zone, divided into two distinct seasons: the dry season and the rainy season. The average annual rainfall is approximately 1.800 mm. The hydrological regime is directly affected by the upstream flow, the tidal regime of the Viet Nam East Sea, and part of the tidal regime of the Gulf of Thailand. Land formed by the process of alluvial deposition of the Mekong River system, parallel to the process of alluvial deposition, gradually raising the height of the ground is the process of accumulating plant remains of forest vegetation, decomposing in flooded and anaerobic conditions. Soil in the VMD primarily includes groups of alluvial soil, acid sulfate soil and saline soil.

Wetlands are the typical ecosystem in the VMD which has a significant ecological values and high biodiversity (Nguyen et al., 2024). The study area is diverse in plant species composition which adapt to the inundation regime, soil conditions. Each plant community has dominated species, forming a typical vegetation-type wetland in the VMD. Among them, *Melaleuca cajuputi*, flooded-grass species, and mangrove plants are the distinctive vegetation communities in wetland ecosystem. The research sites covered four types of wetlands in the VMD including *Melaleuca* forest on claysoil (at Tram Chim National Park, Tra Su Landscape Protection Area), *Melaleuca* forest on peatland at U Minh Thuong National Park, flooded grassland (at Tram Chim National Park and Phu My Species–Habitat Conservation Area) and mangrove forest at Mui Ca Mau National Park (Figure 1).

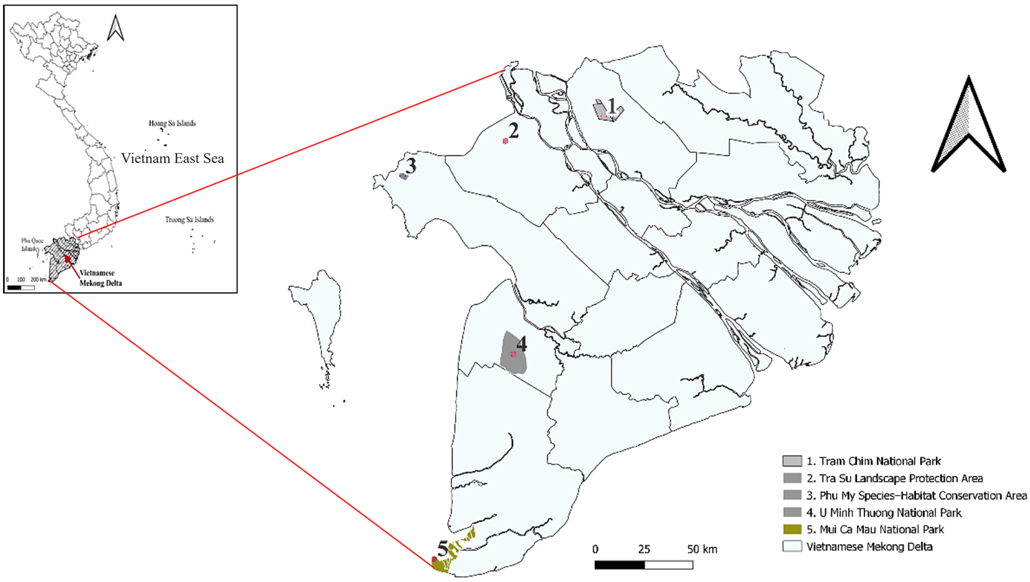

Figure 1. Research sites in VMD

Soil sampling

Soil samples were collected at the two soil layers of various wetland community types during the dry season. The total soil samples in this study were 204 including 44 samples in flooded grasslands, 40 samples in *Melaleuca* forests on clay soil, 20 samples in *Melaleuca* forests on peat soil and 100 samples in mangrove forest. Soil samples in each soil layer including the upper soil layer (0–20 cm) and the lower soil layer (20–60 cm) were collected in polythene bags and were taken to the laboratory. Ring tubes with a volume of 100 cm^3 were also used to collect duplicate soil samples and analyze for bulk density (Table 1).

Laboratory methods

Soil samples were air-dried, ground and passed through a 2 mm sieve and mixed thoroughly. The samples were analyzed in the laboratory to determine soil physicochemical properties and soil carbon content. The soil pH is a measure of the acidity or alkalinity of the soil that affects the amount of nutrients and chemicals that are soluble in soil water. Soil pH-KCl was measured in a 1:5 soil-water ratio (Reeuwijk, 2002). Total soil nitrogen was determined by using Micro-Kjeldahl distillation method (Reeuwijk, 2002). Total phosphorus was determined by phosphorus soluble in dilute acid-fluoride method (Bray-1), phosphate in the extract is determined colorimetrically with the blue ammonium molybdate method with ascorbic acid as reducing agent (Reeuwijk, 2002). Total potassium was determined by a flame photometer at a wavelength of 768 nm. Soil samples in the Ring were dried at 105 °C and then 60 °C to constant mass and the final mass was used to determine bulk density. Organic carbon content in the soil was analyzed by the high-temperature (720 °C) combustion method (Avramidis et al., 2015).

Table 1. Wetland communities in the study area

Wetland community types	Soil types	Research site	Location of the studied wetlands
Flooded grassland	Acid sulfate soil	Tram Chim	10º43’31” N – 105º31’17” E
		Phu My	10º24’58” N – 104°35’24” E
Melaleuca forest on claysoil		Tram Chim	10º43’30” N – 105º31’00” E
		Tra Su	10º34’18” N – 105º02’55” E
Melaleuca forest on peatland		U Minh Thuong	09º35’00” N – 105º05’00” E
Mangrove forest	Saline soil	Mui Ca Mau	08º40’30″ N – 104º47’30″ E

Statistical analysis

Assessment of carbon accumulation in each soil layer of the study area was determined according to the formula (1) (Murdiyarso et al., 2009):

$$Soil\ carbon\ storage\ (MgC\ ha^{-1}) = [Bulk\ density\ (g\ cm^{-3}) \times Depth\ (cm) \times Soil\ organic\ carbon\ (\%)] \quad (1)$$

All statistical analyses in this study were performed using Statgraphic software (Ver. 19). Specifically, to determine which means are significantly different from which others among the four communities, the multiple comparisons (Fisher's least significant difference) procedure was applied. While the t-tests are used for analysing the differences between the two means in the two soil layers. Also, the linear model of simple regression was used to describe the relationship between soil carbon content and other variables of soil characteristics at the 95% confidence level.

RESULTS AND DISCUSSION

Soil physicochemical properties in different types of wetland communities

The analysis of soil physicochemical properties in different wetland types is presented in Table 2. The pH values of flooded grasslands and *Melaleuca* forests were consistently acidic, ranging from 3.69 to 3.82, while mangrove forest soils maintained neutral pH levels (6.78±0.42). Across two soil depths, pH values varied from 3.77 to 6.71 at 0–20 cm and 3.53 to 6.85 at 20–60 cm (Figure 2). Notably, the subsoil layers (20–60 cm) of flooded grasslands and *Melaleuca* forests exhibited lower pH values (3.53±0.47 and 3.80±0.49, respectively) compared to the topsoil (3.84±0.43 and 3.77±0.28), indicating a decrease in pH with depth. Soils with a pH value below 4.5 can be unfavorable for the growth and development of plants. The pH values directly affects the solubility of Al^{3+}, Fe^{2+}, Fe^{3+}, the availability of phosphorus, and nutrient absorption by plants (Saari et al., 2004). Soils with a pH value below 4.5 can adversely affect plant growth biochemical processes, and soil microbial activity. However, certain species, including *Melaleuca cajuputi* and flooded-grass species (e.g. *Lepironia articulata*, *Eleocharis ochrostachys*, *Eleocharis dulcis*), are well-adapted to the acidic conditions of acid sulfate soils and can thrive in such environments (Serbesoff-King, 2003; Safford et al., 2009; Michael, 2013; Quan et al., 2018). Compared to the findings in Southern Vietnam (Phu Quoc National Park and U Minh Thuong National Park), where pH values in *Melaleuca* forests ranged from 3.68 to 5.0 (Tran et al., 2015), the pH values recorded in this study were slightly lower (ranged from 3.77–3.84 (0–20 cm layer) and 3.53–3.8 (20–60 cm layer). Conversely, mangrove forest soils exhibited neutral pH values – ranged from 6.71–6.85 which consistent with studies on mangrove soils in Ca Mau (Le et al., 2021), Bangladesh (Hossain et al., 2012), and Southern China (Zou et al., 2023).

The bulk density of wetland soils varied significantly among wetland types and soil depths. In flooded grasslands, bulk density ranged from 0.991±0.190 to 1.121±0.315 g cm^{-3} ($p > 0.05$), while in *Melaleuca* forests on clay soil, it ranged from 0.856±0.156 to 1.064±0.123 g cm^{-3} ($p < 0.05$). Mangrove forest soils exhibited slightly lower bulk density (0.876±0.188 to 0.933±0.149 g cm^{-3}) ($p > 0.05$). In contrast, the lowest bulk density values were observed in *Melaleuca* forests on peatland, ranging from 0.196±0.039 to 0.492±0.230 g cm^{-3} ($p < 0.05$) (Fig. 2). The bulk density was observed to be highest in flooded

Table 2. Soil physicochemical properties in different types of wetlands (Mean ± SD)

Wetland community types	Soil types	pH	Soil bulk density (g.cm^{-3})	Total nitrogen (%N)	Total phosphorus (%P_2O_5)	Total potassium (%K_2O)
Flooded grassland	Acid sulfate soil	3.69 ±0.47^{a}	1.056 ±0.265^{c}	0.251 ±0.123^{b}	0.023 ±0.008^{a}	0.161 ±0.052^{a}
Melaleuca forest on claysoil		3.68 ±0.28^{a}	0.960 ±0.174^{b}	0.207 ±0.135^{ab}	0.658 ±0.29^{9}b	0.141 ±0.063^{a}
Melaleuca forest on peatland		3.82 ±0.62^{a}	0.343 ±0.124^{a}	0.944 ±0.429^{c}	2.272± 0.963^{c}	0.123 ±0.038^{a}
Mangrove forest	Saline soil	6.78 ±0.42^{b}	0.904 ±0.172^{b}	0.170 ±0.076^{a}	0.096 ±0.038^{a}	8.467 ±1.238^{b}

Note: a, b, c in the same column denotes statistically significant differences (P-value < 0.05).

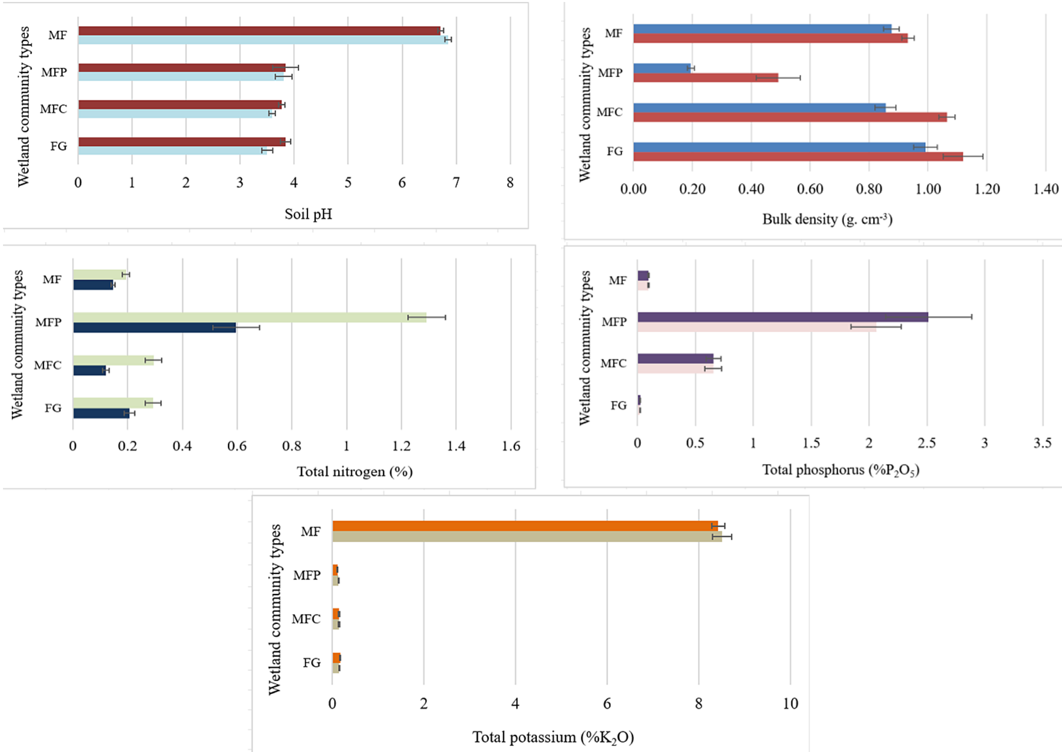

Figure 2. The soil physicochemical properties in the two soil layers of wetlands (MF: Mangrove forest; MFP: *Melaleuca* forest on peatland; MFC: *Melaleuca* forest on claysoil; FG: Flooded grassland)

grassland wetland soils compared to other sites. The lowest bulk density value was found in the upper soil layer (0–20 cm) of *Melaleuca* forest on peatland and gradually increased with depth.

Nutrient concentrations varied among the wetland ecosystems. The total nitrogen was lowest in mangrove ecosystem (0.170±0.076%) and highest in *Melaleuca* forest on peatland (0.944±0.429%). *Melaleuca* forest on peatland also reached the highest value of total phosphorus (2.272±0.963% P_2O_5), succeed by *Melaleuca* forest on claysoil (0.658±0.299% P_2O_5), mangrove forest (0.096±0.038% P_2O_5) and flooded grassland (0.023±0.008% P_2O_5). In contrast, the highest total potassium content was observed in the mangrove forest (8.467±1.238% K_2O) compared to other ecosystems (0.161–0.141% K_2O). Therefore, mangrove plants are adapted to lower concentration of nitrogen and phosphorus, but higher potassium levels compared to plant species in freshwater wetlands. Soil nutrients including nitrogen, phosphorus and potassim are major factors affecting to mangrove forest composition, structure and productivity (Hossain and Nuruddin, 2016). Prolonged inundation may exacerbate nutrient release and the subsequent loss of soil fertility, impacting nutrient cycling (Sánchez-Rodríguez et al., 2019). For inland wetland type, *Melaleuca* forests on peat soil had significantly higher nitrogen and phosphorus concentrations than the remaining ecosystems, while total potassium levels did not show statistically significant difference. The total nitrogen in the topsoil ranged from 0.194±0.09% in mangrove forest to 1.292±0.21% in *Melaleuca* forest on peatland. In the below soil layer, total nitrogen concentration was 0.120±0.056% in *Melaleuca* forest on claysoil and 0.596±0.270% in *Melaleuca* forest on peatland. A statistically significant difference in total nitrogen was observed between the two soil layers in acid sulfate soil type, with nitrogen content gradually decreasing in the lower soil layer. In contrast, no difference was found between the two soil layers in mangrove forests. This suggests that the upper layer of *Melaleuca* forest and flooded grassland accumulates more organic matter with higher nitrogen content than mangrove forests.

Similarly, total phosphorus in *Melaleuca* forest on peatland was highest with 2.514±1.057% P_2O_5 in the 0–20 cm layer and 2.061±0.687% P_2O_5 in the 20–60 cm layer. The potassium content in mangrove soils was 8.427±1.003% K_2O in the topsoil layer and 8.507±1.445% K_2O in the lower soil layer. While the potassium content in wetland types on acid sulfate soils was much lower than that in mangrove soils, fluctuating from 0.108–0.171% K_2O in the upper layer and 0.137–0.151% K_2O in the lower layer. The results also showed that there was no statistically significant difference in phosphorus and potassium content between the two soil layers of wetland ecosystems.

Soil organic carbon at different soil depths in wetland communities

The SOC stock differed significantly among wetland types (Table 3). Based on the formation process from the sea edge to the inland in the VMD, mangrove forest had the lowest SOC stock (183.58±33.78 MgC ha^{-1}), followed by flooded grassland (290.75±105.44 MgC ha^{-1}) and *Melaleuca* forest on clay soil (251.85±55.76 MgC ha^{-1}). *Melaleuca* forest on peatland exhibited highest total SOC stock (545.78±91.24 MgC ha^{-1}). According to the soil layers, SOC stock in the topsoil ranged from 58.89±15.01 MgC ha^{-1} in mangroves to 179.01±36.76 MgC ha^{-1} in peatland *Melaleuca* forest. Similarly, in the subsoil, SOC stock was highest in peatland *Melaleuca* forest, (339.19±73.13 MgC ha^{-1}) ($p < 0.05$). Other studies have reported SOC stocks of *Melaleuca* forest were 360±100 MgC ha^{-1} (Adame et al., 2020), and 41.68-110.23 MgC ha^{-1} (Tran and Dargusch, 2016) in Australia to 159.36±21.01 MgC ha^{-1} and 784.68±54.72 MgC ha^{-1} (Tran et al., 2015) in Southern Vietnam. For mangrove ecosystem, reported SOC stocks include 282±8.1 MgC ha^{-1} in estuarine mangroves and 250±5.0 MgC ha^{-1} in marine mangroves (Zhang et al., 2024), 81.26±10.16 MgC ha^{-1} on the southwest coast of India (Harishma et al., 2020), and 667.4±11.8 MgC ha^{-1} in Can Gio, Vietnam (Dung et al., 2016). These variations in SOC stocks were consistent with the values observed in this study due to differences in soil depths considered in the estimates. The analysed data indicated that SOC stock distribution is closely related to hydrology, vegetation and soil properties.

The SOC content was found to be highest (46.530±8.832%) in 0–20 cm depth in the *Melaleuca* forest on peatland ($p < 0.05$) and lowest (3.362±0.633%) in 20–60 cm depth in the mangrove forest. The average organic carbon content in mangrove soil was lower than previously reported values for the Indo-Pacific region where carbon concentration ranged from 7.9% to 14.6% (Donato et al., 2011) and in regenerated forests in the VMD (9.98±0.93 %) (Nam et al., 2016). However, it was lightly higher than values reported for the Can Gio mangrove forest (2.60±0.06%) (Dung et al., 2016) and the Ca Mau mangrove forest (2.02±0.87%) (Tue et al., 2014). SOC content generally decreased with depth, with higher values in the topsoil layer (0–20 cm), compared to the subsoil layer (20–60 cm). Interestingly, mangrove forests did not show significant differences in SOC content between the two layers, indicating uniform carbon distribution. However, deeper soil layers in mangrove forest showed fluctuations in organic carbon content, as reported by Nam et al. (2016).

Influences of soil characteristics and vegetation communities on soil carbon stock in wetlands

Effects of soil characteristics on soil carbon stock in the VMD wetlands

The important driving factor for soil organic carbon accumulation is related to plant community characteristics and soil factors (Kang et al., 2024; Dung et al., 2016; Guo et al., 2025). Firstly, soil carbon storage depends on soil carbon content and bulk density. According to Islam et

Table 3. Soil organic carbon stock in different types of wetland communities

Wetland community types	SOC content (%)			SOC stock (MgC ha^{-1})		Total SOC stock (MgC ha^{-1})
	0–20 cm	20–60 cm	Mean	0–20 cm	20–60 cm	
Flooded grassland	6.047 ±1.227$^{b, B}$	3.668 ±0.952$^{a, A}$	4.857 ±1.620^{a}	120.51 ±35.12^{c}	170.25 ±78.53^{b}	290.75 ±105.44^{b}
Melaleuca forest on clay soil	5.232 ±1.702$^{b, B}$	3.974 ±1.358$^{a, A}$	4.603 ±1.648^{a}	85.84 ±18.92^{b}	166.01 ±45.41^{b}	251.85 ±55.76^{b}
Melaleuca forest on peatland	46.530 ±8.832$^{c, B}$	22.631 ±11.042$^{b, A}$	34.58 ±15.65^{b}	179.01 ±36.76^{d}	339.19 ±73.13^{c}	545.78 ±91.24^{c}
Mangrove forest	3.382 ±0.551$^{a, A}$	3.362 ±0.633$^{a, A}$	3.037 ±0.591^{a}	58.89 ±15.01^{a}	124.69 ±26.26^{a}	183.58 ±33.78^{a}

Note: $^{a, b, c}$ in the same column denotes statistically significant ($p < 0.05$); $^{A, B}$ denotes a statistically significant difference between two soil layers ($p < 0.05$).

al. (2021), high SOC concentrations were found in the topsoil samples (0–20 cm). The topsoil receives more residue inputs, which are then mineralized. Therefore, this topsoil has a higher SOC than other soil layers and can sequester atmospheric CO_2. In addition, soil bulk density has an impact on soil porosity, aeration, and construction, which in turn has an impact on SOC content and SOC stock (Zou et al., 2023). This study shows that SOC has a negative correlation with soil bulk density (r = -0.68). Higher bulk density reduces soil porosity, impairs aeration, and hinders microbial activity and root growth, resulting in lower organic carbon content (Kang et al., 2024). The study showed that bulk density and organic matter in mangrove soil are lower than inland acid sulfate soils due to the frequent tidal impact. Acid sulfate soil, located farther from the Mekong Rivers, have higher clay content compared to sand and silt, contributing to their denser texture (Ly et al., 2022). Furthermore, flowing water deposits sediments and particulate nutrients in wetlands increasing soil density (Adame et al., 2020). Consequently, the bulk density of acid sulfate soil was higher than in saline and peat soil. The rate of sediment accumulation in wetland ecosystems is another critical factor controlling carbon sequestration rates (Chmura et al., 2003; MacKenzie et al., 2016). Wetlands with higher sediment deposition rates can store more organic carbon, enhancing their role as carbon sinks.

Nutrients in soil including nitrogen availability strongly impacts the soil organic carbon through impacts to root system and organism activities (Kuzyakov et al., 2000; Manu et al., 2024). There was a statistically significant relationship between SOC content and total nitrogen. The correlation coefficient equals 0.91 (with P-value is less than 0.05), indicating a relatively strong relationship between the variables. There was also a moderately strong relationship between the SOC and total phosphorus (r = 0.81). It is consistent with the conclusions of Lu et al. (2011), Huimin et al. (2023), Zou et al. (2023) and Kang et al. (2024). The vegetation layer grows faster, leading to the decreasing of soil mineralization and the release of nutrients. This is because of the need to consume nutrients for plant growth. The source of nutrients for plants includes their own photosynthesis and the main part obtained from the soil. Therefore, the plant growth rate is relatively fast, the demand for soil nutrients increases, which will affect the accumulation of nutrients and carbon storage in the soil (Xiang et al., 2024). Addressing the nutrient imbalances in future restoration may be effective method for ecosystem recovery (Dharmayasa et al., 2024).

Effects of vegetation communities on soil carbon stock in the VMD wetlands

The distribution of SOC content was also related to the distribution of vegetation (Jobbágy and Jackson, 2000; Ji et al., 2020; Guo et al., 2025). *Melaleuca cajuputi* population is the dominant species that distributed naturally at various wetlands in VMD. *Melaleuca* forest in these regions were formed on the claysoil and peatsoil. This ecosystem mainly distributed in the upstream region of VMD belonging Dong Thap and An Giang province. In comparative analysis, the wetland communities that were composed with a high percentage of vegetation coverage (*Melaleuca* forest on peatland) had a significantly higher SOC content. According to (Ly et al., 2022) in depth 0–20 cm, higher SOC stock in these forest types that may link to a high level of carbon inputs, such as leaf litter and root biomass from the forest trees. This is suited following the studies of Teartisup et al. (2021) and Demenois et al. (2017) who suggested that the highest vegetation-covered areas with stable plant communities had enriched SOC content and high SOC stock. However, the carbon stock in *Melaleuca* forests on peat soil is much higher than that in *Melaleuca* forests on clay soil. This is because *Melaleuca* forest on peatland has the thick peat layer in the soil. The structural characteristics of peatland forests are a greater abundance and diversity of lianas and herbaceous species (e.g. *Stenochloena palustri*s, *Blechnum serrulatum*, *Cayratia trifolia*) on the forest floor (Le et al., 2016). The incompleted decomposition of vegetation due to the anoxic conditions causes the accumulation of large amounts of organic matter. This procession creates a thick peat layer, which is rich in carbon. In contrast, in forest ecosystem on claysoi, water regulation and management also implemented for fire prevention and fighting measures. These activities affect to the decomposose of soil organic matter as well as the nutrient leaching. This led to low carbon storage in the soil forest (Tran and Dargusch, 2016).

Flooded grassland ecosystems are charateristic of wetlands in the VMD (e.g. Tram Chim National Park and Phu My Species–Habitat Conservation Area). These ecosystems are diverse in flooded-grass species (*Eleocharis dulcis* (Burm.f.) Trin. ex Hensch., *Eleocharis atropurpurea* (Retz.) Presl and Presl, *Lepironia articulata* (Retz.) Domin, *Oryza rufipogon* Griff. and *Nymphaea* spp.) Although both *Melaleuca* forest and grassland are distributed on acid sulfate soil, there are notable differences in SOC stock between these ecosystems. Seasonally inundated grasslands have been identified as a wetland type that increases soil carbon stocks compared to soils in *Melaleuca* forest on clay soil, likely due to the higher net primary production of grasslands. This can be attributed to the organic matter in grassland, which consists of diverse herbaceous plants that decompose more readily. Additionally, the higher SOC content in flooded grassland is linked to slower decomposition rates caused by reduced microbial activity in anaerobic environment (Jia et al., 2020). Grassland vegetation played an essential role in maintaining soil microbial communities and supporting soil-based ecosystem services, including the ability of soil carbon sequestration (Sánchez-Rodríguez et al., 2019). Furthermore, due to the nature of grassland floodplain, where carbon fluxes are predominantly formed by photosynthesis, the flooded grassland acts as significant carbon pool, with carbon storage occurring at a much faster rate (Lindenberger et al., 2025).

Mangrove forest is another important wetland type that plays a vital role in carbon storage. Mangrove ecosystems have an average annual carbon sequestration rate estimated at 6 to 8 Mg $CO_2 \cdot ha^{-1}$ (Harishma et al., 2020) and their soils hold moderate to high carbon fractions, accounting for 71–98% in estuarine areas and 49–90% in coastal zones (Donato et al., 2011). Mangrove plant communities distributed along the coastal region of Vietnam. Due to favorable natural conditions, the Ca Mau Cape area is a suitable ecological environment for the growth and development of mangrove plants. Mangrove plant communities in Mui Ca Mau are distributed successively according to soil characteristics, tidal regimes and other natural conditions in each area. The dominated plant species in the Ca Mau Cape mangrove forest are *Rhizophora apiculata* Blume, *Avicennia alba* Blume, *Avicennia officinalis* L., *Sonneratia caseolaris* (L.) Engl. (Tue et al., 2014), *Bruguiera parviflora* (Roxb.) Wight and Arn. ex Griff. and other mangrove plants (Nguyen and Lu, 2024). Species assemblage plays a significant role in sediment deposition due to the complex trunk and root structures of mangrove plants (MacKenzie et al., 2016). Most of the soil carbon stock in the layer 0–20 cm is accounted for by autochthonous carbon, such as litter from plants and roots, while some are derived from the tide. Additionally, estuarine mangroves accumulated more SOC in sediments than marine mangroves, primarily caused by the additional terrestrial organic carbon inputs (Zhang et al., 2024). Soil carbon stock increases with the development of mangrove ecosystem because of litter accumulates and organic matter decomposes in the soil (Lunstrum and Chen, 2014; Lu et al., 2023). The structure of mangrove forest, such as tree and seedling density, stem diameter, canopy cover are strongly related to organic matter in mangrove soil (Dharmayasa et al., 2024, Nam et al., 2016). The SOC content was higher in the inland wetland communities compared with the mangrove community in this study. This is result from interior communities may be attributable to less erosion and a more stable hydrological environment, thus allowing more carbon to be stored in the soil (Dung et al., 2016; Guo et al., 2021; Zou et al., 2023).

Seasonally flooded wetland communities are among the most significant wetlands in the VMD, valued not only for their rich biodiversity but also for their role in carbon sequestration. The ability of wetlands to slow chemical decomposition under anaerobic soil and sediment conditions highlights their critical role in the global carbon cycle. (Carnell et al., 2018). The mineralization of SOC is inhibited under waterlogged conditions by restricting microbial growth and activities (Guo et al., 2023). Different types of wetland land use covered with vegetation caused significant changes in the concentration, distribution of SOC, which affect soil carbon sequestration, dynamics, and carbon cycling in wetland ecosystems (Ji et al., 2020). In some cases, soil carbon concentration decreases in areas converted from forested wetlands to flooded grasslands due to reduced carbon inputs, physical disturbances, and altered hydro-periods. However, carbon pools do not necessarily decrease because of increases in soil bulk density (Hernandez et al., 2015). In the VMD, mangrove plants typically grow on muddy soils near the sea edge, whereas peatland formations develop in swamp areas, supporting diverse vegetation such as grasses, shrubs and trees. Consequently, the variations in SOC stock are closely linked to the specific characteristics of vegetation formations.

CONCLUSIONS

This study highlights the critical role of wetlands in the VMD as key ecosystems for biodiversity conservation and carbon sequestration. Significant variations in SOC stocks were observed across different wetland types, with *Melaleuca* forests on peatland exhibiting the highest SOC stock, followed by flooded grasslands, *Melaleuca* forests on clay soil, and mangrove forests. These differences are primarily influenced by hydrological conditions, vegetation types, and soil properties. Given the high carbon storage potential of *Melaleuca* forests on peatland, implementing appropriate management practices and preventing the conversion of wetland types should be taken to maintain the storage and stability of SOC in these wetlands.

The findings highlight the interplay between soil properties, vegetation, and hydrological regimes in influencing carbon storage. Wetland ecosystems with higher vegetation coverage and stable hydrological conditions, such as *Melaleuca* forests on peatland, exhibit enhanced carbon sequestration potential. Moreover, the strong correlations observed between SOC and soil nutrients, particularly nitrogen and phosphorus, further emphasize the importance of nutrient management in wetland restoration efforts. This study provides essential baseline data for wetland conservation and sustainable management, emphasizing the importance of protecting high-carbon ecosystems such as peatlands. Effective conservation strategies should prioritize these ecosystems to mitigate carbon emissions, enhance biodiversity, and ensure the long-term sustainability of the VMD's wetlands.

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