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CARBON POOL AND RESPIRATION OF RHIZOSPHERE SOILS OF DIFFERENT MANGROVE PLANT SPECIES IN BANGLADESH SUNDARBANS

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Abstract

Bangladesh Sundarbans like other mangrove ecosystems are vital carbon reservoirs in the global carbon cycle. Soil respiration, a key carbon flux, is closely linked to climate change. Despite extensive research on the Sundarbans, a gap exists in studying rhizosphere soil carbon pool (SOC) and respiration (Rs), which is crucial for understanding its role in global climate dynamics, especially the local climate. This study investigated SOC pools and Rs rates of oligohaline, mesohaline, and polyhaline zones of the Bangladesh Sundarban Mangrove Forests (SMF). The oligohaline zone exhibited the highest average SOC content (11.26 ± 5.52 t/ha), followed by the mesohaline zone (9.91 ± 3.09 t/ha) and the polyhaline zone (9.86 ± 4.16 t/ha). The Rs rate was comparatively higher in the mesohaline zone (28.19 ± 5.02 mg CO_2/g soil), followed by the polyhaline zone (27.81 ± 4.38 mg CO_2/g soil), and the oligohaline zone (27.63 ± 4.16 mg CO_2/g soil) though the differences were not significant. Further analyses explored the influences of plant species on SOC and Rs. While rhizosphere soil of distinct plant species displayed varying SOC values, Rs did not exhibit significant differences among different plant species, and no significant relation was observed between Rs and SOC values. Mangroves were noted to store substantial amounts of organic carbon in their soils, yet they released relatively less carbon dioxide (CO_2) through soil respiration compared to other tropical forests. This unique characteristic underscores the critical role of mangroves in global climate change dynamics. Conclusively, this study offers insightful information about the carbon dynamics of the Bangladesh SMF, emphasizing the significance of mangroves as carbon reservoirs with the potential to influence climate change adaptation strategies.

Introduction

Mangrove ecosystems, acting as the land-water interface, serve as vast and dynamic carbon reservoirs, playing a pivotal function in the worldwide cycling of carbon and serving as a sink for atmospheric CO_2 (Pandey and Pandey 2013, Zhu and Yan 2022). The Sundarban mangrove forests (SMF) in Bangladesh, spanning approximately 6,000 square kilometers, have been categorized into oligohaline, mesohaline, and polyhaline ecological zones depending upon salinity (Nazrul-Islam 2003, Ahmed *et al.* 2023).

Soil and vegetation carbon sequestration plays a pivotal role in mitigating climate change by offsetting the impacts of greenhouse gases (GHGs) (Janzen 2004, Meliho *et al.* 2023). Globally, soil holds more than 2300 billion tonnes of organic carbon, making it the largest terrestrial reservoir of organic carbon (Stockmann *et al.* 2013). Another estimate showed that the soil organic carbon (SOC) stock stores 1,500 PgC in the top meter of soil, surpassing the combined carbon content of both the atmosphere and terrestrial vegetation (Poulter *et al*. 2021). Notably, over 70% of the total SOC in all terrestrial ecosystems is concentrated within forest ecosystems (Jandl *et al.* 2007). At regional and global scales, the variability of SOC is linked to factors like net primary

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productivity, latitude, coastal geomorphology, and sea-level trends. Meanwhile, site-specific distinctions arise from differences in stand age, species composition, soil properties such as salinity, pH, organic matter, elevation, plant–microbe interactions, plant-litter biochemistry, and tidal patterns (Kauffman *et al.* 2020, Rahman *et al.* 2021). Wetlands make up about 5% of the land's surface and they sink more CO_2 than any other land ecosystem. Because sulfate inhibits methanogenesis, estuarine wetlands have a higher capacity for sequestering carbon than other wetland systems (Bridgham *et al*. 2006, Mitra *et al*. 2012). Consequently, even slight alterations in the size of the forest SOC reservoir can have significant global implications for climate change, leading to potential increases in concentrations of GHGs in the atmosphere and contributing to global warming (Kweku *et al*. 2018, Cai and Chang 2020). Global warming is expected to accelerate the decomposition of SOC, potentially resulting in increased carbon emissions from soils and creating a positive feedback loop for climate change, exacerbating global warming (Cox *et al.* 2000, Jones *et al.* 2005).

Soil respiration (Rs) represents the primary pathway through which carbon exits terrestrial ecosystems, making it the second-largest global carbon flux. Soil respiration, driven by both plant root and microbial activities, plays a vital role in carbon cycling within terrestrial ecosystems. This process involves soil organisms respiring CO_2 to obtain energy from the breakdown of organic matter to support their life processes (Morote *et al.* 2022). High salinity levels act as a factor that diminishes the activity of soil microorganisms, leading to the inhibition of organic matter decomposition and potentially causing a significant decline in Rs (Zeng *et al.* 2013). Soil respiration is closely intertwined with climate change, as the CO_2 released is a greenhouse gas contributing to atmospheric heat retention and surface warming. Elevated greenhouse gas concentrations alter radiation patterns, leading to reduced energy release and increased temperatures. This CO_2-driven global warming further stimulates soil respiration due to the temperature-respiration relationship, ultimately releasing more CO_2 until temperatures reach a maximum around 45°C (Luo and Zhou 2006, Martín Rubio and Rodríguez 2017). Both Rs and SOC serve as critical indicators of soil quality and fertility (Moharana *et al*. 2012, Propa *et al.* 2021). Despite extensive research on the coastal zones and Bangladesh Sundarbans, focusing on topics such as species diversity (Ahmed *et al.* 2018), phytoplankton diversity and water quality (Ahmed *et al.* 2019), edaphic characteristics and contamination level (Ataullah *et al*. 2017, 2018), carbon stock in various plant species (Ahmed *et al.* 2021), forest cover and community structure changes (Ahmed *et al.* 2011, 2018), anatomical adaptation of mangrove species (Rashid *et al.* 2020), there exists a noticeable gap in the study of SOC and Rs of the rhizosphere soil of this mangrove forests. This gap is particularly significant given their relevance in the context of global climate change. Therefore, this research aims to investigate SOC and Rs of the rhizosphere soil of Bangladesh SMF, to assess their role in current global climate changes.

Materials and Methods

A scientific expedition was conducted in the SMF of Bangladesh during the winter season, from January 13, 2021, to January 20, 2021. Thirty-eight quadrats were established in various ecological zones within the Bangladesh SMF (Fig. 1). Out of these quadrats, eleven were placed in the oligohaline zone, fourteen in the mesohaline zone, and thirteen in the polyhaline zone.

Three rhizosphere soil samples were collected from the rhizosphere of dominant plant species based on plant abundance (number) from each of the 38 quadrats (10 m × 10 m). A soil auger was used to collect soil samples at two depths: 0–7.5 cm and 7.5–15 cm. The organic carbon content of the soil was determined using the Walkley and Black method (1934). Bulk density was calculated using the formula of Sahu *et al.* (2016) and Propa *et al*. (2021):

Bulk density (BD) = Oven Dry Weight of Soil / Auger volume

Subsequently, soil organic carbon was calculated with the formula outlined by Sahu *et al.* (2016):

SOC (t/ha) = Bulk density (g/cm^3) × soil depth (cm) × organic carbon (%)

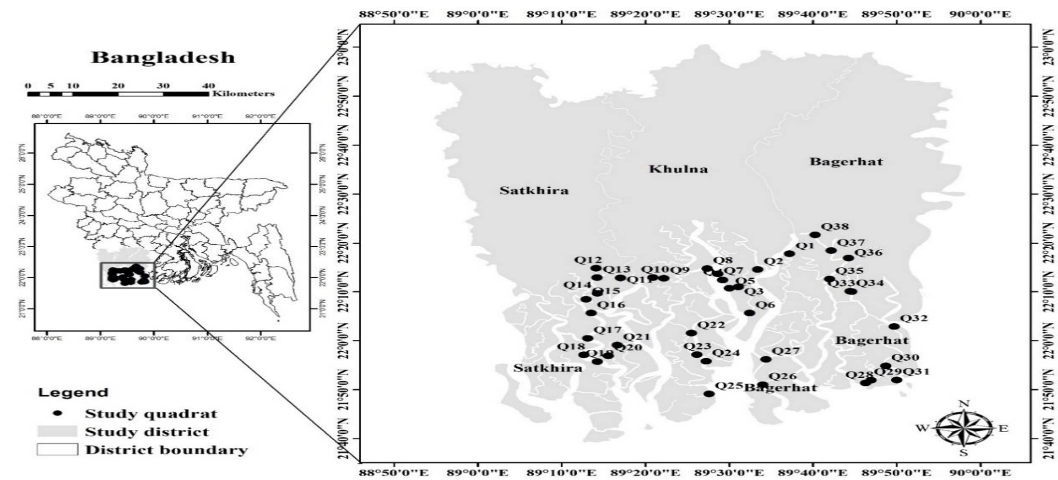

Fig. 1. Map of Bangladesh Sundarban Mangrove Forest (SMF) showing locations of different quadrats (black circles indicates the study area and Q indicates quadrat)

Soil respiration rate was determined by measuring CO_2 evolution, achieved through chemical conversion to CO_3^- in the presence of excess OH^-. Chemical titration was used to calculate the amount of CO_2 by measuring the initial and final OH^- levels. This chemical titration method, among three options, proved effective and straightforward for measuring soil CO_2 respiration. It involved placing 25 gm of fresh equivalent soil with 30% moisture content in mason jars in a dark place, adding an alkaline solution (KOH or NaOH) in a falcon tube to react with CO_2 evolved from the soil, followed by $BaCl_2$ addition and centrifugation. The supernatant, mixed with distilled water and phenolphthalein, was titrated with HCl, and the endpoint corresponded to the CO_2 released by soil microorganisms (Propa *et al.* 2021). The SOC and Rs in rhizosphere soil were compared among quadrats and plant species using one-way ANOVA with Tukey HSD post hoc tests ($\alpha = 0.05$) to detect significant differences. Pearson correlation analysis was used to evaluate the relationship between SOC and Rs.

Results and Discussion

Soil organic carbon values didn't differ significantly among the three ecological zones of Bangladesh SMF. Although no significant differences existed in soil organic carbon content among the three ecological zones of Bangladesh SMF, the oligohaline zone had the highest SOC value. This suggests that the oligohaline zone stores more carbon in its soil compared to the other two zones. The average soil organic carbon (SOC) content varied between 9.86 ± 4.16 t/ha, and 11.26 ± 5.52 t/ha (Table 1).

There were variations among the quadrats within each of the three ecological zones. A higher carbon concentration was observed in the upper layer, except for the mesohaline zone, although this difference was not statistically significant (Table 1). Soil samples were collected from the rhizosphere of the predominant vegetation within each respective quadrat. Significantly, the dominant plant species varied among quadrats, resulting in differing individual species counts within the overall studied quadrat. The SOC value of the rhizosphere of different plants ranged from 4.98 ± 2.61 to 25.45 ± 2.97 t/ha (Table 2). The order of SOC sequences in the rhizosphere soil of different plants was as follows: *A. rotundifolia* (4.98 ± 2.61) < *A. corniculata* (8.1 ± 0.88) < *C. decandra* (9.05 ± 3.67) < *E. agallocha* (9.43±4.11) < *A. officinalis* (9.7 ± 2.17) < *C. ramiflora* (10.19 ± 2.21) < *H. fomes* (10.2 ± 4.18) < *P. paludosa* (10.24 ± 2.03) < *N. fruticans* (10.29 ± 1.61) < *T. dioica* (10.78 ± 0.02) < *A. cuculata* (12.02 ± 5.74) < *B. gymnorrhiza* (12.26 ± 3.64) < *S. apetala* (13.21 ± 3.3) < *X. moluccensis* (15.64 ± 4.97) < *A. aureum* (15.67 ± 6.06) < *C. odollam* (25.45 ± 2.97) t/ha (Table 2)

Table 1. Soil organic carbon (SOC) and Soil respiration (Rs) of rhizosphere soils of different ecological zones of Bangladesh SMF (U = upper layer, 0-7.5 cm; L = lower layer, 7.5-15 cm).

Ecological zone	Layer	SOC (t/ha)	Average	Rs (mg CO_2/g soil)	Average
Oligohaline zone	U	11.85 ± 6.65	11.26±5.52	27.11 ± 4.11	27.63 ± 4.16
	L	10.67 ± 3.48		28.15 ± 4.21	
Mesohaline zone	U	9.45 ± 2.60	9.91±3.09	28.46 ± 5.43	28.19 ± 5.02
	L	10.38 ± 3.48		27.91 ± 4.62	
Polyhaline zone	U	10.33 ± 4.28	9.86±4.16	26.87 ± 4.18	27.81 ± 4.38
	L	9.39 ± 4.03		28.76 ± 4.43	

** The values didn’t vary significantly.

Table 2. Average soil organic carbon (SOC) and Soil respiration (Rs) in rhizosphere soils of different mangrove plant species found in Bangladesh SMF.

Plant Name	SOC (t/ha)	Rs (mg CO_2/g soil)
Acrostichum aureum L	15.67 ± 6.06^{b}	29.46 ± 3.14^{ab}
Aegialitis rotundifolia Roxb.	4.98 ± 2.61^{d}	27.54 ± 5.52^{abc}
Aegialitis rotundifolia Roxb.	8.1 ± 0.88^{cd}	25.32 ± 3.01^{bc}
Aglaia cuculata (Roxb.) Pellegr	12.02 ± 5.74^{bcd}	28.88 ± 1.64^{ab}
Avicennia officinalis L.	9.7 ± 2.17^{bcd}	29.10 ± 2.83^{ab}
Bruguiera gymnorrhiza (L.) Lamk.	12.26 ± 3.64^{bc}	27.30 ± 2.74^{abc}
Cerbera odollam Gaertn.	25.45 ± 2.97^{a}	24 ± 2.04^{c}
Ceriops decandra (Griff.) Ding Hou.	9.05 ± 3.67^{bcd}	27.66 ± 4.94^{abc}
Cynometra ramiflora L.	10.19 ± 2.21^{bc}	27.9 ± 4.37^{abc}
Excoecaria agallocha L.	9.43 ± 4.11^{bcd}	27.55 ± 4.66^{abc}
Heritiera fomes Buch.-Ham.	10.2 ± 4.18^{bcd}	28.43 ± 4.70^{abc}
Nypa fruticans Wurmb.	10.29 ± 1.61^{bc}	31.80 ± 3.23^{a}
Phoenix paludosa Roxb.	10.24 ± 2.03^{bc}	29.03 ± 3.98^{abc}
Sonneratia apetala Buch.-Ham.	13.21 ± 3.3^{b}	27.39 ± 4.99^{abc}
Tamarix dioica Roxb. ex Roth	10.78 ± 0.01^{b}	26.58 ± 9.42^{abc}
Xylocarpus moluccensis (Lamk.) M. Roem.	15.64 ± 4.97^{b}	26.18 ± 8.03^{abc}

** Means sharing similar letter/s vertically are not significantly different, where ($\alpha = 0.05$).

Mangroves' high sedimentation rates facilitate organic compound accumulation in soils, driven by their aboveground and belowground biomass production (Gnanamoorthy *et al.* 2019). Our current study revealed that the average SOC value in oligohaline, mesohaline, and polyhaline zones was 11.26 ± 5.52 t/ha, 9.91 ± 3.09 t/ha, and 9.86 ± 4.16 t/ha, respectively. While the difference in SOC concerning soil salinity was not statistically significant, it was observed that SOC decreased in the high saline zone. This decline may be explained by the fact that salinity in the soil reduces plant productivity, leading to decreased carbon input into the soil (Setia *et al.* 2013). Significant differences in SOC values were observed among the various quadrats of the Bangladesh SMF. This variation can be attributed to the fact that increasing salinity in the Sundarbans inhibits plant growth due to fluctuations in freshwater flow and spatial nutrient discrepancies, thereby influencing carbon stocks across different quadrats (Wahid *et al.* 2007). The SOC estimates in our current study for the Bangladesh SMF at a depth of 7.5 cm (ranging from 9.86 ± 4.16 to 11.26 ± 5.52 t/ha) are comparable to SOC levels observed in other studies, such as the Micronesian coastal fringes of Palau (128.1 t/ha) and Yap (119.5 t/ha) (Kauffman *et al.* 2011), Mangrove forests of Hunter Estuary in southeast Australia at a 20 cm depth (57.31 mg /ha) (Howe *et al*. 2009), and SOC levels in Bangladesh SMF at a 1-meter depth, which range from 112 (90-134) mg/ha. (Rahman *et al.* 2015). Soil organic carbon variation is influenced by considering soil depth, as SOC concentration varies with depth; furthermore, coring for sampling can impact bulk density estimation, which can change estimates of SOC value (Gross and Harrison 2018, Rahman *et al.* 2021). The SOC concentrations exhibit significant variations in distinct mangrove ecosystems, primarily driven by factors such as tidal gradients, forest age, species composition, biomass and sediment deposition (Khan *et al.* 2007). As branches, leaves, and other forest debris fall to the ground and undergo the process of decomposition, they become integrated into the soil surface. Additionally, as plant roots decay, they contribute to the enrichment of the soil with organic matter at various depths (Lacerda *et al*. 1995) Given the distinct anatomy and morphology of various plant species growing in different ecological zones, a significant variation in SOC values was found in rhizosphere soil ($F = 4.74$, $\alpha < 0.05$). The rate of soil respiration (Rs) in Bangladesh's three ecological zones, as observed in the study, showed no significant variation. The mean soil respiration (Rs) content fluctuated between 27.63 ± 4.16 and 28.19 ± 5.02 mg CO_2/g soil (Table 1). Unlike SOC, the rate of Rs was highest in the mesohaline zone and lowest in the oligohaline zone, though this difference was not significant. Among different quadrats of the oligohaline zone, no significant variation in Rs rate was observed (Fig. 2b). In the oligohaline zone, there was no significant correlation between SOC and Rs ($r = -0.119$; $P > 0.05$) (Fig. 5a). In the mesohaline zone, there was a significant difference between the Rs values of quadrats Q-8 (23.44 ± 5.3 mg CO_2/g soil) and Q-23 (33.3 ± 5.74 mg CO_2/g soil). However, the other quadrats did not exhibit any significant differences among themselves, nor did they differ significantly from Q-8 and Q-23 (Fig. 3b). Within the mesohaline zone, no significant association was observed between SOC and Rs ($r = 0.117$; $P > 0.05$) (Fig. 5b) While in the polyhaline zone, no significant difference in Rs rate was found between Q-13 (22.66 ± 4.52 mg CO_2/g soil) and Q-21 (24.3 ± 3.62 mg CO_2/g soil); they exhibited a significant variation compared to Q-25 (32.28 ± 3.88 mg CO_2/g soil. Additionally, the remaining quadrats within this zone did not exhibit any significant distinctions when compared to all the quadrats studied in the same zone (Fig. 4b). In the polyhaline zone, there was a lack of significant correlation between SOC and Rs ($r = -0.120$; $P > 0.05$) (Fig. 5C). While there was a higher CO_2 flux from the soil observed in the lower layer, except the mesohaline zone, it's important to note that this difference was not statistically significant (Table 1). Additionally, although it appeared that in the oligohaline and polyhaline zones, increased depth led to a decrease in SOC value and a parallel increase in Rs rate, and in the mesohaline zone, increased depth led to an increase in SOC value and a parallel decrease in Rs rate, it could be mentioned that this relationship did not find statistically significant (Table 1). The Rs value of the rhizosphere of different plants ranged from 24 ± 2.04 to 31.80 ± 3.23 mg CO_2/g soil (Table 2). The order of Rs sequences in the rhizosphere soil of different plants was as follows: *C. odollam* (24 ± 2.04) < *A. corniculata* (25.32 ± 3.01) < *X. moluccensis* (26.18 ± 8.03) < *T. dioica* (26.58 ± 9.42) < *B. gymnorrhiza* (27.30 ± 2.74) < *S. apetala* (27.39 ± 4.99) < *A. rotundifolia* (27.54 ± 5.52) < *E. agallocha* (27.55±4.66) < *C. decandra* (27.66 ± 4.94) < *C. ramiflora* (27.9 ± 4.37) < *H. fomes* (28.43 ± 4.70) < *A. cuculata* (28.88 ± 1.64) < *P. paludosa* (29.03 ± 3.98) < *A. officinalis* (29.10 ± 2.83) < *A. aureum* (29.46 ± 3.14) < *N. fruticans* (31.80 ± 3.23) mg CO_2/g soil (Table 2). Pairwise correlation analysis indicated that SOC concentrations were not significant predictors of Rs (r = - 0.006, P > 0.05) (Fig. 6).

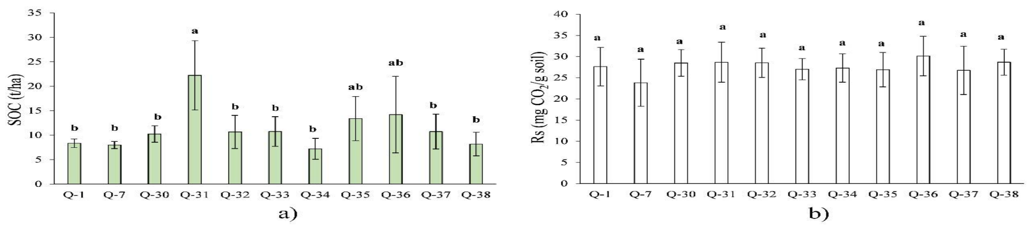

Fig. 2. Average soil organic carbon (SOC) (a) and soil respiration (Rs) (b) of rhizosphere soils of different quadrats (Q) of oligohaline zone of Bangladesh SMF. (Means sharing similar letter/s are not significantly different).

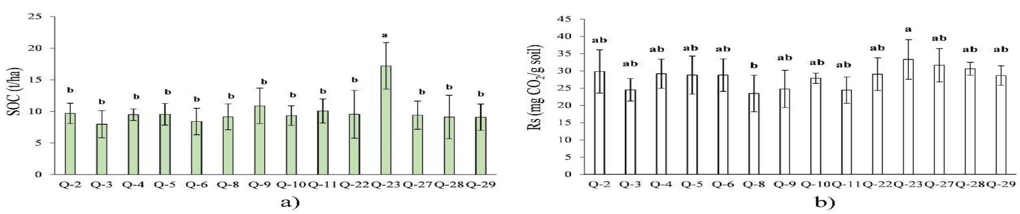

Fig. 3. Average soil organic carbon (SOC) (a) and soil respiration (Rs) (b) of rhizosphere soils of different quadrats (Q) of mesohaline zone of Bangladesh SMF. (Means sharing similar letter/s are not significantly different).

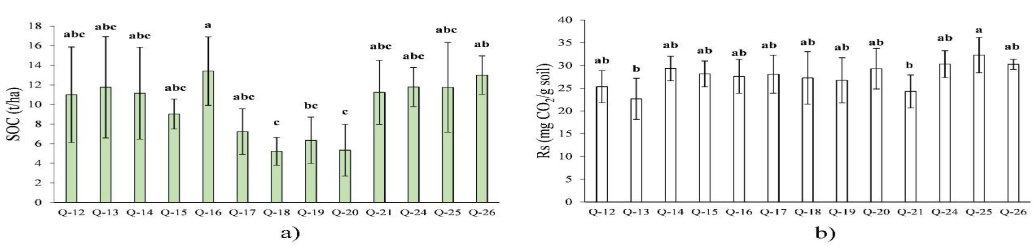

Fig. 4. Average soil organic carbon (SOC) (a) and soil respiration (Rs) (b) of rhizosphere soils of different quadrats (Q) of polyhaline zone of Bangladesh SMF. (Means sharing similar letter/s are not significantly different).

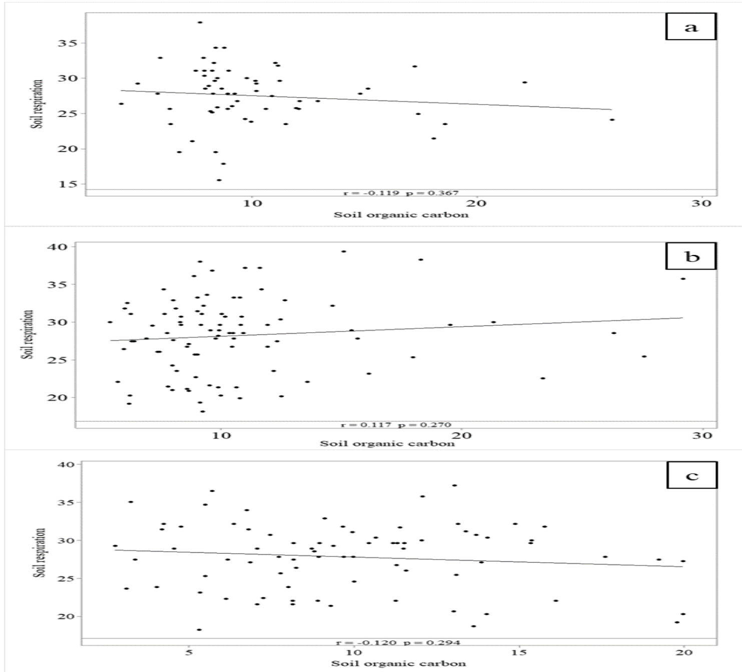

Fig. 5. Relationship between soil organic carbon and soil respiration of rhizosphere soils of (a) Oligohaline zone, (b) Mesohaline zone, and (C) Polyhaline zone Bangladesh SMF.

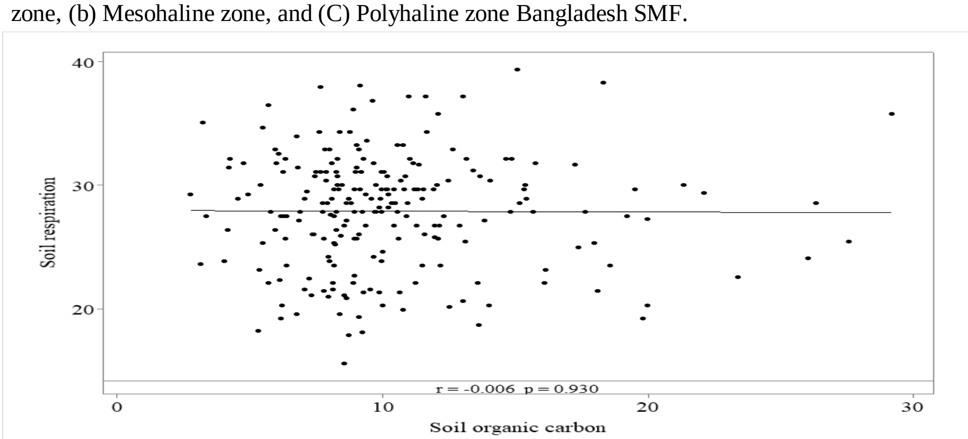

Fig. 6. Relationship between soil organic carbon and soil respiration of rhizosphere soils of overall Bangladesh SMF.

However, it aligns with the findings of Aryal *et al.* (2017). The Rs rate in Bangladesh SMF varied between 27.63 ± 4.16 and 28.19 ± 5.02 mg CO_2/g soil, whereas in the secondary mangrove forest of eastern Thailand, the average Rs rate varied between 0.456 to 0.876 µmol CO_2 m^{-2} s^{-1} (Poungparn *et al.* 2009) and in Sal Forest (deciduous Forest) of Bangladesh was between 75.95 to 91.8 mg CO_2/g soil (Propa *et al.* 2021). Indeed, according to Luo and Zhou (2006), Rs tends to increase within the pH range of 4 to 6. In the case of the sal forest, the pH levels fall within this range, ranging from 4.73 to 6.03 (Propa *et al.* 2021). However, the average soil pH in the SMF is slightly alkaline, ranging from 7.0 to 7.9 (Ataullah *et al.* 2017). This alkaline pH range could potentially lead to a decrease in the rate of Rs within the SMF. Another contributing factor to the lower values of Rs (soil respiration) in mangrove soils is the frequent occurrence of anaerobic conditions (Lovelock *et al*. 2014). These conditions can hinder the activity and respiration of microorganisms and benthic organisms in mangrove forests in contrast to terrestrial forests (Poungparn *et al*. 2009).

Rhizosphere Rs exhibited no significant variations among the three ecological zones in the SMF, as salinity had no significant effect on soil CO_2 emissions (Das *et al.* 2017). Also, no significant differences were found among the rhizosphere soil respiration of different mangrove plant species ($F = 0.66$, $\alpha > 0.05$). Mangroves can sequester as much as five times more organic material than tropical upland forests (Donato *et al*. 2011), owing to their high productivity and slow rates of soil decomposition, notably in their soils (Alongi 2012), but release CO_2 via soil respiration less than other tropical forests. So, mangrove ecosystems play a pivotal role in current global climate changes.

In conclusion, this study highlights the vital role of Bangladesh SMF as significant carbon reservoirs, despite observed changes in tree composition and soil organic carbon due to increasing salinity. While plant species influence soil organic carbon, soil respiration rates exhibit surprising complexity, suggesting further research is needed to understand the unique carbon cycling mechanisms of mangroves. Despite complex interactions, mangroves release comparatively lower carbon dioxide amounts, emphasizing their significance in climate change mitigation. Further research is warranted to understand why mangrove soil respiration rates differ from other forests and the contributing factors. Overall, this research underscores the critical contribution of mangroves to global carbon cycling and climate change adaptation strategies.

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References

Ahmed A, Ahmed T and Ataullah M 2021. Carbon stock of different parts of major plant species of three ecological zones of Bangladesh Sundarbans. Bangladesh J. Bot. **50**(2): 373-385.

Ahmed A, Akter N, Hasan S and Ataullah M 2019. Spatio-temporal variations of water quality and phytoplankton diversity of the different rivers flowing within Sundarban mangrove wetland ecosystem of Bangladesh. J. Biodivers. Conserv. Bioresour. Manag. **5**(1): 61-76.

Ahmed A, Ataullah M, Rashid P, Paul AR, Dutta S and Ali MS, 2018. Species diversity, change in forest cover an area of the Sundarbans, Bangladesh. Bangladesh J. Bot. **47**(3): 351-360.

Ahmed A, Aziz A, Khan ANA, Islam MN, Iqubal KF, Nazma M and Islam MS 2011. Tree diversity as affected by salinity in the Sundarban mangrove forests, Bangladesh. Bangladesh J. Bot. **40**(2): 197-202.

Ahmed S, Sarker SK, Kamruzzaman M, Ema JA, Naabeh CSS, Cudjoe E, Chowdhury FI, Pretzsch H 2023. How biotic, abiotic, and functional variables drive belowground soil carbon stocks along stress gradient in the Sundarbans Mangrove Forest?. J. Environ. Manage. **337**: 117772.

Alongi DM 2012. Carbon sequestration in mangrove forests. Carbon Manag. **3**: 313-322.

Aryal DR, De Jong BHJ, Mendoza-Vega J, Ochoa-Gaona S and Esparza-Olguín L 2017. Soil organic carbon stocks and soil respiration in tropical secondary forests in Southern Mexico. Glob. Soil Secur. pp. 153-165.

Ataullah M, Chowdhury MMR, Hoque S and Ahmed A 2017. Physico-chemical properties of soils and ecological zonations of soil habitats of Sundarbans of Bangladesh. Int. J. Pure Appl. Res. **1**(1): 80-93.

Ataullah M, Hoque S, Rashid P and Ahmed A 2018. Spatial variation and contamination levels of different metals in soils of Bangladesh Sundarbans. Indian For. **144**(5): 412-423.

Bridgham SD, Megonigal JP, Keller JK, Bliss NB and Trettin C 2006. The carbon balance of North American wetlands. Wetlands **26**: 889-916.

Cai Y and Chang SX 2020. Disturbance effects on soil carbon and greenhouse gas emissions in forest ecosystems. Forests **11**(3): 297.

Cox PM, Betts RA, Jones CD, Spall SA and Totterdell IJ 2000. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. Nature **408**(6809): 184-187.

Das S, Ganguly D, Ray R, Jana TK and De TK 2017. Microbial activity determining soil CO_2 emission in the Sundarban mangrove forest, India. Trop. Ecol. **58**(3): 525-537.

Donato DC, Kauffman JB, Murdiyarso D, Kurnianto S, Stidham M and Kanninen M 2011. Mangroves among the most carbon-rich forests in the tropics. Nat. Geosci. **4**: 293-297.

Gnanamoorthy P, Selvam V, Ramasubramanian R, Chakraborty S, Pramit D and Karipot A 2019. Soil Organic Carbon Stock in Natural and Restored Mangrove Forests in Pichavaram South-East Coast of India. Indian J. Geo-Mar. Sci. **48**: 801-808.

Gross CD and Harrison RB 2018. Quantifying and comparing soil carbon stocks: underestimation with the core sampling method. Soil Sci. Soc. Am. J. **82**: 949-959.

Howe AJ, Rodriguez JF and Saco PM 2009. Surface evolution and carbon sequestration in disturbed and undisturbed wetland soils of the Hunter estuary, southeast Australia. Estuar. Coast. Shelf Sci. **84**: 75-83.

Jandl R, Lindner M, Vesterdal L, Bauwens B, Baritz R, Hagedorn F, Johnson DW, Minkkinen K and Byrne KA 2007. How strongly can forest management influence soil carbon sequestration? Geoderma **137**(3-4): 253-268.

Janzen HH 2004. Carbon cycling in earth systems—a soil science perspective. Agric. Ecosyst. Environ. **104**(3): 399-417.

Jones C, McConnell C, Coleman K, Cox P, Falloon P, Jenkinson D and Powlson D 2005. Global climate change and soil carbon stocks; predictions from two contrasting models for the turnover of organic carbon in soil. Glob. Chang. Biol. **11**(1): 154-166.

Kauffman JB, Adame MF, Arifanti VB, Schile-Beers LM, Bernardino AF, Bhomia RK, Donato DC, Feller IC, Ferreira TO, Jesus Garcia MDC, MacKenzie RA, Megonigal JP, Murdiyarso D, Simpson L and Hernandez TH 2020. Total ecosystem carbon stocks of mangroves across broad global environmental and physical gradients. Ecol. Monogr. **90**(2): e01405.

Kauffman JB, Heider C, Cole TG, Dwire KA, Donato and DC 2011. Ecosystem carbon stocks of Micronesian mangrove forests. Wetlands **31**: 343-352.

Khan MNI, Suwa R and Hagihara A 2007. Carbon and nitrogen pools in a mangrove stand of *Kandelia obovata* (S., L.) Yong: vertical distribution in the soil-vegetation system. Wetl. Ecol. Manag. **15**(2): 141-155.

Kweku DW, Bismark O, Maxwell A, Desmond KA, Danso KB, Oti-Mensah EA, Quachie AT and Adormaa BB 2018. Greenhouse effect: greenhouse gases and their impact on global warming. J. Sci. Res. Rep. **17**(6): 1-9.

Lacerda LD, Ittekkot V and Patchineelam SR 1995. Biogeochemistry of mangrove soil organic matter: a comparison between *Rhizophora* and *Avicennia* soils in South-eastern Brazil. Estuar. Coast. Shelf Sci. **40**: 713-720.

Lovelock CE, Feller IC, Reef R and Ruess RW 2014. Variable effects of nutrient enrichment on soil respiration in mangrove forests. Plant soil. **379**: 135-148.

Luo Y and Zhou X 2006. Soil respiration and the environment. Amsterdam; Boston: Elsevier Academic Press. ISBN **10**: 0-12-088782-7.

Martín Rubio L and Rodríguez SB 2017. Carbon Dioxide Titration Method for Soil Respiration Measurements. Universidad De Valladolid, Spain, pp. 66.

Meliho M, Boulmane M, Khattabi A, Dansou CE, Orlando CA, Mhammdi N and Noumonvi KD 2023. Spatial Prediction of Soil Organic Carbon Stock in the Moroccan High Atlas Using Machine Learning. Remote Sens. **15**(10): 2494.

Mitra A, Banerjee K and Sett S 2012. Spatial variation in organic carbon density of mangrove soil in Indian Sundarbans. Natl. Acad. Sci. Lett. **35**: 147-154.

Moharana PC, Sharma BM, Biswas DR, Dwivedi BS and Singh RV 2012. Long-term effect of nutrient management on soil fertility and soil organic carbon pools under a 6-year-old pearl millet–wheat cropping system in an Inceptisol of subtropical India. Field Crops Res. **136**: 32-41.

Morote FAG, Abellán MA, Rubio E, García EM, Saucedo FG, Córdoba MIP and Serrano FRL 2022. Productivity and Seasonality Drive Total Soil Respiration in Semi-Arid Juniper Woodlands (*Juniperus thurifera* L., Southern Spain). Forests **13**: 538.

Nazrul-Islam AKM 2003. Mangrove forest ecology of Sundarban: the study of change in water, soil, and plant diversity. *In:* AK Ghosh, JK Ghosh and MK Mukhopadhaya (Eds.), Sustainable Environment: A Statistical Analysis (pp. 126-147). Oxford University Press.

Pandey CN and Pandey R 2013. Carbon sequestration in mangroves of Gujarat, India. Int. J. Botany Res. **3**(2): 57-70.

Poulter B, Fluet-Chouinard E, Hugelius G, Koven C, Fatoyinbo L, Page SE and Wijedasa LS 2021. A review of global wetland carbon stocks and management challenges. *In*: Wetland Carbon and Environmental Management (pp. 1-20).

Poungparn S, Komiyama A, Tanaka A, Sangtiean T, Maknual C, Kato S, Tanapermpool P and Patanaponpaiboon P 2009. Carbon dioxide emission through soil respiration in a secondary mangrove forest of eastern Thailand. J. Trop. Ecol. **25**(4): 393-400.

Propa MJ, Hossain MI and Ahmed A 2021. Soil carbon stock and respiration of rhizosphere soils of *Shorea robusta* Roxb. Ex. Gaertn. f. in relation to some environmental variables of different Sal forests of Bangladesh. Bangladesh J. Bot. **50**(3): 685-693.

Rahman MM, Khan MNI, Hoque AKF and Ahmed I 2015. Carbon stock in the Sundarbans mangrove forest: spatial variations in vegetation types and salinity zones. Wetl. Ecol. Manag. **23**: 269–283.

Rahman MS, Donoghue DN and Bracken LJ 2021. Is soil organic carbon underestimated in the largest mangrove forest ecosystems? Evidence from the Bangladesh Sundarbans. Catena **200**: 105159.

Rashid P, Shethi KJ and Ahmed A 2020. Leaf anatomical adaptation of eighteen mangrove plant species from Sundarbans in Bangladesh. Bangladesh J. Bot. **49**(4): 903-911.

Sahu SC, Kumar M and Ravindranath NH 2016. Carbon stocks in natural and planted mangrove forests of Mahanadi mangrove wetland, East Coast of India. Curr. Sci. **110**(12): 2253-2260.

Setia R, Gottschalk P, Smith P, Marschner P, Baldock J, Setia D and Smith J 2013. Soil salinity decreases global soil organic carbon stocks. Sci. Total Environ. **465**: 267-272.

Stockmann U, Adams MA, Crawford JW, Field DJ, Henakaarchchi N, Jenkins M, Minasny B, McBratney AB, De Courcelles VDR, Singh K, Wheeler I, Zimmermann M 2013. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agric. Ecosyst. Environ. **164**: 80-99.

Wahid SM, Mukand SB and Bhuiyan AR 2007. Hydrologic monitoring and analysis in the Sundarbans mangrove ecosystem, Bangladesh. J. Hydrol. **332**: 381-395.

Walkley A and Black IA 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci. **37**(1): 29-38.

Zeng WZ, Xu C, Wu JW, Huang JS and Ma T 2013. Effect of salinity on soil respiration and nitrogen dynamics. Ecol. Chem. Eng. S. **20**(3): 519-530.

Zhu JJ and Yan B 2022. Blue carbon sink function and carbon neutrality potential of mangroves. Sci. Total Environ. **822**: 153438.

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