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Understanding carbon storage dynamics in Ayeyarwady delta's mangrove ecosystem in Myanmar: insights for restoration efforts

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Keywords: blue carbon, coastal ecosystem, mangrove species, restoration, organic matter

Abstract

Mangroves are highly valued for their ecosystem services, providing a wide range of ecological, social, and economic benefits, including their role as carbon-rich ecosystems. Recent research suggests that preserving mangrove forests can offer a cost-effective strategy for mitigating CO_2 emissions. However, extensive deforestation has placed mangrove ecosystems under severe global threats. Currently, the assessment of mangrove restoration outcomes, particularly regarding soil carbon stocks, is inadequate. Therefore, this study aims to investigate the impact of restoration on soil organic carbon (SOC) in Shwe Thaung Yan, Ayeyarwady coastal region of Myanmar. The study aimed to quantify and compare carbon stocks in different soil layers, examine the carbon sequestration potential of various mangrove species, and evaluate the effectiveness of mangrove restoration efforts. Soil samples were collected in 2015 (pre-restoration) and 2021 (post-restoration) at various soil depths and analyzed for SOC concentration, organic matter content, and bulk density using the Loss on Ignition (LOI) procedure. Significant changes in soil properties were observed between 2015 and 2021, with higher SOC and carbon concentrations observed in 2021. The average soil carbon stocks in 2021 (1954.43 ± 33.24 Mg C ha^{-1}) were approximately 2.7 times higher than the estimated carbon stocks in 2015 (732.26 ± 6.99 Mg C ha^{-1}). Furthermore, the study revealed variations in SOC accumulation among different soil depths, with higher carbon stocks found in the upper soil layers. This study highlights the positive impact of mangrove restoration on SOC accumulation and emphasizes the significance of considering soil carbon dynamics in restoration initiatives. The findings offer valuable insights for the conservation and management of mangrove ecosystems, especially concerning their potential for carbon sequestration and their contribution to mitigating climate change.

1. Introduction

Mangroves are highly productive ecosystems with substantial ecological, social and economic significance (Veettil *et al* 2018). They provide a wide array of ecosystem services, including water purification, wave dissipation, wildlife habitat, and nutrient cycling (Liu *et al* 2014, Sasmito *et al* 2020). These ecosystems are primarily distributed in tropical and subtropical regions, occupying the intertidal zone between the sea and land (Giri *et al* 2011). Despite their critical importance in providing economic and ecological services to humans (Estoque *et al* 2018), global mangrove cover has experienced alarming rates of decline throughout the twentieth century (Duke *et al* 2007, Donato *et al* 2011, de Lacerda *et al* 2022). Due to increased global awareness, conservation policies and invaluable efforts to preserve and regenerate, the rate of

mangrove loss, has slowly decreased in past two decades (Bunting *et al* 2022, de Lacerda *et al* 2022). However, rapid coastal population growth, the desire for infrastructure development, and economic and political pressures for large-scale conversion of mangrove forests into commercial use still pose critical threats to these ecosystems.

Mangrove forests play a crucial role in carbon cycling and are among the most carbon-rich forests, effectively allocating a large quantity of carbon below the ground (Donato *et al* 2011). The high burial rates of carbon in mangroves create an efficient carbon sink, storing a significant amount of organic carbon in the sediments beneath the ground surface (Donato *et al* 2011, Breithaupt *et al* 2012). The carbon sequestered in the biomass and soil of vegetated costal region (e.g. Mangrove forest) is termed as 'blue carbon' (Mcleod *et al* 2011). Recent research has highlighted the importance of mangrove forests in sequestering soil organic carbon (SOC) (Jakovac *et al* 2020, Jennerjahn, 2020, Kauffman *et al* 2020, McHarg *et al* 2022). Mangrove forests can store large amounts of SOC in their root systems and sediments (Kauffman *et al* 2020). It is estimated that mangrove ecosystem contributes 10%–15% of global coastal carbon sequestration (Mcleod *et al* 2011, Liu *et al* 2014, Sasmito *et al* 2020), with approximately 75% of carbon are stored in soil sediments (MacKenzie *et al* 2021). The loss of mangroves leads to the emission of carbon dioxide into the atmosphere, resulting to global warming (Chen *et al* 2021). Therefore, conducting an assessment of the total carbon stock in the soil will help in identifying areas that significantly contribute to mitigating the causes of global climate change.

The global area covered by mangrove forests is approximately 14.8 million ha (FAO 2020), more than a third of which is found in South-East Asia (Estoque *et al* 2018). Despite their crucial ecological and socioeconomic importance, the conservation of mangroves lags behind the rate of destruction. According to Jakovac *et al* (2020), 137–636 km^2 of mangroves are lost annually that represent 0.16%–0.39% of the global ecosystem loss. These recent losses have posed additional risks to blue carbon stocks. In Myanmar, mangroves are found along the Bay of Bengal and Andaman Sea coastline, covering approximately 462,954 ha (Aye *et al* 2023), that accounts for 3.6% of global mangroves (Giri *et al* 2011, Zöckler and Aung 2019, Bunting *et al* 2022). Mangrove forests in Myanmar play an important role in the coastal ecosystems and livelihoods of people living in those regions (Zöckler and Aung, 2019). They protect coastlines from erosion, provide food and habitat for aquatic species, and sequester SOC. Despite their undeniable importance, mangrove forests in Myanmar are facing threats from sea-level rise and land-use conversion for agriculture, industry, and urban development (Mcleod *et al* 2011, Jakovac *et al* 2020). Although, the mangroves restoration program in Myanmar was initiated in 1980 (Aye *et al* 2023), a study showed that the extent of mangroves in Myanmar has decreased by 459.89 km^2 between 1996 and 2016 (Bunting *et al* 2022). Due to increased deforestation, Aye *et al* (2023) stated Myanmar as 'mangrove deforestation hotspot' in Southeast Asia. To address this issue, mangrove restoration efforts have been implemented in Myanmar.

The restoration of mangroves is a critical endeavour aimed at revitalizing and preserving these unique and vital ecosystems (Webb *et al* 2014, Zöckler and Aung 2019, Su *et al* 2021). The restoration of mangroves not only helps to mitigate the impacts of climate change but also provides benefits to coastal communities and the environment, ensuring a healthier and more resilient future for all (Webb *et al* 2014, Su *et al* 2021). Therefore, it is crucial to improve restoration policies for global mangrove ecosystem conservation (Veettil *et al* 2018, Su *et al* 2021). Between 1980 and 2004, restoration efforts in the Ayeyarwady Delta involved replanting mangroves in old rice paddies and abandoned agricultural sites, covering an area of 13,000 hectares (Zöckler and Aung 2019). As a result, conservation efforts after 2016 have increased the mangrove coverage by 74.07 km^2 between 2016 and 2020 (Bunting *et al* 2022). The increased focus on restoration efforts not only contributes to the conservation and protection of biodiversity but also enhances SOC stock. (Detailed information on the restoration efforts is provided in the method section)

Studies on the temporal and spatial distribution of SOC in mangrove ecosystems have been conducted on a global scale (Jakovac *et al* 2020) and in various countries, namely China (Wang *et al* 2013), Gabon (Trettin *et al* 2021), and Indonesia (Kusumaningtyas *et al* 2019). It is estimated that mean SOC at 1m depth ranges between 86–729 Mg C ha^{-1} (Sanderman *et al* 2018). As of 2012, Myanmar's potential carbon stock is 1.18×10^8 Mg C. On the contrary, over the period 2000–2012, Myanmar has loss 7.99% of mangrove carbon stock which is four times more than the global average (Hamilton and Friess 2018). Nevertheless, there is limited research in mangrove ecosystems in Myanmar, especially in estimating the soil carbon stock (Veettil *et al* 2018, Zöckler and Aung 2019, Aye *et al* 2023). The scarcity of research in this area is concerning, given that SOC is a crucial indicator of soil health and plays a vital role in carbon cycling, nutrient retention, and water storage. To address this gap and improve the management and conservation of Myanmar's mangrove ecosystems, this study aims to estimate the spatial and temporal levels of SOC in selected mangrove forests. Our goal is to quantify SOC stocks in mangrove forests after six years of restoration (between 2015 and 2021). The main objectives of this study are—(i) to quantify and compare the carbon stock present in soil layers of various depths within mangrove ecosystems, (ii) to understand the role of different mangrove species in sequestering and storing carbon, (iii) to investigate the effectiveness of mangrove restoration initiative and estimate the

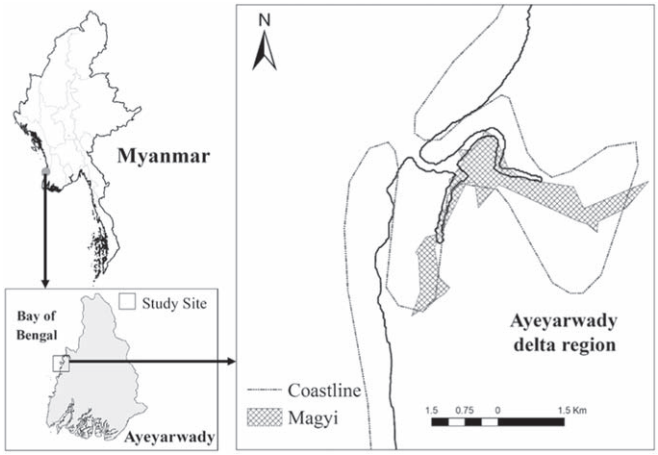

Figure 1. Map of study area.

amount of carbon stock in the soil, and (iv) to determine if restoration of mangrove forest increases SOC. The results of this research will provide valuable information for conservation and management efforts aimed at preserving and restoring mangrove ecosystems for their carbon sequestration potential. To our knowledge, this study represents the first-ever attempt to assess the effectiveness of mangrove restoration in Myanmar in terms of blue carbon stock.

2. Materials and methods

2.1. Study and sampling site

Myanmar has the fourth largest mangrove area in Southeast Asia after Indonesia, Malaysia, and Papua New Guinea (Hamilton and Friess 2018, Bunting *et al* 2022). Myanmar's coastline is 2832 kilometres long and is separated into three coastal zones; (i) the Rakhine Coastal Region, (ii) the Ayeyarwady Delta and the Gulf of Mottama Coastal Region, and (iii) the Taninthayi Coastal Region, stretching along the Bay of Bengal and Andaman Sea (Zöckler and Aung 2019). This study was conducted in Magyi tidal stream, located in the Ayeyarwady delta region in the southern part of the country (figure 1).

Ayeyarwady has experienced a loss of over 20% of its total forest area, including mangroves, from 1990 to 2000 (Veettil *et al* 2018). The area was subjected to afforestation and restoration after 2015. Therefore, the study area is crucial for restoration and its impact on carbon sequestration. Magyi is characterized by the prevalence of mangrove swamps that stretch for eight kilometres (Aung 2015). This region experiences a monsoon-influenced, humid, sub-tropical climate, with an average annual temperature of 27 °C and mean annual precipitation is 3102 mm. The predominant mangrove species found in this region include *Rhizophora apiculata, Bruguiera gymnorhiza, Ceriops decandra,* and *Ceriops tagal.*

2.2. Restoration efforts of mangrove in Magyi

The mangrove ecosystem of Magyi has experienced significant degradation due to natural disturbances and human activities, including the conversion of agricultural land, aquaculture ponds, and salt ponds (Soe-Htun *et al* 2009). Magyi mangrove ecosystem holds great importance as it provides ecological security to the coastal area and livelihood support for coastal fishermen. Additionally, it plays a crucial role in carbon sequestration, with significant carbon storage in its below-ground biomass. Recognizing the significance of preserving Magyi's mangrove forests, the Worldview International Foundation has partnered with the Department of Marine Science at the University of Pathein since 2014 to safeguard these vital ecosystems (Aung 2015). This collaboration has facilitated the exchange of knowledge, resources, and expertise, leading to a more comprehensive and efficient approach to mangrove conservation.

The restoration efforts have primarily focused on strategically planting mangroves in areas that have experienced degradation. This process involves the introduction of new mangrove seedlings, allowing them to establish themselves and recreate the structure and function of the original mangrove ecosystems. The restoration program included 3 different species: *Rhizophora* sp, *Bruguiera* sp and *Ceriops* sp. Concurrently, forest monitoring programs have provided valuable insights into the health and progress of the restored areas. As a result of these initiatives, the mangrove forests in Magyi have demonstrated remarkable recovery. This

restoration is anticipated to bolster the resilience of the coastal region, offering protection against natural disasters and safeguarding the livelihoods of local communities, particularly those reliant on coastal resources.

2.3. Field sampling and laboratory analysis

In September 2015 and 2021, soil sampling was carried out in the mangrove forest, specifically along the tidal creeks, during the neap tide period. The data collected in 2015 mark the pre-restoration, while data collected in 2021 is the post-restoration period. Soil collection, measurement and analysis was done following Breithaupt *et al* (2023). Samples were collected from site mentioned above (figure 1). These plots were mostly dominated by *Rhizophora* sp, *Bruguiera* sp and *Ceriops* sp. Further, in each plots, three soil cores were selected (representing each species) and a stainless steel soil corer of 4.5 cm diameter and 1m depth was used. A common practice of estimating carbon stock is to collect the soil from 1m depth (Jardine and Siikamäki 2014). Each core was separated into three equal segments based on depth interval of 0–33.33 cm (Layer 1), 33.34–66.66 cm (Layer 2) and 66.67–100 cm (Layer 3). To avoid oxygen and moisture loss, the samples were placed in separate labelled containers and sealed. All soil samples were stored in a cool place and transported to the laboratory of the Department of Marine Science, Pathein University for oven drying and analysis. Soil samples were kept in a dark freezer at a temperature of −4 °C until analysis.

2.3.1. Estimation of soil components

The samples were prepared for the Loss on Ignition (LOI) procedure (Breithaupt *et al* 2023). The LOI method is based on the principle that organic carbon in soil combusts when exposed to high temperatures. The weight loss after ignition is used to estimate the organic carbon content (Breithaupt *et al* 2023). The method consists of two steps—(i) drying of samples to remove water, and (ii) combustion to remove soil organic matter.

Initially, any debris and large roots present in the soil samples were removed, and the wet weight of samples were recorded. The samples were then dried in a muffle furnace at 80 °C until they reached a constant mass to ensure no residual moisture content. Weight of each sample were recorded every hour until a constant weight was achieved (it took approximately eight to ten hours). These dry soil sample were then grounded and harmonized. To determine organic carbon by LOI, sample were placed in muffle furnace at 500 °C for three to five hours for combustion (Radabaugh *et al* 2018) with an assumption that the high temperature causes the organic matter to combust, leaving behind inorganic components (Radabaugh *et al* 2018, Breithaupt *et al* 2023). Therefore, SOC is estimated using bulk density (g cm^{-3}), soil depth interval (cm) and concentration of organic carbon (%) content –

$$\text{Weight of organic carbon (g)} = \text{dry weight of sample (80 °C)} - \text{dry weight of sample (500 °C)}$$

$$\text{Concentration of organic carbon (\%)} = \frac{\text{weight of organic carbon (g)}}{\text{dry weight of sample (80 °C) (g)}} \times 100$$

$$\text{Bulk density (g cm}^{-3}) = \frac{\text{dry weight of sample at 800 °C(g)}}{\text{volume of soil sample (cm}^3)}$$

The soil organic carbon (g cm^{-3}) present in core section was computed as –

$$\text{Soil organic carbon (SOC) in core section} = \text{bulk density} \times \frac{\text{concentration of organic carbon}}{100}$$

$$\text{Soil organic carbon (SOC) in core} = \text{SOC in core section} \times \text{soil depth interval}$$

These calculation was repeated for all sampled sites, then the average of total carbon stock was determined.

2.3.2. Estimation of soil organic carbon stock

Soil organic carbon stock (ton ha^{-1}m^{-1}) refers to the total amount of carbon stored in a soil of given study area. It represents the cumulative carbon content within a specific depth range. Estimating soil carbon stock is important for understanding carbon cycling and evaluating the potential of soils to sequester carbon (Kauffman and Donato, 2012). The total soil carbon stock was estimated as -

$$\text{Soil organic carbon stock} = \frac{\text{SOC in core (1)} + \ldots \text{SOC in core (n)}}{\text{n}}$$

One main objective of this study is to determine the change in carbon stock in Magyi region after restoration. As mentioned above, restoration project was carried out between 2015 and 2021. Therefore, to estimate change in carbon stock between six years, we used following formula –

$$\text{Change in SOC between 2015 and 2021 (in \%)} = \frac{(\text{SOC in 2021} - \text{SOC in 2015})}{\text{SOC in 2015}} \times 100\%$$

Table 1. Variation in soil components present in three layers of soil in Maygi region in 2015 and 2021.

Soil Layers (cm)	OM (%)	Carbon concentration (%)	Bulk density (g cm^{-3})	Soil organic carbon stock (Mg C ha^{-1})
		2015 (n = 28)		
Layer 1	$21.19^{a} \pm 1.09$	$11.68^{a} \pm 0.45$	$0.68^{a} \pm 0.01$	$257.50^{a} \pm 10.4$
Layer 2	$22.97^{a} \pm 0.97$	$12.42^{a} \pm 0.41$	$0.63^{a,b} \pm 0.02$	$246.78^{a,b} \pm 5.12$
Layer 3	$23.22^{a} \pm 0.89$	$12.52^{a} \pm 0.37$	$0.60^{b} \pm 0.02$	$234.47^{b} \pm 3.09$
F value	1.24	1.24	5.38	2.76
p-value	0.290	0.290	0.005	0.065
		2021 (n = 32)		
Layer 1	$39.94^{b} \pm 1.30$	$19.46^{b} \pm 0.53$	$1.02^{a} \pm 0.03$	$651.0^{a} \pm 20.2$
Layer 2	$41.89^{b} \pm 1.32$	$20.27^{b} \pm 0.54$	$0.93^{b} \pm 0.02$	$625.6^{a} \pm 18.1$
Layer 3	$46.17^{a} \pm 1.17$	$22.05^{a} \pm 0.48$	$0.92^{b} \pm 0.02$	$677.7^{a} \pm 19.0$
F value	6.35	6.35	4.89	1.86
p-value	0.002	0.002	0.008	0.158

F-values represent the one-way ANOVA while, *p*-value represent the significant of ANOVA. Means in the same columns followed by different letters are significantly different at $p < 0.05$ according to Tukey's HSD test.

2.4. Statistical analysis

The data on SOC concentration and other soil components were analysed by one-way analysis of variance (ANOVA). Prior to performing ANOVA, the data were assessed for homogeneity of variance and normality of distribution. To identify significant of differences between means across various mangrove species and soil layers between 2015 and 2021, Tukey's HSD test was conducted at a significance level of $p < 0.05$. These statistical analysis were conducted using R statistical package software with 'oneway.test()' function in 'car' package (R Development Core Team 2017).

3. Result

3.1. Soil properties along the soil depth

The percentage of soil organic matter (OM) and carbon increases with increasing soil depth, as observed in the soil sample collected in 2015 (table 1). The mean ± standard error of mean for OM ranges from 21.19 ± 1.09% at soil Layer 1 (depth between 0 and 33.33cm) to 23.22 ± 0.89% at soil Layer 3 (depth between 66.67 and 100cm), with no significant difference among layers. A similar pattern was observed for the percentage of carbon. In contrast, there was a significant decrease in bulk density (BD) with increasing soil depth ($F = 5.38$, $p = 0.005$).

On the contrary, significant differences were observed in post-restoration soil samples, particularly in soil properties such as organic matter (OM), carbon percentage, and bulk density (BD) among different soil layers. Soil OM significantly increased with soil depth, ranging from 39.94 ± 1.30% to 46.17 ± 1.17% ($F = 6.35$, $p = 0.002$). A similar pattern was observed in soil carbon concentration across different soil layers (table 1). Furthermore, the ANOVA analysis showed a highly significant difference ($p = 0.008$) between BD and soil layers, which decreased with increasing soil depth (table 1). A comparison between the 2021 soil sample to that of 2015 revealed an increase in OM, percentage of carbon, and BD (figure 2).

3.2. Soil properties of different mangrove communities

The soil properties of different mangrove communities are presented in table 2. It can be inferred that in 2015, soil organic matter (OM) was relatively high in areas covered by *Ceriops* sp (22.63 ± 1.12%), followed by *Bruguiera* sp (22.48 ± 0.89%) and *Rhizophora* sp (22.27 ± 0.97%). However, no significant difference was observed between mangrove species and soil properties (OM, carbon concentration, and BD) (table 2). On the other hand, the soil samples from 2021 showed that the highest percentage of OM was in the areas covered by *Bruguiera* sp (44.35 ± 1.34%), followed by *Ceriops* sp (42.10 ± 1.21%) and *Rhizophora* sp (41.56 ± 1.31%), with no significant differences. Similar distribution patterns were observed for carbon concentration and BD (table 2). Comparing the 2021 soil sample to that of 2015, significant increases were observed in OM, carbon concentration, and bulk density (figure 2).

3.3. Soil organic carbon (SOC) stock

The SOC stock for the top 100 cm soil collected in 2015 and 2021 are shown in table 1. A significant difference was noticed in the SOC stored in soil sample collected in 2015. The mean ± standard error SOC decrease with the increase in soil depth from 257.50 ± 10.4 to 234.47 ± 3.09 ($F = 2.76$, $p = 0.065$). However, SOC was lowest in the mid-layer of soil in a sample collected in 2021 (625.6 ± 18.1). Additionally, SOC was not affected by soil

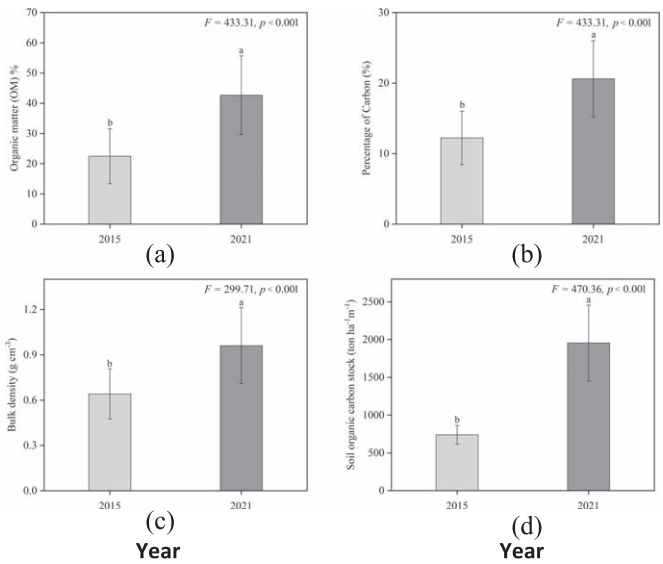

Figure 2. Mean ± SD organic matter (a), concentration carbon in soil (b), bulk density (c), and soil organic carbon (SOC) stock (d) in two different years. F-values represent the one-way ANOVA. Means followed by different letters are significantly different at $p < 0.05$ according to the Tukey's HSD test.

Table 2. Variation in soil components present in three major mangrove species in Maygi region in 2015 and 2021.

Species	OM (%)	Carbon concentration (%)	Bulk density (g cm^{-3})	Soil organic carbon stock (Mg C ha^{-1})
		2015 (n = 28)		
Bruguiera sp	22.48^{a} ± 0.89	12.22^{a} ± 0.37	0.62^{a} ± 0.01	240.91 ^{a} ± 3.97
Ceriops sp	22.63^{a} ± 1.12	12.28^{a} ± 0.46	0.66^{a} ± 0.01	258.40 ^{a} ± 10.3
Rhizophora sp	22.27^{a} ± 0.97	12.13^{a} ± 0.41	0.63^{a} ± 0.01	239.44 ^{a} ± 4.73
F value	0.03	0.03	0.91	2.30
p-value	0.967	0.967	0.405	0.102
		2021 (n = 32)		
Bruguiera sp	44.35^{a} ± 1.34	21.29^{a} ± 0.55	0.98^{a} ± 0.03	685.8^{a} ± 20.6
Ceriops sp	42.10^{a} ± 1.21	20.36^{a} ± 0.50	0.98^{a} ± 0.02	655.6^{a,b} ± 17.1
Rhizophora sp	41.56^{a} ± 1.31	20.13^{a} ± 0.54	0.91^{a} ± 0.01	612.8^{b} ± 19.3
F value	1.32	1.32	2.29	3.73
p-value	0.268	0.268	0.103	0.025

F-values represent the one-way ANOVA while, *p*-value represent the significant of ANOVA. Means in the same columns followed by different letters are significantly different at $p < 0.05$ according to Tukey's HSD test.

depth as no significant difference were found. *Ceriops* sp shows higher SOC stock in 2015 while *Bruguiera* sp in soil sample of 2021. The soil samples of 2021 shows a significant difference in SOC stock among species ($F = 3.73$, $p < 0.025$).

The results revealed that the total SOC sequestered in a 1m depth soil layers for Magyi mangrove forest significantly increase over six years ($p < 0.05$) between 2015 and 2021 ($F = 470.36$, $p < 0.001$) (figure 2). An exponential increase of 164% in SOC stock were noticed between 2015 and 2021. The mean ± standard error SOC in 2015 was 738.7 ± 13.4, while 1954.4 ± 49.6 in 2021. To summarize above, it was found that the carbon stock increased by approximately 2.7 time because of restoration effort between 2015 and 2021.

4. Discussion

4.1. Effect of restoration on carbon stock

Mangrove forests play a crucial role in mitigating global climate change by sequestering carbon dioxide from the atmosphere and storing significant amounts of carbon, primarily in their soils (Kauffman *et al* 2020). They are increasingly recognized as important contributors to climate change mitigation, given their significantly high carbon burial rates (McHarg *et al* 2022). The results presented here reveal the potential for carbon sequestration in the soil of Magyi forest area in the Ayeyarwady delta region due to the efforts in mangrove restoration. Soil samples were collected both before and after the restoration, in 2015 and 2021, respectively. Our findings from

soil carbon measurements, demonstrated the importance of the soil carbon reservoir following mangrove reforestation and draw attention to its value for carbon emissions mitigation. The average carbon stock of Magyi mangrove forest in 2021 is approximately 2.7 times higher than that in 2015 (figure 2). This result supports our objective that the amount of soil carbon increases after restoration. The estimated soil carbon in 2021 was 1954.43 ± 33.24 MgC. ha^{-1}. According to previous studies, mangrove forest in the Indo-Pacific Region has an annual carbon sequestration capacity between 288–3400 MgC ha^{-1} (Donato *et al* 2011, Kauffman *et al* 2011, Ezcurra *et al* 2016, Kusumaningtyas *et al* 2019, Raghbor *et al* 2022). The carbon sequestration capacity of Magyi mangrove forest is similar to that of other mangroves forests in the world. This evidence demonstrated that the restoration of mangrove forest significantly increases the amount of soil carbon stock and, subsequently, carbon sequestration. This finding is supported by Chen *et al* (2021), Sasmito *et al* (2020), and Thura *et al* (2023). The high accumulation of carbon in Magyi costal region can be from autochthonous (e.g. carbon is produced and deposited in the same location) and allochthonous sources (e.g. carbon is produced in one location and deposited in another) (Johnson *et al* 2020). Mangrove soils are recognized as carbon sinks since the majority of stored carbon within these ecosystems is found in their organic-rich soils (Johnson *et al* 2020, Kauffman *et al* 2020). Efforts aiming at restoring mangroves have been shown to offset carbon emissions, making them a potential component of strategies that aim to reduce emissions from deforestation and forest degradation (REDD+) schemes (Hieu *et al* 2017). Therefore, the success of restoration effort would be crucial in recovering the mangrove ecosystem and services.

4.2. Effect of restoration on OM, carbon concentration and BD

In general, areas with mangroves have higher organic matter content than adjacent estuaries lacking them (Ranjan *et al* 2010). Mangroves produce a substantial amount of aerial and underground biomass and enhance the rate of sedimentation, facilitating the accumulation of organic compounds in the soil and a significant increase in OM (Barreto *et al* 2016, Sasmito *et al* 2020, Trettin *et al* 2021). Between 2015 and 2021, the restoration of mangrove forests has significantly increased soil OM content, carbon concentration, and BD (figure 2). The average OM content in mangrove sediments post-restoration was 42.67%, higher than mangrove forest in China (Tam and Wong, 1998, Liu *et al* 2017), Southern Brazil (Sanders *et al* 2012), and South Africa (Johnson *et al* 2020). Previous studies have reported the increase in soil OM (Chen *et al* 2018) and BD (Thura *et al* 2023) with the increase in age of mangrove forest. This increase in soil properties can be attributed to the greater accumulation of leaf litter and root production in restored forest (Barreto *et al* 2016, Liu *et al* 2017, Hieu *et al* 2017). The dynamics of soil organic matter are influenced by a broad range of biotic and abiotic factors, including inputs from plant material and chemical transformations driven by soil biotic and abiotic processes (Balesdent *et al* 2018, Basile-Doelsch *et al* 2020). On the other hand, the increase concentration of carbon in the mangrove ecosystems is influenced by various factors, including climate, soil texture, land-use history, forest age, forest density, species composition, tidal range, tidal regime, tide inundation, and sediment distribution in relation to autochthonous and allochthonous inputs (Kristensen *et al* 2008, Liu *et al* 2017, Sasmito *et al* 2020). Therefore, the presence of more mangrove roots after restoration enhances soil porosity and water retention capabilities, mitigating soil compaction through biological activity and the deposition of organic matter in the mangrove soil (Bunting *et al* 2022). The afforestation-based restoration efforts have altered the soil properties, therefore, highlighting its significance in the global context of carbon sequestration and climate change mitigation.

4.3. Post restoration mangrove community and carbon stock

Our research demonstrated that the amount of carbon storage of mangroves varies among species. Three species —*Bruguiera* sp, *Ceriops* sp, and *Rhizophora* sp—were used for afforestation and rehabilitation, as they are known to support carbon accumulation. Mixed species restoration of mangrove ecosystem often hold greater carbon stock than monoculture (Kauffman *et al* 2020, Chowdhury *et al* 2023). The diversity of mixed species and the richness of above-ground biomass have significantly influence the increase in soil organic carbon stock in Magyi soil over the six-year reforestation period (table 2). Lang'at *et al* (2013) found that forests with mixed species developed denser root networks below-ground at faster rates compared to homogenous forests, and within 3 to 4 years, below-ground biomass had exceeded above-ground biomass. Moreover, in this study we found that the amount of SOC stock was high in soil surrounded by *Ceriops* sp and *Bruguiera* sp in the sample collected in 2015 and 2021, respectively. Although *Rhizophora* sp is most common mangrove species, the amount of SOC stock was comparatively lower than other two species. Study showed that SOC stock at 1 meter soil depth in mangrove forest covered by *Rhizophora* sp and *Bruguiera* sp was 360.5 and 437.2 MgC ha^{-1} , respectively (Kauffman *et al* 2020). The rate of carbon accumulation depends on the genus of tree, forest structure, root structure, soil characteristics and environmental condition (Kauffman *et al* 2020). The variation in carbon deposition in Magyi region can be explained based on—(i) structure of root, (ii) amount of matter decomposition and (iii)

environmental factors. *Rhizophora* species have a conspicuous stilt-like roots that grow from the main stem (Méndez-Alonzo *et al* 2015), thus, they have fewer below-ground roots compared to other species of mangrove (Ezcurra *et al* 2016). Therefore, the extensive below-ground root systems of *Bruguiera* and *Ceriops* species enable them to access deeper soil layers, facilitating the deposition of organic matter and carbon sequestration at greater depths. On the other hand, the decomposition rates of organic matter can vary among different mangrove species (Kauffman *et al* 2020, Naidu *et al* 2022). In this study, it is observed that the organic matter present in areas covered by *Rhizophora* is less compared to the other two species (table 2). Faster decomposition rates lead to a more efficient transfer of carbon into the soil, resulting in higher carbon stocks. Finally, environmental factors, such as tidal inundation and nutrient availability, can affect the growth and productivity of mangroves (Sasmito *et al* 2020). *Bruguiera* and *Ceriops* species often thrive in nutrient-rich environments and experience frequent tidal inundation, which supports their higher productivity and SOC stock compared to *Rhizophora* species.

5. Conclusion

In this study, we investigated and quantified changes in soil carbon stocks in Magyi mangrove forest over a six-year period (2015–2021) using repeated field measurements. The results of the study revealed several key findings. Firstly, the estimated soil carbon stock in 2021 (1954.43 ± 33.24 Mg C ha^{-1}) were approximately 2.7 times higher than the estimated carbon stock in 2015 (732.26 ± 6.99 Mg C ha^{-1}), confirming our objective to determine the increase in soil carbon in the mangroves forest after restoration. This indicates that mangrove reforestation efforts can effectively enhance carbon sequestration and contribute to climate change mitigation. Secondly, the study examined the soil properties of different mangrove communities, specifically focusing on three dominant species: *Bruguiera* sp, *Ceriops* sp, and *Rhizophora* sp. It was found that the amount of carbon trapped in soil sediment around *Rhizophora* species is significantly smaller compared to *Bruguiera* sp and *Ceriops* sp. Thirdly, no significant relationship was found between SOC along soil horizons. Overall, the findings of this study provide valuable insights into the carbon sequestration potential of mangrove ecosystems and the effectiveness of mangrove restoration efforts.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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