Assessment of organic carbon stocks in mangrove sediments: A case study from the Maubesi Region along the Indonesia-Timor Leste Border

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Abstract. Global warming is caused by industrial activities, land, sea, and air transportation, the conversion of forest land into agriculture, aquaculture, and livestock farming, as well as the increasing use of groundwater. The release of emissions into the air from mangrove forests is lower compared to terrestrial forests, as the decomposition of aquatic plant litter does not release carbon into the atmosphere. Mangrove ecosystems serve as the largest source of organic matter input in coastal areas. Mangroves supply organic matter derived from mangrove litter, such as leaves, twigs, and stems. This study aims to analyze the carbon stock in the sediment of the Maubesi mangrove forest in Malaka Regency, located at coordinates 124° 57' 5.692" - 125° 0' 38.904" E and 9° 30' 40.819" – 9° 35' 47.391" S. This research employs a purposive sampling method, where samples are collected using a modified sediment core with a PVC pipe at a depth of 30 cm. The collected samples are dried and analyzed using the Loss On Ignition (LOI) method. The sampling locations were determined based on a mangrove cover stratification map. The results show that the carbon storage value per station ranges from 90,200 to 435,200 tons ha^{-1}, with the highest value found in class 4, totaling 978,800 tons ha^{-1}, and the lowest in class 1, totaling 554,600 tons ha^{-1}. The Dry Bulk Density at the study site ranges from 0.00240 to 0.00319 mm. The sediment grain size is dominated by sand (0.05-2 mm) and silt (0.002-0.05 mm), with a small amount of clay (less than 0.002 mm). The sand in the Maubesi mangrove forest is predominantly very fine sand (0.05-0.1 mm) and fine sand (0.1-0.25 mm), with a content ranging between 10-30%. The sediment texture in the Maubesi mangrove forest is dominated by silty loam, loamy sand, and sandy loam. The analysis results indicate that the carbon storage value in the Maubesi area decreases with increasing sediment depth.

Key Words: mangrove, carbon, global warming, density.

Introduction. The increase in Earth's average CO_2 levels is primarily due to greenhouse gas emissions, such as carbon dioxide emissions. Global warming is caused by industrial activities, land, sea, and air transportation, the conversion of forest land into agriculture, aquaculture, and livestock farming, as well as the increasing use of groundwater. The impacts of global warming include natural disasters such as flash floods, droughts, and rising sea levels. Additionally, global warming can accelerate the formation of air pollution, such as tropospheric ozone and other harmful particulate matter (Zandalinas et al 2021). One of the strategies and efforts that can be undertaken to address this issue is to enhance the role of forests as carbon dioxide sinks, including through the promotion of reforestation in mangrove ecosystems (Kusmana et al 2020).

Indonesia is one of the countries with the largest mangrove forest ecosystems in the world, covering approximately 8.60 million hectares, which have changed over time due to degradation. The destruction of these ecosystems has contributed to the global warming (CO_2) observed today (Santoso et al 2021). As of 2024, the area of mangrove forests in good condition is 3,311,245 hectares. These mangrove forests present an economic opportunity as part of blue carbon initiatives. The Regulation of the Minister of Environment and Forestry No. 21 of 2022 outlines the Implementation Procedures for Applying Carbon Economic Value, and Regulation No. 7 of 2023 specifies the Procedures for Carbon Trading in the Forestry Sector, which includes mangrove ecosystems in carbon trading. This potential represents a significant opportunity for local governments and communities to utilize these mechanisms for mangrove conservation in their regions, as the funds that Indonesia could absorb through global carbon markets are estimated to reach IDR 3,000 trillion (Irama 2020).

The declining quality and quantity of mangrove ecosystems year after year have led to highly concerning impacts, such as coastal erosion, seawater intrusion extending further inland, and an increase in diseases like malaria, as well as affecting the income of fishermen in the capture fisheries sector (Wijaya et al 2023). One piece of evidence of global warming due to mangrove ecosystem degradation occurred on the East Coast of North Sumatra, specifically on Tapak Kuda Island in East Langkat, resulting in the disappearance of the island. This has caused 56.32% of fish species to become rare or difficult to find, leading to a 33.89% decline in income, with fishermen being the most significantly affected group (Aritonang et al 2022).

Mangrove forests, categorized as wetland ecosystems, can store carbon ranging from 800 to 1,200 tons per hectare (Hikmah et al 2022). The release of emissions into the air from mangrove forests is lower compared to terrestrial forests, as the decomposition of aquatic plant litter does not release carbon into the atmosphere. Currently, mangrove ecosystems face threats such as land conversion, deforestation, and the impacts of climate change, including rising sea levels (Joandani et al 2019).

Mangrove ecosystems serve as the largest source of organic matter input in coastal areas. Mangroves supply organic matter derived from mangrove litter, such as leaves, twigs, and stems (Mukhtar et al 2021). According to Lukman et al (2022), the carbon within sediments can accumulate over long periods, up to thousands of years. Tidal processes and grain size can influence the deposition and release of carbon. Hapsari et al (2020) explain that tides affect the movement of mangrove litter, the distribution of grain size, and the amount of sediment transport, which are sources of carbon in these ecosystems.

The mangrove forests of Malaka Regency are an area with an ecosystem that plays a crucial role in the environment and the local community. This ecosystem protects the coastline from erosion, provides habitats for various fish and bird species, and functions as a carbon sink. Additionally, mangroves help maintain water quality by filtering pollutants and providing breeding grounds for many organisms. For coastal communities, mangrove forests serve as vital fishing grounds for fishermen. Based on flora inventory data collected in 2003 and 2018 by the Natural Resources Conservation Agency (BBKSDA), this area is known to have significant mangrove biodiversity. There are 11 types of mangroves at the sapling level, 12 types at the pole level, and 11 types at the tree level. However, although the area is dominated by mangrove forests covering 2,397 hectares (73.4% of the total area of 3,246 hectares), the quality of land cover has declined. Approximately 519.27 hectares of mangrove forests have been degraded due to human activities such as pond construction, settlements, and natural phenomena. Research on organic carbon in mangrove forests has been widely conducted in various regions of Indonesia, such as by Cinco-Castro & Herrera-Silveira (2020) in Segara Anakan Lagoon, Hapsari et al (2022) in Bintan Island, and Hickmah et al (2021) in Karimunjawa, as well as Rahman et al (2020) in Sulawesi. However, analyses of carbon stocks in mangrove forests have primarily focused on areas in Java, Bali, Sulawesi, and Sumatra. Meanwhile, similar research in the Timor Island region of East Nusa Tenggara remains scarce.

The purpose of this study is to analyze carbon stocks in the sediment of mangrove forests in Maubesi, Malaka Regency. The estimated carbon absorption data is expected to serve as baseline information for climate change mitigation policies, particularly in the management of mangrove ecosystems in Maubesi, Malaka Regency, East Nusa Tenggara, as well as other mangrove ecosystems in Indonesia.

Material and Method

Description of the study sites. This research is focused in Malaka Regency, specifically in Maubesi Subdistrict, within the Maubesi Mangrove Forest Nature Reserve area, located in West Timor, Timor Island, East Nusa Tenggara. The study site is situated at coordinates 124° 57' 5.692" - 125° 0' 38.904" E and 9° 30' 40.819" – 9° 35' 47.391" S. This area was chosen due to its crucial role in the mangrove ecosystem and the limited number of studies on carbon stocks in this region. The research employs a purposive sampling method. The sampling locations were determined based on a stratification map (vegetation grouping) of mangrove cover in Maubesi, Malaka Regency, East Nusa Tenggara, and according to mangrove species groups present in the area, such as tree mangroves. Sediment sampling was conducted at four points (1.1, 1.2, 1.3, and 1.4) using a modified sediment core with a PVC pipe measuring 50 cm in length and 5 cm in diameter. Analysis of soil organic carbon content was carried out using the Loss On Ignition (LOI) method.

Samples were taken using a modified sediment *core* with a PVC pipe with a depth of 30 cm with a diameter of 6 cm stuck vertically rotated into the sediment. After the modified core entered the soil to a depth of 30 cm, the modified core was withdrawn. Then the sediment was measured by dividing it using intervals of 0-10 cm, 10-20 cm, and 20-30 cm in the three classes and 4 station points then the samples were put in plastic samples (Figure 1).

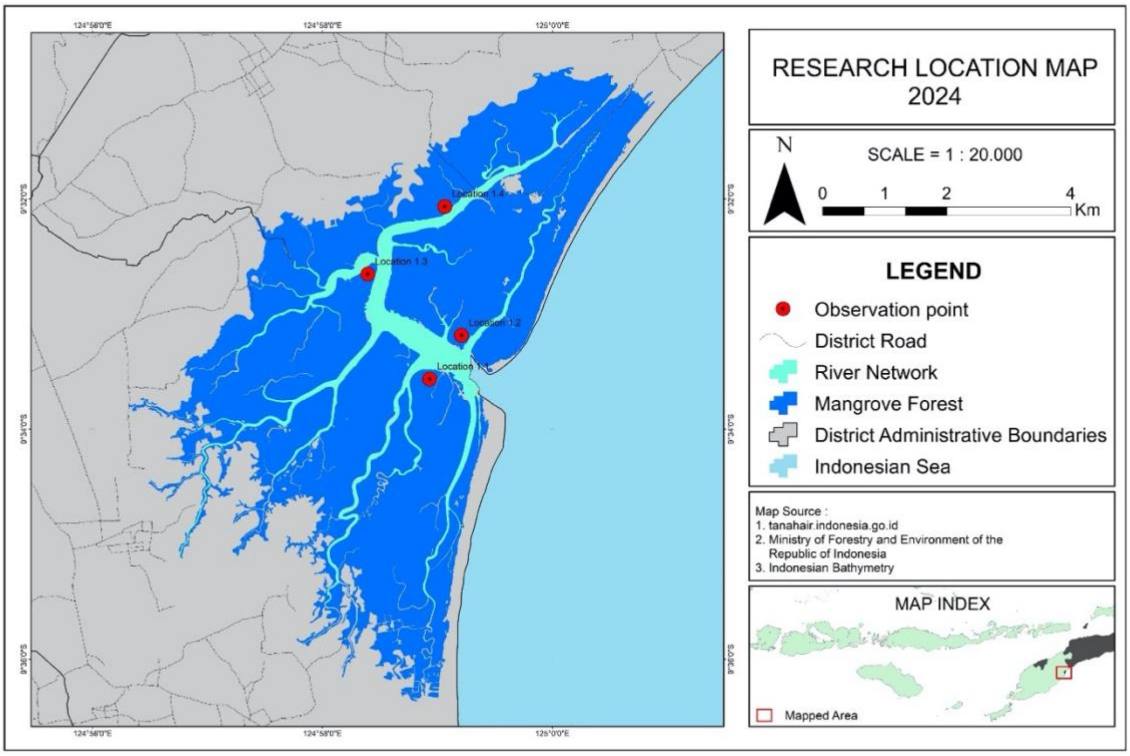

Figure 1. Research station point in Maubesi mangrove forest, Malaka Regency, Indonesia.

Sediment sample processing method. Sediment samples were collected at each point using a modified sediment core with a PVC pipe measuring 50 cm in length and 5 cm in diameter. Analysis of soil organic carbon content was conducted using the Loss On Ignition (LOI) method (Kauffman & Donato 2012). Sediment samples were placed into aluminum dishes and then inserted into an oven at a temperature of 60°C for 48 hours. After drying, the samples were ground using a mortar to ensure homogeneity before combustion. Each homogenized subsample was placed into a zipper bag (clip-seal plastic bag). Approximately 2 grams of the sample were weighed and placed into a porcelain crucible. The samples were then inserted into a furnace and burned at a temperature of 450°C for 4 hours, after which they were weighed again. The measurement of sediment organic matter was carried out using the LOI (Loss on Ignition) method as follows:

$$\text{Organik Matter} = \frac{(\text{Wt-C})\text{-Wa-C})}{\text{Wt-C}} \times 100$$

Description: Wt- Total weight of the crucible and sample before drying; C- Weight of empty crucible; Wa- Total weight of the crucible and sample after drying.

The data calculated include the volume of sediment samples, bulk density, and the percentage of organic carbon in the sediment. The calculations used in the data analysis are as follows: Dry Bulk Density (DBD) of soil refers to the weight of soil particles per unit volume, including pores. The formula used to calculate DBD is:

$$\text{Soil bulk density} = \frac{\text{Dry weight (g)}}{\text{Wet volume (cm}^3\text{)}}$$

The calculation of Sediment-Organic Carbon Stock (S-OCS) is conducted using Equation 3 and its conversion based on the respective formula 4:

$$\text{SCO (g cm}^{-2}\text{)} = \text{DBD x \%OC100 x SDI}$$

Description: SCO - stok organic carbon (g cm^{-2}); DBD - dry bulk density g cm^{-3}; %OC - organic carbon content; SDI - soil depth interval (cm)

$$\text{SCO (ton ha}^{-1}\text{)} = 102 \text{ x SCO (g cm}^{-2}\text{)}$$

Description: SCO – sediment organic carbon; 100 - conversion factor from (g cm^{-2}) ke (ton ha^{-1}).

If the analysis only provides the organic matter content (for example, via the LOI method), the soil organic carbon (Corg) content is estimated to be 1/1.724 of the soil organic matter content. For instance, if the substrate has an organic matter content of 98%, then Corg = 98% / 1.724. The determined soil carbon content is then converted into tons per hectare (ton ha^{-1}) by multiplying by 100 (the conversion factor from g cm^{-3} to ton ha^{-1}).

***Sediment grain size analysis**.* Sediment grain size analysis was conducted to determine the type of sediment in the water body. The sediment grain size was classified based on the United States Department of Agriculture (USDA) soil particle size classification and the USDA soil texture triangle (Boyd et al 2002), as presented in Table 1 and Figure 2. The grain size analysis was performed using a particle size analyzer, an instrument used to determine the size of nanoparticles in a sample. This device provides results on sediment classification and sediment texture.

Table 1

Sediment grain size classification based on the USDA

Classification of sediment fractions	*USDA grain size (mm)*
Gravel	>2
Very coarse sand	1-2
Coarse sand	0.5-1
Medium sand	0.25-0.5
Fine sand	0.1-0.25
Very fine sand	0.05-0.1

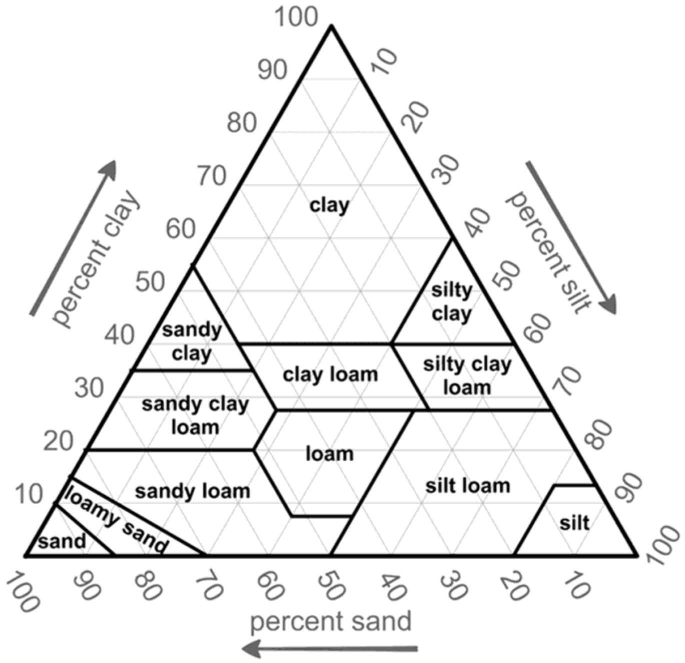

Figure 2. The USDA triangle classifies soil (Boyd et al 2002).

Results. The results of data processing reveal relatively different values at each station; this may be due to the varying locations of the stations or other environmental factors.

Dry bulk density. According to Aldiano et al (2022), dry bulk density is the weight of the dried soil mass per unit volume. The dry bulk density at the research site ranged between 0.00240–0.00319 g $cm^{-}3$ and varied across each station (Figure 3), although the differences based on depth were not significant. The results showed that at all stations, the values tended to fluctuate with increasing depth, or the dry bulk density tended to decrease as the depth increased.

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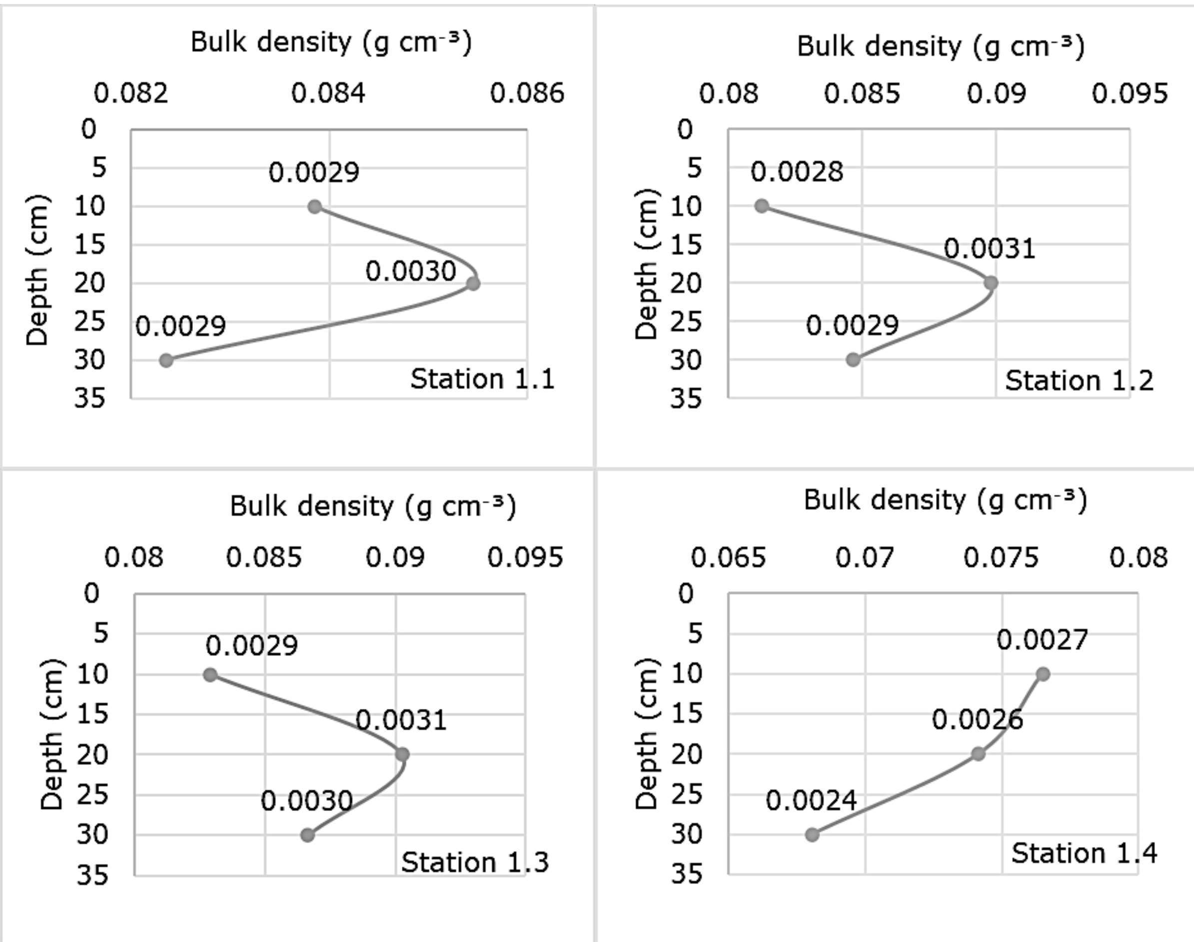

Figure 3. Graph of dry bulk density against depth at each station.

Vertical organic carbon in mangrove sediments. Organic carbon content in sediments is the amount of carbon that can be absorbed and stored by sediments in the form of organic matter that is input to the soil structure and utilized as energy for soil organisms (Aldiano et al 2022). The vertical distribution of organic carbon can be seen in (Figure 4). Organic carbon stocks from each station have different values, this can be influenced by the productivity of litter that falls to the ground at that location. The value of carbon storage per station ranged from 90,200-435,200 tons ha^{-1} and the highest was found in class 4 with a total of 978,800 tons ha^{-1} and the lowest was found in class 1 with a total of 554,600 tons ha^{-1}. This amount is obtained from the sum of each class. The pattern of carbon storage fluctuation per station and per layer is presented in Table 2.

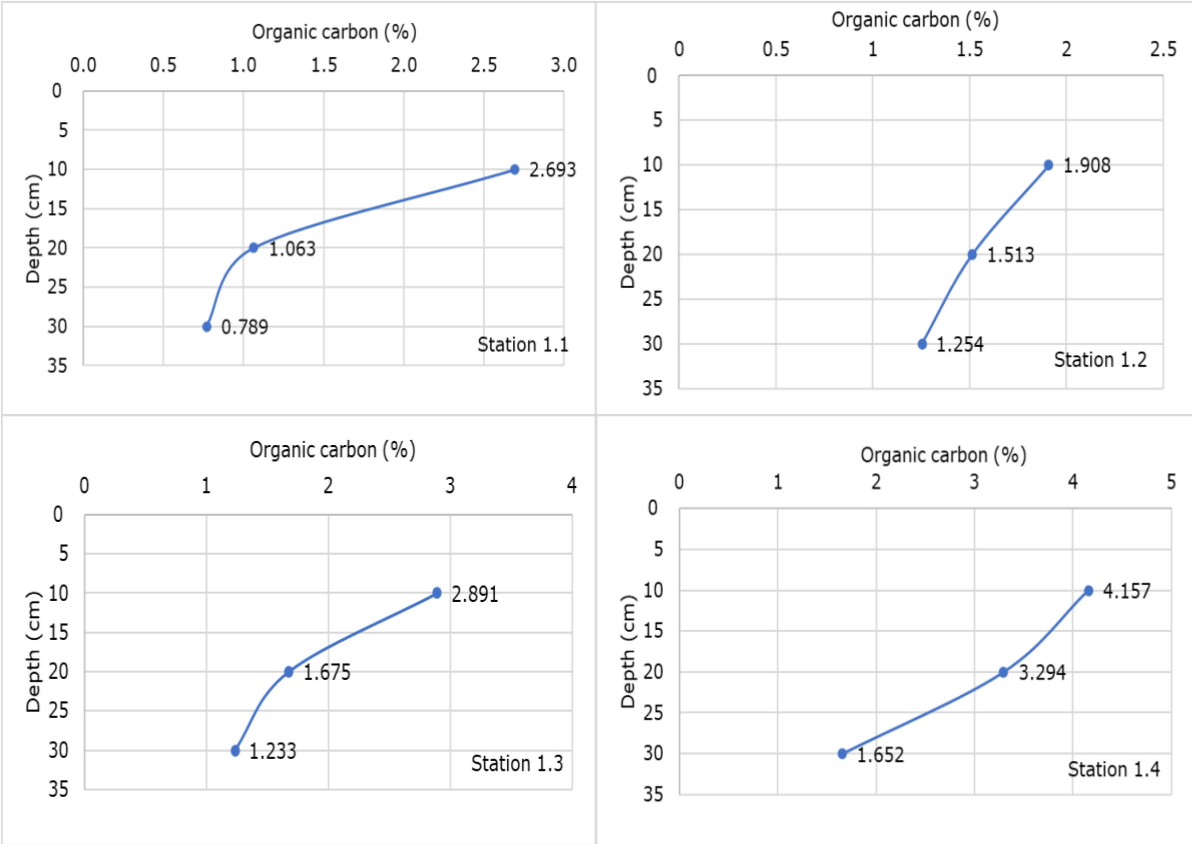

Figure 4. Graph of vertical organic carbon content at each station.

Table 2

Vertical organic carbon content

St	*Intervals (cm)*	*S-OCS (ton ha^{-1})*	*Total S-OCS (ton ha^{-1})*	*Mean S-OCS /Class (ton ha^{-1})*
	0-10	324,200		
1.1	10-20	140,200	554,600	
	20-30	90,200		570,600
	0-10	229,200		
1.2	10-20	189,200	586,600	
	20-30	168,200		
	0-10	330,200		
1.3	10-20	216,200	708,600	
	20-30	162,200		843,600
	0-10	435,200		
1.4	10-20	382,200	978,600	
	20-30	161,200		

Based on Table 2, it is evident that at each station, the carbon content decreases with increasing depth. This condition is influenced by organic matter, which tends to accumulate in the topsoil layer due to inputs from litter decomposition, plant roots, and biological activity at the surface. As the soil layer deepens, the organic matter content typically decreases due to limited input of organic material and slower decomposition processes (Souza et al 2023). Additionally, this is influenced by the activity of microorganisms and soil fauna, which decompose organic matter more actively in the surface layers. In deeper layers, this biological activity declines, resulting in a lower accumulation of organic carbon (Poeplau et al 2019).

Table 2 shows that the highest average carbon content in the Maubesi area is found at stations 1.3 and 1.4, with a value of 843,600, compared to stations 1.1 and 1.2, which have a value of 570,600. The higher carbon content at stations 1.3 and 1.4 is influenced by differences in vegetation, as different types of vegetation have varying capacities to absorb and store carbon. Denser and more diverse vegetation tends to store more carbon (Hofhansl et al 2020).

***Sediment grain size**.* The sediment grain size in the Maubesi region, located on the border of Indonesia and Timor-Leste, is dominated by sand (0.05–2 mm) and clay (0.002–0.05 mm). The sand in the Maubesi region on the Indonesia-Timor-Leste border is predominantly fine (0.1–0.25 mm), with a content ranging between 10–30%. The sediment texture in the Maubesi region on the Indonesia-Timor-Leste border is primarily characterized by fine sand, loamy sand, and sandy loam, based on calculations using the USDA soil texture triangle. The grain size at stations 1.1, 1.2, and 1.3 is more dominated by sand compared to other stations, which are dominated by clay, while station 1.4 contains sandy clay. The distribution of grain size per station is illustrated in Figure 5.

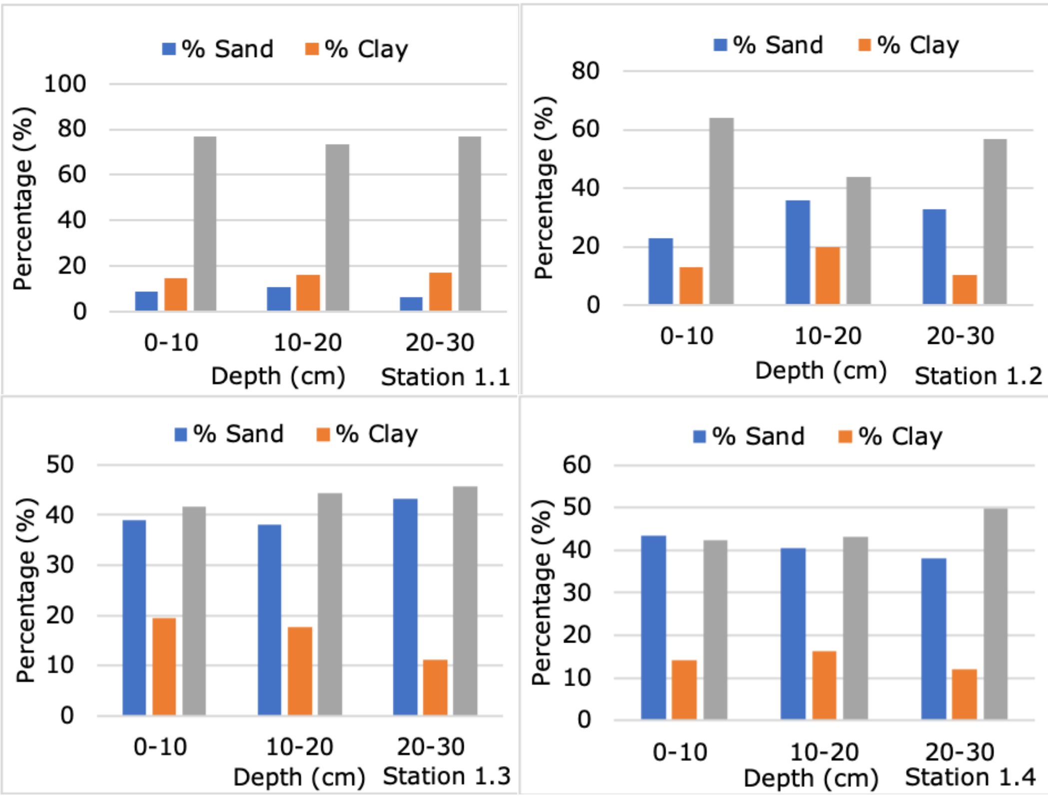

Figure 5. Percentage of vertical sediment grain size at each station.

Discussion. Mangrove ecosystems play a crucial role in preventing coastal erosion, trapping sediments, and serving as spawning grounds, nurseries, and feeding areas for fish (Handayani et al 2020). The border between Indonesia and Timor-Leste is demarcated by Alor Island, which can cause tidal changes (from ebb to flood or vice versa) to occur more slowly compared to areas directly adjacent to the open sea. These tidal changes can influence the movement of sediments and mangrove litter. The topography of the seabed, the shape of the bay, and the width of the strait can significantly affect tidal patterns. High tides create waterlogged and anaerobic conditions, slowing down the carbon cycle due to prolonged decomposition processes, which reduces the release of carbon. During high tide, seawater transports sediments and litter to the inner parts of the mangrove forest, while during low tide, it carries them back to the sea. Larger particles tend to settle more easily compared to smaller ones (Hapsari et al 2022). These tidal conditions influence the extent to which seawater reaches the mangrove ecosystem, contributing to variations in carbon storage across different research locations. Sondak and Kaligis (2022) explain that variations in organic carbon content in mangrove ecosystems are influenced by geographical conditions, such as differences in environmental types, river dominance, and tidal dominance. These processes affect the accumulation, storage, and composition of organic matter in sediments.

Based on Table 2, station 1.4 has the highest organic carbon storage compared to other stations, which is associated with its vegetation type consisting of tree mangroves and understorey plants. Understorey vegetation has a dense root system that traps litter from tree mangroves, allowing it to be stored for a longer period within the ecosystem. Thoha et al (2024) explain that fallen mangrove litter forms organic carbon and undergoes decomposition.

Furthermore, Hapsari et al (2022) explain that, in addition to being related to the dense root system, the amount of litter stored and trapped is also influenced by tidal processes. Sediment carbon stocks are higher in areas with calm currents and shorter tidal intervals. Besides affecting the movement of litter in and out, tides also influence sediment movement and the distribution patterns of grain size (Hartoko et al 2022). In larger mangrove areas, sediments with finer grain sizes, such as mud or silt, are more common compared to coarser grain sizes like sand. At station 1.1, the mangrove area has the lowest carbon stock compared to other stations. This may occur because station 1.1 is dominated by sandy sediments, accounting for 77%. As stated by Sakmiana et al (2023), sandy sediments indicate depositional environments with strong waves and currents. This results in lower storage of organic carbon. Sandy sediments have larger pores, making organic carbon more susceptible to being washed away by currents and hindering its accumulation.

Conclusions. The value of carbon storage per station ranged from 90,200-435,200 tonnes ha^{-1}, and the highest was found at station 1.4 with a total of 978,800 tonnes ha^{-1}, and the lowest was found at station 1.1 with a total of 554,600 tonnes ha^{-1}. Dry bulk density at the study site has values between 0.00240-0.00319 g cm^{-3}. Sediment grain size at the Indonesia Timor Leste Border is dominated by sand (0.05-2mm) and silt (0.002-0.05mm) with little clay content (0.002mm). The sand in the Malacca mangrove forest is predominantly 0.05-0.1mm (very fine sand) and 0.1-0.25mm (fine sand), with contents ranging from 10-30%. Sediment texture in Maubesi mangrove forest is dominated by silty loam, loamy sand, and sandy loam. Based on the results of the above analysis, it can be stated that the carbon content in sediments tends to decrease with increasing depth. This is due to reduced biological activity and organic matter input in the deeper sediment layers. The results of this research can help central regional governments and institutions in completing carbon content data in Indonesia. It is hoped that this data will become the main data for mangrove rehabilitation in the Indonesian Border area.

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