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# ESTIMATING THE TOTAL CARBON STOCK IN THE MANGROVE FOREST OF KOTA MARUDU, SABAH, MALAYSIA

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**Abstract:** Mangrove forests are capable of storing vast amounts of carbon and are recognised as one of the highest carbon densities in the world. This research examines the mangrove forest in Kota Marudu, Sabah, Malaysia, specifically its soil's physico-chemical properties and total carbon stock. Using two 100-metre-long transect lines with seven-metre diameter circle subplots established at every 25 metres, a forest inventory and an allometric equation were used to determine the aboveground and belowground biomass. The carbon content was estimated to be 50% of biomass. Simultaneously, soil samples were collected at depths of 0-15 cm, 15-30 cm, 30-50 cm, and 50-100 cm for soil analysis and bulk density. A CHNS elemental analyser was used to determine the carbon content in the soil. The results showed that the Kota Marudu mangrove forest has a total carbon stock of 1,010.65 Mg C ha$^{-1}$, where around 80% of it was contributed by the soil carbon pool at 876.16 Mg C ha$^{-1}$. The results also revealed that the living tree and roots carbon pool were measured at 100.87 Mg C ha$^{-1}$ and 33.62 Mg C ha$^{-1}$, respectively. These findings highlight the crucial role of mangrove forests in carbon sequestering and mitigating climate change.

Keywords: Mangrove forest, aboveground carbon, belowground carbon, soil carbon, carbon pool.

## Introduction

Mangrove forests are vital ecosystems found in tidal zones of high-salinity or brackish marine environments across tropical and subtropical coastal regions worldwide (Romanach *et al.,* 2018). These habitats support diverse mangrove tree species such as *Rhizophora, Bruguiera, Sonneratia, Ceriops, Avicennia*, and *Xylocarpus* (Hidayah *et al.,* 2022). Mangrove forests are excellent at storing carbon for an extended duration and are recognised as having one of the highest carbon densities in the world (Adame *et al.,* 2020). Recent studies (Kauffman *et al.,* 2018; Taillardat, 2018) highlighted that mangrove ecosystems can store three to five times more carbon than terrestrial forests, with a significant portion stored in their soil carbon pools (Zakaria & Sharma, 2020). They are also acknowledged as one of the most efficient ways to capture atmospheric carbon stocks and mitigate the continuous increase in global temperatures (Amir, 2018). Despite covering less than 1% of the total tropical rainforest areas worldwide, mangrove forests can sequester approximately 12.53 Gt carbon per year or about 3% of the carbon captured by tropical rainforests (Zakaria & Sharma, 2020).

Despite their numerous benefits, mangrove ecosystems face threats from human activities and natural disturbance. The global reduction of mangrove forests is estimated to be 1% to 2% per year, totalling a 35% loss since 2000 (Lai *et al.,* 2022). Between 1980 and 2005, the world's mangrove areas declined from 18.8 million ha to 15.6 million ha (Omar & Misman, 2020). This reduction is due to activities such as land clearing, overharvesting of natural resources such as fish and wood, coral reef destruction, pollution, storms, lightning strikes, and climate change (Abdulaali *et al.,* 2022). Asia recorded the largest mangrove forest loss since 1980, primarily due to conversion to agricultural, urban and industrial land uses (Omar & Misman, 2020). Such conversions and deforestation of mangrove forests generate a significant amount of carbon emissions, which accounts for a big portion of atmospheric greenhouse gases (Sasmito *et al.*, 2020).

Malaysia has approximately 629,038 ha of mangrove areas, with Sabah possessing almost 57%, Sarawak (26%) and Peninsular Malaysia (17%) (Omar & Misman, 2020; Abdulaali *et al.,* 2022). The country's mangroves declined from 700,000 ha in 1975 to 572,000 ha in 2000 due to the intensive harvesting of valuable trees and strong sea waves (Omar & Misman, 2020). However, between 2000 and 2005, the annual rate of mangrove loss decelerated, with a reduction of 102,000 ha compared with the previous 187,000 ha. Malaysia has implemented many initiatives to conserve and restore its mangrove ecosystems. The government is committed to enhancing protection efforts, especially after the tsunami on 26th December 2004 (Omar *et al.,* 2020). Conserving the remaining mangrove forests is crucial for reducing global greenhouse gas emissions and supporting climate change mitigation initiatives.

Quantifying mangrove forest carbon stocks is necessary to support nationally determined contributions for the Reducing Carbon Emissions from Deforestation and Forest Degradation in Developing Countries (REDD+) programme (Taillardat, 2022). The data are also critical for achieving Sustainable Development Goals, specifically in preventing environmental damage and supporting climate change initiatives (Hidayah *et al.,* 2022). Thus, this study aims to quantify the total ecosystem carbon stock (aboveground, belowground, and soil) in the mangrove forest of Kota Marudu, Sabah, Malaysia with the hope that it can provide useful supplementary information for national and federal efforts to mitigate climate change.

## Materials and Methods

### *Study Area*

The research was conducted in the Kota Marudu mangrove forest in Sabah, Malaysia (Figure 1). The forest is part of the Tun Mustapha Park, the largest multiuse marine protected area in Malaysia, located within the scientific boundary

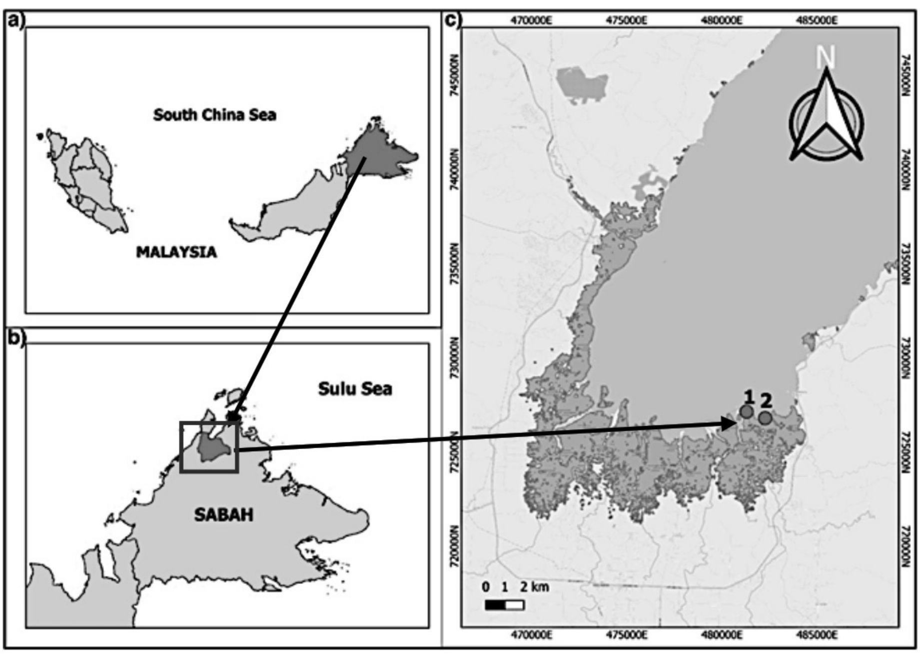


Figure 1: (a) Malaysia's map, (b) Sabah's map shows the location of the study area, and (c) the location of the Kota Marudu mangrove forest area, where two transect lines were established

of the Coral Triangle. This area was gazetted on 19th May 2016 and has unique biodiversity that supports a series of complex and linked habitats. About 13,980 ha of the total areas are covered with mangrove forests. Two sites within the mangrove area were randomly selected to determine the soil's physical and chemical properties and soil carbon stocks, with the *Rhizophora* tree species dominating these study sites.

## Procedures

### *Sampling Design*

Two 100-metre-long transect lines were established randomly in the study area. The transect line method followed the protocol outlined by Kauffman and Donato (2012). Seven-metre radius circular subplots were established at intervals of 25 metres along the two lines, totalling 10 subplots. A forest inventory was conducted to measure the aboveground and belowground carbon pool while soil sampling was carried out to collect soil for soil carbon stock analysis. Field data collection took place twice, in September 2019 and January 2020.

### *Field Data Collection*

Trees' diameter at breast height (DBH) and height were measured using forest inventory techniques. The equipment used included a DBH meter and TruPulse 360 rangefinder. All trees within the seven-metre radius with a DBH exceeding 5 cm were measured. Soil samples were collected from four different depths: 0-15 cm, 15-30 cm, 30-50 cm, and 50-100 cm, totalling 40 samples. Two types of soil were collected, namely composite soil and undisturbed soil. Composite soil samples were obtained by inserting a PVC pipe into the soil, slicing it into four different depth intervals, and storing them ins sealed plastics for laboratory analysis. Undisturbed soil samples were collected using a bulk-density cylindrical ring with a volume of 98.125 $cm^3$.

### *Soil Analysis*

All undisturbed and composite soil samples were analysed for their physicochemical properties. Composite soil samples were air-dried at room temperature and sieved through a 2 mm soil sieve before being analysed. The analysis involved determining the percentage of soil moisture content, organic matter, soil texture, bulk density, soil pH, and soil nutrient contents. The percentage of soil moisture content was determined through the gravimetric approach after oven-drying at 105°C for 24 hours (Shukla *et al.,* 2014) while the pipette method was used to determine the percentages of silt, clay, and sand. Soil texture was then defined using the percentages of silt, clay, and sand obtained from the pipette method and the United States Department of Agriculture's soil classification triangle. In addition, undisturbed soils were measured for bulk density (Han *et al.,* 2016).

The soil pH was determined using a 1:2:5 ratio of soil to water and analysed using a soil pH meter. Soil salinity was measured using a portable refractometer. The percentage of organic matter in the soil was determined using the loss-in-ignition method, which involved igniting 10 g of soil in a furnace at 500°C for 24 hours. The acid digestion method using an aqua regia solution was used to extract the base cations magnesium ($Mg^{2+}$), calcium ($Ca^{2+}$), sodium ($Na^+$), and potassium ($K^+$), as well as the acid cation aluminium ($Al^{3+}$). The samples were diluted and analysed using an inductively coupled plasma-optical emission spectrometry machine (Hatta *et al.,* 2022). The acid cation hydrogen ($H^+$) was analysed using a vario MACRO cube CHNS elemental analyser. Additionally, the elemental analyser was used to analyse the carbon and nitrogen contents in the soil. These elements were combined to calculate the cation exchange capacity (CEC) of the soil (Culman *et al.,* 2019).

### *Analysis of Aboveground and Belowground Biomass*

The aboveground biomass in the mangrove forest in Kota Marudu, Sabah, Malaysia was determined using an allometric equation established by Fromard *et al.* (1998) for *Rhizophora* spp. The equation is $W = 0.128DBH^{2.60}$, where DBH is the diameter at breast height. While there are other equations available to estimate the aboveground biomass in trees, inadequate information on species distribution in the study area has limited the choice of allometric equation (Wong *et al.,* 2020). Clough and Scott (1989) and Ong *et al.* (2004) have also developed allometric equations for this purpose. However, Komiyama *et al.* (2008) noted that their equations have a relative error of -9.84 to +10.3% and +6.81 to -10.8%, respectively, compared with Fromard *et al.* (1998), which has a relative error of -8.44 to +6.81%. The aboveground carbon was then estimated to be 50% of biomass (Khokher *et al.,* 2023). As for the belowground biomass, it was estimated using the 3:1 aboveground-to-belowground biomass ratio developed by Kusmana *et al.* (2018) and then converted into carbon using the 0.5 conversion factor.

### *Soil Carbon Stock and Total Carbon Stock*

The soil carbon stock for each layer was calculated using the soil bulk density value, soil carbon content, and soil depth interval (Kauffman & Donato, 2012).

$$\text{Soil carbon } (\text{Mg ha}^{-1}) = \text{BD } (\text{g cm}^{-3}) \times \text{SDI (cm)} \times \text{C (\%C)} \quad \textbf{(1)}$$

where BD = bulk density (g $cm^{-3}$), SDI = soil depth interval (cm), and C = carbon content (%). The values of the soil carbon stock for each depth were then summed to obtain the total soil carbon stock for the area. The total ecosystem carbon pools in the Kota Marudu mangrove forest were determined by adding up the measured carbon pools, which are live plants carbon pool, roots carbon pool, and soil carbon pool. The study also assessed the site's potential as a carbon source or sink by converting the total ecosystem carbon stock into carbon dioxide equivalents ($CO_2e$).

## Results and Discussion

### *Soil Physico-chemical Properties of the Mangrove Forest*

Analysing the physical and chemical properties of soil can provide basic information for sustaining the forest ecosystem (Hailemariam *et al.,* 2023). These properties, along with climatic conditions and land use history, influence the composition of plant communities within forests (Suratman *et al.,* 2015). The physical properties of the Kota Marudu mangrove forest's soil (Table 1) show no significant differences in soil bulk density and soil moisture content across different depths. Bulk density has a big influence on soil organic carbon, typically increasing with depth (Joshi & Bhatta, 2023). However, this study observed an inconsistent

Table 1: The soil physical properties of the mangrove forest in Kota Marudu, Sabah, Malaysia

| Soil Depth (cm) | Bulk Density (g $cm^{-3}$) | Moisture Content (%) | Clay (%) | Silt (%) | Sand (%) | Types of Soil Texture |
|---|---|---|---|---|---|---|
| 0-15 | 0.92 ± 0.02a | 32.57 ± 1.46a | 26 ± 6.86a | 10 ± 3.94a | 60 ± 6.70a | Sandy clay loam |
| 15-30 | 0.95 ± 0.06a | 32.71 ± 1.29a | 13 ± 7.20a | 29 ± 9.62a | 57 ± 8.48a | Sandy loam |
| 30-50 | 0.91 ± 0.03a | 33.74 ± 1.92a | 30 ± 4.09a | 17 ± 6.63a | 50 ± 1.85a | Sandy clay loam |
| 50-100 | 0.94 ± 0.03a | 33.07 ± 1.41a | 20 ± 2.09a | 17 ± 5.74a | 60 ± 12.78a | Sandy clay loam |

Notes: Value is the mean ± standard error of the measurement. The same letter within the column indicates no significant difference ($p > 0.05$) between the mean measurements based on Tukey's post hoc test trend in bulk density across depths, with mean values increasing from the first (0-15 cm) to the second depth (15-30 cm), decreasing at the third depth (30-50 cm), and then increasing again at the fourth depth (50-100 cm). Additionally, no significant difference was found in the mean soil bulk density across depths, which ranges from 0.91 g $cm^{-3}$ to 0.94 g $cm^{-3}$. The soil bulk density values reported in this study are higher than those reported by Hemati *et al.* (2014) for mangrove forests in Peninsular Malaysia, which ranged from 0.57 g $cm^{-3}$ to 0.65 g $cm^{-3}$.

The soil in Kota Marudu's mangrove forest is coarse-textured, with sand particles making up 50% to 60% of its composition. Clay content ranges from 13% to 30% while silt constitutes 17% to 29%. Two types of soil texture were found in Kota Marudu's mangrove forest: Sandy clay loam and sandy loam. Dewiyanti *et al.* (2021) in their study of Indonesia's mangrove ecosystem, found the same high range of sand and clay contents in mangrove soil. Ismoyo *et al.* (2017) attributed the high sand content to mangrove forests' proximity to the coast, where sand from nearby beaches was carried inland by high waves.

The soil chemical properties in the study area are outlined in Table 2. The soil in Kota Marudu's mangrove forest is acidic, with pH levels ranging from 3.31 to 3.66. Apart from influencing soil nutrient availability, pH levels also affect soil carbon content and metal solubility (Zubi *et al.,* 2021). The high level of acidity may stem from soil oxidation due to human activities (Dewiyanti *et al*., 2021). The soil organic matter did not vary across different depths, ranging from 7.92% to 8.86%. Part of the soil organic carbon is stored inside soil organic matter. Chaikaew and Chavanich (2017) conducted a study on the spatial distribution of soil organic matter in Thailand's mangrove forests, which found comparable levels of soil organic matter with this study, ranging from 9.19% to 12.47%. Their study also further justifies the positive relationship between the percentage of soil organic matter and soil organic carbon content.

Carbon content is an essential element in soil as it is the source of energy for microorganisms inhabiting it (Zubi *et al*., 2021). Given that nitrogen is positively correlated with soil carbon content, both elements are vital for plant growth and soil carbon storage. Soil carbon content can also indicate soil fertility, as carbon is a product of living organisms (Dewiyanti *et al.,* 2021). The carbon content (Table 3) in the Kota Marudu mangrove forest's soil is high, ranging from 8.25 ± 0.63% to 9.70 ± 0.53%. This range is similar to the soil carbon content recorded by Arianto *et al.* (2015) in their study of a mangrove forest dominated by *Rhizophora mucronata* species, which is 6.24%. This study shares a similar

Table 2: The soil chemical properties of the mangrove forest in Kota Marudu, Sabah, Malaysia

| Soil Depth (cm) | pH (1:2:5) | Salinity (ppt) | Soil Organic Matter (%) | Acid Cations (meq/100) | | | Base Cations (meq/100 g) | | | CEC (meq/ 100 g) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | $Al^{3+}$ | $H^+$ | $Mg^{2+}$ | $Ca^{2+}$ | $Na^+$ | $K^+$ | |
| 0-15 | 3.66 ± 0.19a | 6.99 ± 0.42a | 8.55 ± 0.79a | 1.84 ± 0.16a | 0.87 ± 0.31a | 0.78 ± 0.12a | 0.51 ± 0.02a | 2.21 ± 0.17a | 0.33 ± 0.02a | 5.58 ± 0.46a |
| 15-30 | 3.36 ± 0.08a | 7.11 ± 1.09b | 8.77 ± 1.18a | 1.99 ± 0.14b | 0.85 ± 0.24a | 1.08 ± 0.05a | 0.67 ± 0.01a | 2.12 ± 0.10a | 0.40 ± 0.02a | 7.18 ± 0.53a |
| 30-50 | 3.31 ± 0.08a | 9.03 ± 1.98b | 7.92 ± 0.43a | 1.51 ± 0.09b | 0.94 ± 0.23a | 0.81 ± 0.06a | 0.56 ± 0.02a | 2.88 ± 0.11a | 0.30 ± 0.01b | 5.33 ± 0.52a |
| 50-100 | 3.32 ± 0.07a | 7.88 ± 2.09b | 8.86 ± 1.25a | 2.14 ± 0.14a | 0.81 ± 0.22a | 1.19 ± 0.8a | 0.78 ± 0.01a | 2.06 ± 0.19a | 0.47 ± 0.02a | 7.76 ± 0.42a |

Notes: Value is the mean ± standard error of the measurement. The same letter within the column indicates no significant difference ($p > 0.05$) between the mean measurements based on Tukey's post hoc test

Table 3: The soil nutrient content of the mangrove forest in Kota Marudu, Sabah, Malaysia

| Soil Depth (cm) | Carbon (%) | Nitrogen (%) | P (ppm) | K (ppm) | S (%) | C:N Ratio |
|---|---|---|---|---|---|---|
| 0-15 | 8.25 ± 0.63a | 0.31 ± 0.05a | 0.13 ± 0.02a | 9.62 ± 1.39a | 8.25 ± 0.63a | 0.31 ± 0.05a |
| 15-30 | 8.66 ± 0.27a | 0.29 ± 0.04a | 0.09 ± 0.01a | 12.25 ± 1.32a | 8.66 ± 0.27a | 0.29 ± 0.04a |
| 30-50 | 9.44 ± 0.62a | 0.29 ± 0.04a | 0.12 ± 0.02a | 12.06 ± 1.61a | 9.44 ± 0.62a | 0.29 ± 0.04a |
| 50-100 | 9.70 ± 0.53a | 0.27 ± 0.02a | 0.06 ± 0.01a | 12.71 ± 1.11a | 9.70 ± 0.53a | 0.27 ± 0.02a |

Notes: Value is the mean ± standard error of the measurement. The same letter within the column indicates no significant difference ($p > 0.05$) between the mean measurements based on Tukey's post hoc test

ecological context, further supporting the notion that mangrove forests dominated by *Rhizophora* species tend to exhibit a higher carbon content compared with sites dominated by other species.

### *Mangrove Tree DBH Distribution*

Table 4 summarises the stand characteristics of mangrove trees in Kota Marudu, Sabah, Malaysia. The mangrove trees exhibit a DBH range of 5 cm to 47.4 cm, with a mean of 18.88 cm. Their heights range from 5.03 m to 32.31 m, with a mean height of 17.42 m.

In the study area (Figure 2), there were 104 trees, which were dominated by the *Rhizophora apiculata* species. The trees were categorised into five DBH classes: 0-15 cm, 10-20 cm, 20-30 cm, 30-40 cm, and 40-50 cm. The least number of trees were in the 40-50 cm DBH class while the majority were in the 0-10 cm class, followed by the 20-30 cm class.

### *The Aboveground and Belowground Biomass of the Mangrove Forest in Kota Marudu, Sabah, Malaysia*

Measurements of forest biomass are essential to estimate the carbon stock in a forest and its potential to sequester carbon from the atmosphere (Islam *et al.,* 2022). Figure 3 presents the aboveground and belowground biomass for both living trees and roots in the mangrove forest in Kota Marudu, Sabah, Malaysia. The aboveground tree biomass is higher than the belowground biomass due to the roots being constantly exposed to harsh environmental conditions such as high salinity

Table 4: The stand characteristics of mangrove trees in Kota Marudu, Sabah, Malaysia

| Site | DBH (cm) | | | | Height (m) | | | |
|---|---|---|---|---|---|---|---|---|
| | Min | Max | Mean | SD | Min | Max | Mean | SD |
| Kota Marudu | 5.0 | 47.4 | 18.88 | 10.39 | 5.03 | 32.31 | 17.42 | 6.76 |

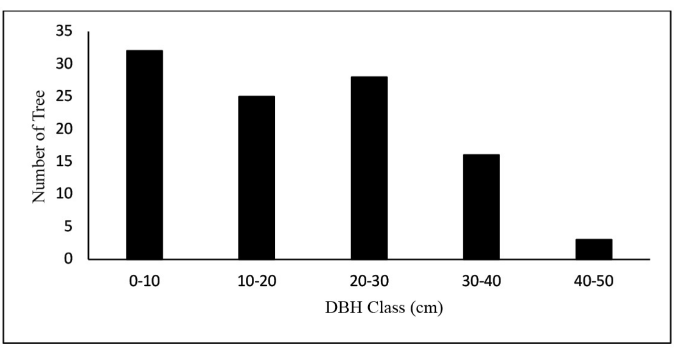


Figure 2: The standing tree is based on its diameter at breast height (DBH) classification

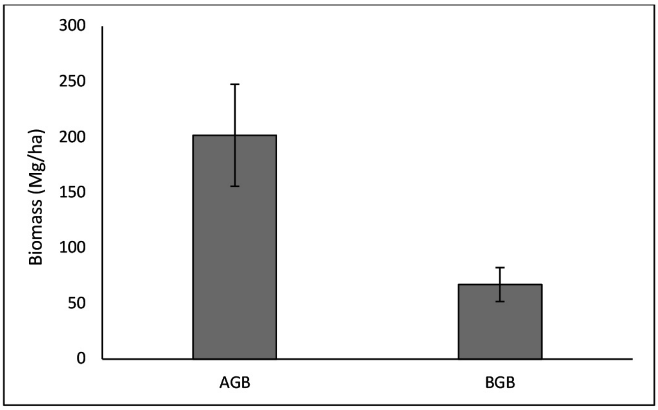


Figure 3: Aboveground (AGB) and belowground biomass (BGB) for standing living and root trees in mangroves forest at Kota Marudu, Sabah, Malaysia

levels and water tables (Kusmana *et al.,* 2018). The value of the aboveground tree biomass in the Kota Marudu mangrove forest is 201.74 Mg ha$^{-1}$. This finding is similar to Hatta *et al.* (2022), who reported an aboveground tree biomass of 273.15 Mg ha$^{-1}$ in the mangrove forest in Kudat, Sabah. On the other hand, Suhaili *et al.* (2020) reported a lower value (134.59 Mg ha$^{-1}$) of aboveground tree biomass in the *Rhizophora*-dominated mangrove forest in Sulaman Lake Forest Reserve, Tuaran, Sabah. Hemati *et al.* (2015) found a higher value of aboveground tree biomass in the mangrove area in Selangor, Malaysia, at 305.03 Mg ha$^{-1}$. Many factors influence the amount of aboveground tree biomass in mangrove areas, including species composition and environmental conditions such as disturbed and undisturbed areas. Tengku Zarawie *et al*. (2015) also mentioned that the tree's distance from the sea impacts tree biomass. Trees growing near the landward area have higher aboveground biomass values than those more exposed to seawater due to the high salinity levels that can stunt tree growth (Komiyama *et al*., 2008).

As a consequence of the extra effort and time needed to extract samples for belowground biomass, there is limited literature on its estimation in mangrove forests (Njana *et al.,* 2015; Adame *et al*., 2017). The belowground biomass in the Kota Marudu mangrove forest is 33.62 Mg ha$^{-1}$. This value is similar to that recorded in a *Rhizophora*-dominated mangrove forest in Terengganu, Malaysia (Islam *et al*., 2022), which is 33.84 Mg ha$^{-1}$. Adame *et al.* (2017) mentioned a variety of root biomass according to species and the age of the trees. Komiyama *et al.* (2000) published a compilation of belowground biomass by species, in which the highest value was found in *Avicennia* forests at 160.3 Mg ha$^{-1}$, followed by *Sonneratia* forests at 32.4 Mg ha$^{-1}$, and the least in *Rhizophora* forests at 17.4 Mg ha$^{-1}$. The variation in belowground biomass is also influenced by factors such as extraction methods, forest structure, and the anoxic environment of the mangrove forest (Hemati *et al.,* 2015; Hatta *et al*., 2022).

### *The Soil Carbon Stock in the Mangrove Forest in Kota Marudu, Sabah, Malaysia*

The trend for soil carbon stock is shown in Figure 4. The value of soil carbon stock increases with depth. The deepest layer (50-100 cm) has a significantly higher value of soil carbon stock at 470.77 Mg C ha$^{-1}$, followed by the third layer (30-50 cm) at 169.20 Mg C ha$^{-1}$. The lowest value was recorded in the surface layer at 112.35 Mg C ha$^{-1}$. These findings are supported by Hemati *et al*. (2015), whose study also showed a similar pattern of soil carbon stock increasing with depth. Conversely, Hong *et al*. (2017) found the opposite trend, with

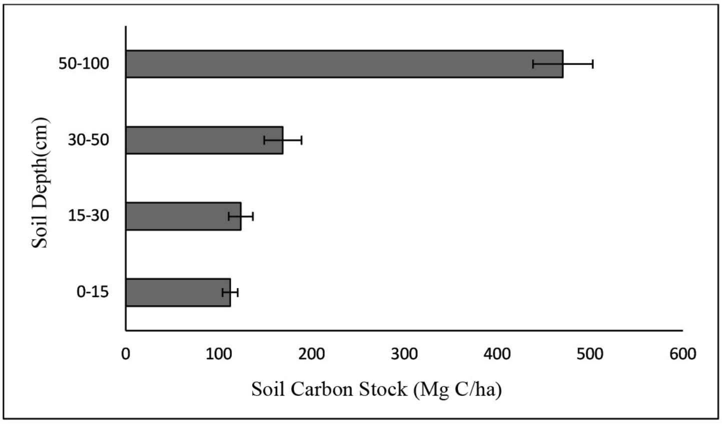


Figure 4: Soil carbon stock by sampling depth in mangroves forest at Kota Marudu, Sabah, Malaysia

significantly higher soil organic carbon at the surface area compared with lower sections. These differences are due to the disturbance history of the mangrove area, tidal inundation patterns, and forest age. Donato *et al.* (2012) also noted that the distance from the sea could influence soil carbon stock in marine mangroves due to the increase in soil depth (Sugiatmo *et al.,* 2023).

***The Total Carbon Stock at the Mangrove Forest in Kota Marudu, Sabah, Malaysia***

Table 5 shows the comparison of the total carbon stocks in mangrove forest ecosystems at different study sites. Almost 87% of the carbon stock in this study area is stored inside the soil carbon pool. This finding is similar to studies conducted by Suhaili *et al.* (2020) in the mangrove forest of Sulaman Lake Forest

Table 5: Comparison of total carbon stocks in mangrove forest ecosystems at different study sites

| Study Site | Aboveground Carbon (Mg C ha$^{-1}$) | Belowground Carbon (Mg C ha$^{-1}$) | Soil Carbon (Mg C ha$^{-1}$) | Total Ecosystem Carbon Stock (Mg C ha$^{-1}$) | $CO_2$ Equivalent (Mg C ha-1) | Reference |
|---|---|---|---|---|---|---|
| Selangor, Malaysia | 48.17 (32%) | 13.12 (8%) | 90.11 (60%) | 151.4 | 55.64 | Hong *et al.* (2017) |
| Tuaran, Malaysia | 67.30 (15%) | 22.44 (5%) | 351.98 (80%) | 441.72 | 1,621.11 | Suhaili *et al.* (2020) |
| Kudat, Malaysia | 136.58 (30%) | 45.53 (10%) | 273.76 (60%) | 455.87 | 1,673.04 | Hatta *et al.* (2022) |
| Central Java, Indonesia | 30.27 (4%) | 10.99 (2%) | 671.87 (94%) | 713.13 | 2,617.19 | Sugiatmo *et al.* (2023) |
| Kota Marudu, Malaysia | 100.87 (10%) | 33.62 (3%) | 876.16 (87%) | 1,010.65 | 3,709.09 | Present study |

Notes: Value is the mean (percentage) of the measurement

Reserve, Tuaran, Sabah, Malaysia and Alongi *et al.* (2016) in Sumatra, Indonesia, where the soil carbon pool contributed 78% and 80%, respectively. However, Hong *et al.* (2017) and Hatta *et al*. (2022) found that the soil carbon pool in their study area in Peninsular Malaysia and Kudat, Sabah, Malaysia, respectively, stored only 60% of the total carbon pool while 30% to 32% and 10% to 8%, respectively were stored by the aboveground (standing trees) and belowground (roots) carbon pool. In comparison, Kida *et al.* (2021) found a higher percentage of soil carbon pool in a mangrove forest in Trat, Thailand, which was 87%. Sugiatmo *et al*. (2023) also recorded a higher percentage of soil carbon pool compared with this study, which was 94%. The remaining 6% of the total carbon pool is contributed by the aboveground (4%) and belowground (2%) carbon pools. These findings further demonstrate how mangrove soils can store more carbon than trees and roots compared with other major worldwide forest domains like the tropics.

The results regarding the total carbon stocks in different study sites also showed a variation in numbers, ranging from 151.4 Mg C ha$^{-1}$ to 1,010.65 Mg C ha$^{-1}$. These differences in measurements are influenced by several environmental factors such as the site's temperature, rainfall, nutrient availability, and soil salinity (Sugiatmo *et al.,* 2023). Table 5 also indicates that the total carbon stock in the mangrove ecosystem in Kota Marudu shows that soil has the highest value, with a carbon stock value of 876.16 Mg C ha$^{-1}$, followed by aboveground carbon for living trees at 100.87 Mg C ha$^{-1}$, and belowground carbon at 33.62 Mg ha$^{-1}$. The value of the total carbon pool is similar to the total carbon stock in the mangrove forest in Central Java, Indonesia, which is 713.13 Mg C ha$^{-1}$ (Sugiatmo, *et al*. 2023), but higher than that in the study by Hong *et al.* (2017) in Peninsular Malaysia.

The history of disturbance such as human activities, age, tree species, soil texture, soil bulk density, and soil depth influence the total carbon stock in mangrove ecosystems. Nevertheless, the results show that mangrove forests play a significant role in mitigating climate change and should be a top priority, akin to terrestrial ecosystems. Despite having lower species diversity and richness compared with terrestrial forests, the ability of mangrove forests to sequester carbon from the atmosphere should not be overlooked. Continuous monitoring and reporting of data are important to support climate change mitigation programmes such as REDD+, at national and regional levels, as well as for mangrove conservation and management purposes (Alimbon & Manseguiao, 2021).

## Conclusions

This study found that the total carbon stock in the mangrove forest in Kota Marudu, Sabah, Malaysia was 1,010.65 Mg C ha$^{-1}$. The soil in the mangrove forest constitutes the major carbon pool in the total ecosystem carbon stock, followed by the aboveground (living trees) and the belowground (roots) components. These findings underscore the crucial role of mangrove forest ecosystems in carbon sequestration. The data from this study can serve as baseline information for policymakers in Malaysia to develop future mangrove action plans.

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## Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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