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Estimation of carbon pool at mangrove forest of Kudat, Sabah, Malaysia

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Abstract. *Hatta SM, Salleh E, Suhaili NS, Besar NA. 2022. Estimation of carbon pool at mangrove forest of Kudat, Sabah, Malaysia. Biodiversitas 23: 4601-4608.* Mangroves play a significant role in reducing tropical carbon emissions and preventing climate change. This study was carried out in Kudat's Tun Mustapha Park mangrove forest. This research aims to quantify the aboveground, belowground, and soil carbon pools. Nine 125-meter-long transect lines were set up, and every 25 meters, a 7-meter-diameter circle was placed. A forest inventory was conducted to determine the diameter at the breast height of standing trees. For soil analysis and bulk density, soil samples were collected at four different depths (0-15 cm, 15-30 cm, 30-50 cm, and 50-100 cm). An ICP-OES analyzer was used to determine the value of soil nutrients, and a CHNS analyzer was used to determine the soil carbon concentration. The aboveground and belowground biomass was calculated using the allometric equation, and the carbon stock was estimated at 50% of the total biomass. The outcome showed a 455.87 $MgCha^{-1}$ total carbon pool. The soil carbon has the highest value with 273.76 $MgCha^{-1}$, followed by aboveground carbon (living trees) with 136.58 $MgCha^{-1}$ and belowground carbon (roots) with 45.53 $MgCha^{-1}$. This study found that soil carbon stock made up almost 60% of the total carbon stock in the mangrove forest.

Keywords: Aboveground, belowground, carbon pool, mangrove, soil carbon

INTRODUCTION

Mangroves are one of the planet's most productive marine ecosystems, offering many species a special habitat opportunity and essential human goods and services. However, due to direct anthropogenic impacts and climate change, mangrove habitats are declining at an alarming rate (Carugati et al. 2018). Mangrove ecosystems are of great ecological and economic importance (Lee et al. 2014). Mangrove habitats are thought to cover between 14 and 15 million ha worldwide and it was estimated there were 137,760 km^2 of mangrove forests in 118 nations and territories in 2000 (Giri et al. 2011). Mangroves occupy for 0.7% of the world's total tropical forest area (statistics from 1990 to 2020), with Asia having the largest concentration at about 6.8 million ha (Kauffman and Donato 2012; FAO 2020). Malaysia, which has 33 million hectares of total land area, holds approximately 537,686 ha of mangrove forest, with more than half of it (364,100 ha) found in Sabah (MENR 2021). The other regions in Malaysia, which are Sarawak and Peninsular Malaysia, covered approximately 132,000 ha (23%) and 104,181 ha (18%) of mangrove forest, respectively (Olaniyi et al. 2012; Marzuki 2019; Suhaili et al. 2020; Tangah et al. 2020).

Mangroves are among the most carbon-rich ecosystems in the world, and because of the significant amounts of carbon they capture and sequester (mainly in soils), which balance out anthropogenic CO_2 emissions, they are thought to play a role in climate regulation and mitigation. The strong primary production rates and the quick soil accretion rates on the forest floor are reflected in the high levels of carbon. Like other forested ecosystems, Mangroves exchange gases with the atmosphere, but they also do so with the nearby coastal waters, just like all coastal wetlands. Tidal linkages are intricate, involving tides, porewater pumping, and subsurface groundwater advection to import and export different quantities of dissolved organic and inorganic solutes and particles (Jennerjahn et al. 2017; Alongi 2018; Friess et al. 2020). Eventually, it will contribute to additional carbon emissions into the atmosphere and consequently lead to global warming problems (Rizal et al. 2018). Therefore, various forms of mitigation programs and schemes have been studied in the effort to reduce the greenhouse gases concentration in the atmosphere (IPCC 2007). Conserving the vegetal biomass of the forest ecosystem as the carbon sinks and sequestration is one of the efforts implemented to mitigate this global warming problem (Soto-Pinto et al. 2010; Cenamo et al. 2012). Mangrove forests store organic carbon 3-5 times higher than terrestrial forests (Donato et al. 2011). The two main carbon pools in the forest ecosystem are the living vegetation and the soil (Kauffman et al. 2011; Chen et al. 2012). The soil carbon pools usually constitute over 50%, and sometimes over 90%, of mangroves' total ecosystem carbon stock (Donato et al. 2011; Kauffman et al. 2011). Even though the carbon pools in the mangrove forest have a significant capacity to hold carbon for a long period, there is still a dearth of knowledge in this area, particularly on the underground carbon pools.

In Southeast Asia, mangroves have been extensively cleared for other land purposes and deforested (Hamilton and Casey 2016; Richards and Friess 2016). Recorded mangrove losses in Indonesia, Malaysia, and Myanmar were 0.26%, 0.41%, and 0.70%, respectively. A significant component of some countries' greenhouse gas (GHG) emissions is caused by mangrove conversion and deforestation, which produces a significant amount of carbon emissions (Murdiyarso et al. 2015; Taillardat et al. 2018). Specifically, mangrove forests are the subject of numerous worldwide conservation discussions. Mangrove ecosystems offer a wide range of functions, yet they are deteriorating or disappearing at an alarming rate despite this (Millennium Ecosystem Assessment 2005; Barbier 2012; Tallis et al. 2012).

The pace of destruction and degradation is still alarmingly high despite all the significant services that a mangrove forest may offer. Unsustainable human activities, such as converting mangrove habitats into aquaculture sites, timber harvesting, and shrimp farming, are to blame for this issue (Bryan-Brown 2020). These practices might undoubtedly have a negative impact on the mangrove forest's ability to perform its natural functions, particularly when it comes to addressing the current problem of reducing climate change. The mangrove ecosystem's carbon pools will be depleted due to destruction or land alterations, which may influence the forest's capacity to sequester and store carbon. Any alterations or losses inside mangrove ecosystems have the potential to make the forest the primary source of atmospheric carbon emissions (Kauffman et al. 2011). To execute better plans and strategies to maintain the forest, a deeper examination of the carbon stores in the mangrove ecosystem and how human activities affect it is urgently required. To counteract carbon emissions and climate change, mangrove forests must be preserved.

Carbon stock evaluation in Peninsular Malaysian mangrove forests is one of the publications that have been made on the Malaysian mangroves by Hong et al. (2017), while the other was made by Suhaili et al. (2020) at a mangrove forest in Sabah and by Chandra et al. (2015) in Sarawak. In addition, Rambok et al. (2010) also published the soil properties of mangrove forests in Sarawak, Malaysia. Even though Sabah was home to more than half of Malaysia's mangroves, not much was known about their importance as global carbon (C) stores. Therefore, it is imperative to close this gap to better understand the role and significance of mangrove forests. The primary goal of this study is to estimate the two major carbon reservoirs in mangrove ecosystems: soil carbon and live plants. The REDD+ (Reducing Emissions from Deforestation and Forest Degradation and Enhancing Forest Carbon Stocks in Developing Country) projects would be realized with the help of this study's practicable data for future management planning.

MATERIALS AND METHODS

Study area

This research was conducted in the Kudat part of Tun Mustapha Park, Sabah, Malaysia (Figure 1). Tun Mustapha Park (TMP) covered approximately 898,762.76 ha in area with more than 50 islands and islets located across Kudat, Pitas, and Kota Marudu Districts in Kudat-Banggi Priority Conservation Area (PCA). This area was gazetted on 19th May 2016, and it has unique biodiversity that supports a series of complex and linked habitats. It is also home to endangered marine animals such as green sea turtles and dugongs.

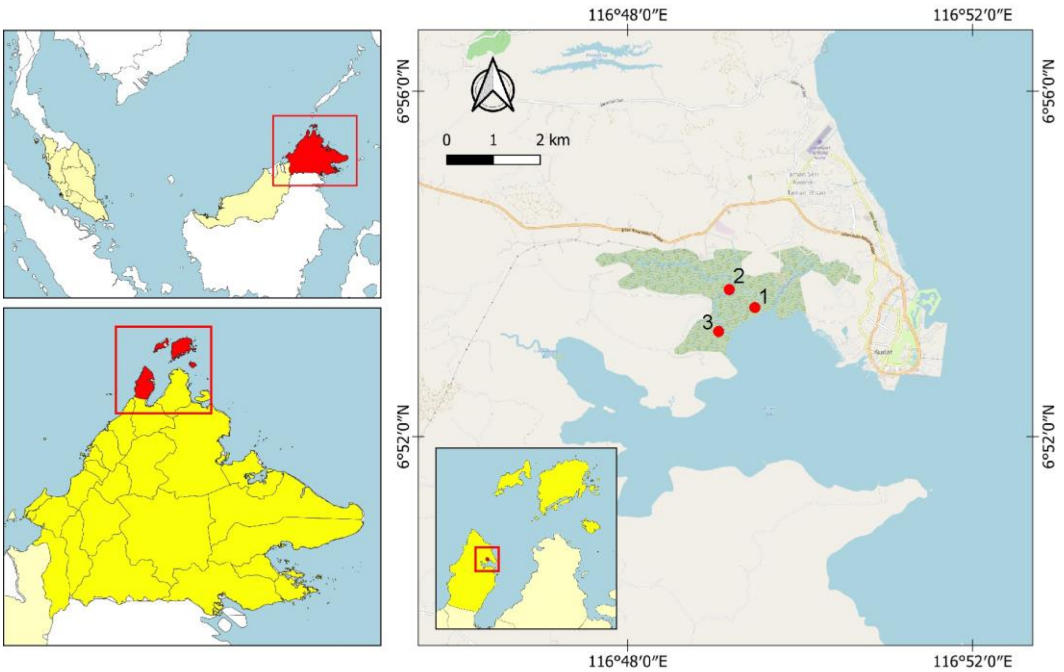

Figure 1. Location of the study area mangrove forest Tun Mustapha Park, Kudat, which is located in the northern part of Sabah, Malaysia

Procedures

Experimental design

A transect method with 3 transect lines with 5 subplots each was established randomly throughout the study area. The subplot was built circular (A= πr^2) with a 7 m radius. The distance between each subplot was 25 m and the length for the transect lines was 125 m. Standing trees' above- and belowground carbon, as well as soil carbon, are the carbon stocks that have been measured in this study. The aboveground and belowground data were estimated using a non-destructive manner, and the soil data were obtained through soil sampling. This study employed the transect line approach, implemented by a published procedure book (Kauffman et al. 2011). The field data collections were done in April and August 2019.

Field data collection

Forest inventory was done to get the diameter breast height (DBH) and tree height of the standing trees with DBH of more than 5 cm. The measurement was done using a DBH meter and TruPulse 360 rangefinder. All trees with more than 5 cm DBH were measured within a 7 m radius. (Komiyama et al. 2005; Kauffman and Donato 2012). The soil sample was taken from 4 depths (0-15 cm, 15-30 cm, 30-50 cm, and 50-100 cm) at each subplot. Twenty (20) samples were collected from each transect, and the total samples for this study were 60 samples. Mixed soil samples were collected to analyze soil properties such as moisture content and organic matter percentage, soil texture, soil carbon content, and soil acidity. In addition, an undisturbed soil sample was collected using a bulk density ring (98.125 cm^3) to analyze soil bulk density.

Data analysis

Soil analysis

After being air dried at room temperature and sieved through a 2 mm soil sieve, all soil samples were examined for their Physico-chemical characteristics. Physical characteristics of the soil included its moisture content, texture, and bulk density, while chemical characteristics included its pH, salinity, cation exchange capacity (CEC), nutrient content, and carbon concentration. Utilizing the gravimetric approach, the amount of moisture in the soil was assessed after it had been dried for 24 hours at 105°C (Shukla et al. 2014). In the meantime, the ratio of a soil's dry mass to its volume is used to describe its bulk density (Han et al. 2016). First, the silt, clay, and sand percentages were determined using the Pipette method. The same numbers were then used to define the soil texture by comparing them to the USDA Soil Classification Triangle.

A portable refractometer was used to test soil salinity, and a soil-distilled water ratio (1:2.5) approach was used to measure soil pH. The Loss-on-ignition method, weighing the soil after it had been ignited at 500°C for 24 hours, was used to determine the percentage of soil organic matter. Total cation exchange capacity (CEC) was calculated by adding base cations (calcium, magnesium, potassium, and sodium) and acid cations, which are exchangeable (hydrogen and aluminum) (Culman et al. 2019). Soil digestion using aqua regia was done to extract the elements (except hydrogen), and an Inductively Couple Plasma-Optical Emission Spectrometry (ICP-OES) machine was used to analyze the samples. The analysis for soil nutrient availability also was done using the same method. While the concentration of carbon, hydrogen, nitrogen, and sulfur was done using A Vario EL CHNS (carbon-hydrogen-nitrogen-sulfur) auto analyzer machine.

Aboveground and belowground biomass analysis

Other equations were developed to quantify mangrove tree biomass, but there is a dearth of data on species distribution at the study site, therefore, the options for allometric equations are constrained (Wong et al. 2020). The aboveground biomass for the primary mangrove zone in Sabah was calculated using an allometric equation for *Rhizophora* spp. because the area was dominated by *Rhizophora* spp. that was developed by Fromard et al. (1998). The only parameter in the equation, W=0.128DBH2.60, is the tree's diameter at breast height.

$$W = 0.128 \times DBH \times 2.60$$

Compared to other equations like Clough and Scott (1989), that has a relative error of -9.84 to +10.3%, and Ong et al. (2004) with a relative error of +6.81 to 10.8%, this allometric equation has a relative error of -8.44 to +6.81% (Komiyama et al. 2008). The result for aboveground biomass was then converted into aboveground carbon using the conversion factor of 0.5 with respect to the supposition that the carbon stock of standing trees is equal to 50% of its biomass (Houghton and Hackler 2001). Finally, using the 3:1 (AGB:BGB) biomass comparison ratio developed by Kusmana et al. (2018), the biomass of roots was calculated, and the carbon content was estimated to be equal to 50% of the biomass.

Soil carbon stock and total carbon pool

The bulk density and carbon concentration of all the undisturbed soil samples were determined from four depths. The soil carbon stock was then calculated using the values as the inputs. First, using the equation below (Kauffman and Donato 2012), the soil carbon stock ($MgCha^{-1}$) for each sampled depth interval was determined. The total soil carbon stock was then estimated by adding the carbon stock for each soil depth:

Soil carbon (Mg ha^{-1}) = Bulk density (g cm^{-3}) × Soil Depth Interval (cm) × Carbon concentration (%C)

By adding up all of the major carbon pools that have been measured, including the aboveground (live plants), belowground (roots), and soil carbon pools, the total ecosystem carbon pools in the Tun Mustapha Park Kudat were estimated. To determine the potential value of the research site in emitting and absorbing carbon dioxide to and from the atmosphere, the entire value of ecosystem carbon stock was then translated into its carbon dioxide equivalents by multiplying it with 3.67 (CO_2e).

Carbon dioxide equivalent (CO_2e) = Total ecosystem carbon stock × 3.67

RESULTS AND DISCUSSION

The study area is dominated by *Rhizophora* spp. with 217 total individual trees in the sampling area (2309.07 m²). Most trees fall into the 5-15 cm class, while the least was found in the 45-60 cm class. For annual rain, Kudat typically receives about 96.4 millimeters (3.8 inches) of precipitation and has 215.55 rainy days (59.05% of the time) annually and temperatures are oppressively hot and cloudy. The temperature rarely falls below 22ºC or rises over 33°C throughout the year, usually fluctuating between 24°C and 32°C.

Soil physicochemical properties

Soil pH value, as well as the soil salinity level, are two factors that have a significant influence on the growth, adaptation, and survival of most mangrove species (Jeyanny et al. 2018). The percentage of soil organic content and its nutrient level are other main components that could affect the mangrove forest's species composition and structure (Hossain and Nuruddin 2016). Assessing soil's physical and chemical characteristics is one way to determine an area's soil fertility level (Rambok et al. 2010). Soil bulk density, moisture content, sand, silt, clay percentage, and soil texture are the soil's physical properties measured in this study (Table 1). The result shows the range of the soil bulk density was from 0.76 ± 0.09 g cm^{-1} to 0.84 ± 0.08 g cm^{-1}, slightly higher compared to the bulk density that was recorded by Hemati et al. (2015) in their study of mangrove forest in Peninsular Malaysia, which range from 0.57 g cm^{-1} to 0.65 g cm-3. The percentage of soil organic matter and soil texture were some of the factors that influenced the soil bulk density (Chaudhari et al. 2013). The soil moisture content analysis shows that few significant variations could be observed on the parameter. It was ranging from 21.42 ± 2.03% to 22.63 ± 1.52%. Among the soil texture's particles, sand makes up the majority, with a range of 54.57% to 61.62%, and silt has the lowest range of percentages of 3.37% to 19.97%. The soil texture in the study area was determined to be sandy clay loam based on the clay, silt, and sand ratio. The soil's high porosity resulted from the high amount of sand in the mixture. Low bulk density and high water holding capacity are typical characteristics of soil with high porosity.

The soil in the study area is acidic, as seen by the pH range of 3.04 to 3.36 (Table 2). It has a more acidic soil compared to the study of Arianto et al. (2015) at a mangrove forest in Sarawak, Malaysia. The range is from 3.93 to 5.41. According to Pazi et al. (2016), the presence of both sulfur-reducing bacteria and acidic clays in the mangrove soil is the factor that causes it to have a neutral to the slightly acidic type of soil. However, some mangrove forests in Malaysia have a very acidic brackish water caused by the formation of sulphuric acid that comes from the aeration of soil sulfates (Arianto et al. 2015; Pazi et al. 2016). Soil salinity increase through the depth, where 12.7 is the lowest and 22.4 is the highest. The mean for soil organic matter ranged from 18.81% to 21.56%. The soil's darker color and low bulk density values can be attributed to the high value of soil organic matter (Rambok et al. 2010). Ca and Na were the two most abundant elements in the soil, according to an analysis of its significant constituents with a range of 2.71 meq/100 g to 4.23 and 0.52 meq/100 g 0.72, respectively. Mg and K have the lowest values, 0.61 meq/100 g to 0.90 meq/100 g and 0.30 meq/100 g to 0.42 meq/100 g compared to others (H and Al), with the lowest value of 1.51 meq/100 g to 1.84 meq/100 g and 0.72 meq/100 g to 1.02 meq/100 g. Because a high soil salinity could hinder tree growth, the high amount of calcium helps to reduce soil salinity (Hemati et al. 2014). The Cation Exchange Capacity (CEC) of the soil rises with depth, reaching a maximum of 8.94 meq/100 g at 50-100 cm and a minimum of 6.68 meq/100 g at 30-50 cm. Results obtained show that among the nutritional components, sulfur has the biggest mean range, followed by nitrogen (0.83 ppm to 0.96 ppm), potassium (0.27 ppm to 0.54 ppm, and phosphorus (0.05 ppm to 0.06 ppm), which has the lowest mean range (0.10 ppm to 0.85 ppm). Additionally, the outcome demonstrates that carbon concentration and the carbon-nitrogen ratio were constant throughout the depths.

Table 1. The physical properties of soil in mangrove forest, Tun Mustapha Park Kudat, Sabah, Malaysia

Soil depth (cm)	Bulk density (g cm^{-1})	Moisture content (%)	Clay (%)	Silt (%)	Sand (%)	Soil texture
0-15	0.84 ± 0.08	21.42 ± 2.03	26.98 ± 6.86	3.37 ± 3.94	62.60 ± 3.94	Sandy clay loam
15-30	0.83 ± 0.08	21.47 ± 1.61	29.96 ± 3.02	19.97 ± 9.61	48.80 ± 9.62	Sandy clay loam
30-50	0.80 ± 0.08	22.63 ± 1.52	37.91 ± 4.09	3.45 ± 6.63	52.15 ± 6.63	Sandy clay
50-100	0.76 ± 0.09	22.17 ± 1.53	33.74 ± 2.30	6.75 ± 5.74	52.20 ± 5.74	Sandy clay loam

Table 2. The chemical properties of soil in mangrove forest, Tun Mustapha Park Kudat, Sabah, Malaysia

Soil depth (cm)	pH (1:2.5)	Salinity (ppt)	Soil organic matter (%)	Acid cations (meq/100)			Base cations (meq/100g)			CEC (meq/100 g)
				Al^{3+}	H^{+}	Mg^{2+}	Ca^{2+}	Na^{+}	K^{+}	
0-15	3.36 ± 0.33	12.7± 1.87	21.56± 2.03	1.02 ± 0.33	1.51 ± 0.41	0.80 ± 0.21	0.66± 0.47	3.24±1.15	0.37± 0.36	7.60 ± 2.93
15-30	3.24 ± 0.25	14.2± 4.87	19.49 ± 1.62	0.97 ± 0.50	1.58 ± 0.22	0.88 ± 0.25	0.72 ± 0.81	3.78±1.35	0.42± 0.21	8.35 ± 3.34
30-50	3.16 ± 0.25	19.6± 8.69	18.81 ± 1.52	0.72 ± 0.25	1.82 ± 0.35	0.61 ± 0.11	0.52 ± 0.21	2.71±0.52	0.30± 0.62	6.68 ± 2.06
50-100	3.04 ± 0.28	22.4±10.38	19.60 ± 1.54	0.94 ± 0.42	1.84 ± 0.34	0.90 ± 0.28	0.64 ± 0.65	4.23±1.51	0.39± 0.59	8.94 ± 3.79

Table 3. Soil nutrient contents in mangrove forest Tun Mustapha Park Kudat, Sabah, Malaysia

Soil depth (cm)	Carbon (%)	Total N (%)	P (ppm)	K (ppm)	S (%)	C:N ratio
0-15	7.83 ± 2.51	0.96 ± 0.83	0.06 ± 0.02	0.37 ± 0.23	1.10 ± 0.57	13.56 ± 7.34
15-30	8.93 ± 0.57	0.83 ± 0.74	0.06 ± 0.01	0.32 ± 0.45	1.37 ± 0.23	15.58 ± 7.37
30-50	8.80 ± 0.43	0.93 ± 0.79	0.05 ± 0.01	0.54 ± 0.25	1.64 ± 0.22	15.36 ± 7.58
50-100	9.65 ± 0.49	0.95 ± 0.84	0.06 ± 0.01	0.27 ± 0.39	1.64 ± 0.35	16.02 ± 8.05

Aboveground carbon stock, belowground carbon stock, soil carbon, and total carbon pool

Figure 2 presents the aboveground and belowground biomass for both living trees and roots in the mangrove forest in Kudat Sabah. Because the roots are constantly exposed to the harsh mangrove environment, which includes high salinity and a high-water table, the aboveground tree biomass has a higher value than the belowground biomass (Kusmana et al. 2018). The findings show the standing trees of mangrove forests in Kudat have aboveground biomass of 273.15 Mg ha^{-1}. Moreover, it is somewhat higher than the aboveground biomass discovered in the mangrove forest's leading species (Rhizophora apiculate), as determined by Suhaili et al. (2020) at Sulaman Lake Forest Reserve, Sabah, Malaysia, which is 134.59 Mg ha^{-1}.

However, compared to the 305.03 Mg ha^{-1} of aboveground biomass observed in an undisturbed mangrove forest at Kuala Selangor Nature Park, Peninsular Malaysia, the aboveground biomass recorded in these research areas is lower (Hemati et al. 2015). These changes in values were influenced by the species composition of the forest and its ecological setting (Komiyama et al. 2008; Chandra et al. 2011). For example, the mangrove forest in Kudat has a similar ecology to the Awat-Awat mangrove forest, close to the settlement and where the Rhizophora species dominate the mangrove (Chandra et al. 2015). Meanwhile, a Non-Governmental Organization (NGO) by the name Malaysian Nature Society is in charge of managing the mangrove forest in Kuala Selangor Nature Park. The Kuala Selangor Nature Park has access restrictions, making it difficult for anyone to engage in human activity there. As a result, most of the land is undisturbed, and this location includes more Avicennia and Bruguiera species (Hemati et al. 2015).

The anoxic environment in the research location, the structure of the forest, and the excavation techniques utilized during measurement are a few factors that could have contributed to the discrepancies in belowground biomass values (Hemati et al. 2014; Njana et al. 2015). Compared to aboveground biomass in mangroves, less research has been done on belowground biomass since it requires more time and effort, in addition to the difficulties of collecting samples (Njana et al. 2015; Adame et al. 2017). In their research at Kuala Selangor Nature Park in Malaysia, Hossain et al. (2008) discovered that the root biomass in that mangrove forest is 0.4924 Mg ha^{-1}. Meanwhile, Komiyama et al. (2000) gathered research on the belowground biomass produced by several mangrove species, including 17.4 Mg ha^{-1} for *Rhizophora* forests, 147.3-160.3 Mg ha^{-1} for *Avicennia* forests, and 32.4 Mg ha^{-1} for Sonneratia forests. Although it is smaller than the study Komiyama et al. (2000) reported, our study discovered a higher value than the Kuala Selangor Nature Park, which is 91.05 Mg ha^{-1}. The anoxic environment in the research location, the structure of the forest, and the excavation techniques utilized during measurement are a few factors that could have contributed to the discrepancies in belowground biomass values (Hemati et al. 2014; Njana et al. 2015).

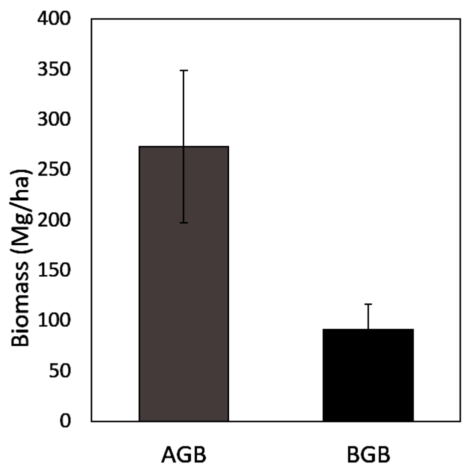

Figure 2. Aboveground (AGB) and belowground biomass (BGB) for standing living and root trees in mangroves Forest at Tun Mustapha Park, Kudat, Sabah, Malaysia

Table 4. Total ecosystem carbon stock in Tun Mustapha Park, Kudat, Sabah, Malaysia

Study site	Aboveground carbon (MgCha^{-1})	Belowground carbon (MgCha^{-1})	Soil carbon (MgCha^{-1})	Total ecosystem carbon pool (MgCha^{-1})	CO_2 equivalent (MgCha^{-1})
Tun Mustapha Park, Kudat	136.58 (30%)	45.53 (10%)	273.76 (60%)	455.87	1673.04

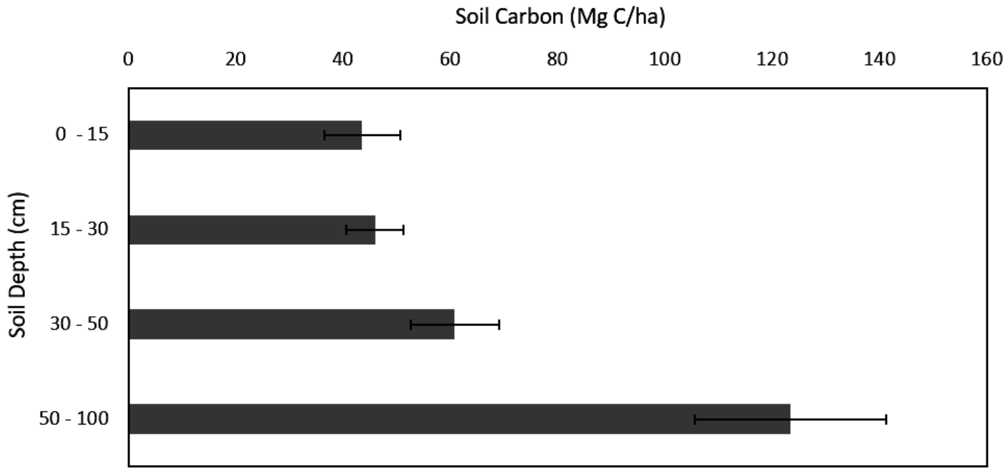

Figure 3. Soil carbon stock by sampling depth in Mangroves Forest at Tun Mustapha Park Kudat, Sabah, Malaysia

According to the sampling depth, Figure 3 illustrates the trend of soil carbon stock. The greatest value, 123.43± 17.81 $MgCha^{-1}$, was discovered in 50-100 cm depth. There is a significant difference between the depth of 50-100 cm and the other depths, which are 43.55 ± 7.04 $MgCha^{-1}$ (0-15 cm), 45.95 ± 5.32 $MgCha^{-1}$ (15-30 cm), and 60.90 ± 8.21 $MgCha^{-1}$ (30-50 cm). In their study, Hemati et al. (2015) found a similar finding that the soil organic carbon increases with depth; however, Hong et al. (2017) observed the reverse tendency, finding that the soil's surface layer has a higher value of organic carbon than the lower section of the soil profile. These results might be affected by the history of disturbance, the pattern of tidal inundation, the age of the forest, the sedimentation, and the species mix (Sherman et al. 2003; Hemati et al. 2015; Hong et al. 2017).

In this study, the soil carbon pool was found to be about 60% of the total carbon stock, which is similar to a previous study by Hong et al. (2017) at Peninsular Malaysia's degraded mangrove forest and Suhaili et al. (2020) at Sulaman Lake Forest Reserve, Sabah. However, these reports differ from a study on the carbon stock value of a natural tropical forest published by Besar et al. (2020). According to their research, soil only accounted for 13% of the ecosystem's total carbon pool, while living trees are responsible for 87%. Large dead roots influenced this difference in the mangrove ecosystem that acts as the nutrient-conserving mechanism compared to the terrestrial roots that recycle their nutrients by deleting litter on the soil surface (Alongi et al. 2012). This is supported by other research showing how mangrove soils store more carbon than trees and roots compared to other major worldwide forest domains like tropical forests, boreal forests, and temperate forests (Donato et al. 2011; Kauffman et al. 2011). The soil carbon turnover rates in the mangrove forest are also a thousand times slower compared to the terrestrial forest soils, resulting in a higher value of soil reservoir than the aboveground carbon pools (Atwood et al. 2017).

Table 4 shows the total ecosystem carbon pool in the mangrove ecosystem at Tun Mustapha Park, Kudat, and found that soil, with a carbon stock value of 273.76 $MgCha^{-1}$, has the highest value, followed by the aboveground carbon for living trees, at 136.58 $MgCha^{-1}$ and belowground with 45.53 $MgCha^{-1}$ (Table 4). The total carbon pool's value is similar to the total Carbon pool at the mangrove forest at Sulaman Lake Forest Reserve, Sabah, which is 441.91 $MgCha^{-1}$ (Suhaili et al. 2020) but was higher than the study by Hong et al. (2017) at Peninsular Malaysia. The total C pool mangrove ecosystem is influenced by the history of disturbance, such as human activities, age, species of trees, and soil texture.

Overall, the total carbon pool in mangrove forests at Tun Mustapha Park, Kudat Sabah, Malaysia, was 455.87 $MgCha^{-1}$. The soils in the mangrove forest are the major contributor to the total ecosystem carbon pools, followed by the aboveground (living trees) and the belowground (roots). The finding from this study showed that the mangrove ecosystem could store an enormous amount of carbon in its pools, especially the soil carbon pools, making it crucial to include this ecosystem in the national climate change mitigation scheme. Furthermore, this quantification of carbon pools also might benefit the nation as it can serve as the baseline data for the policymakers in Malaysia to see and plan the mangrove ecosystem's potential in the carbon trading market.

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