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Soil organic carbon across varying habitat conditions in the mangrove ecosystem in Sembilang National Park, South Sumatra, Indonesia

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Abstract. *Agustriani F, Iskandar I, Yazid M, Ulqodry TZ, Fauziyah. 2024. Soil organic carbon across varying habitat conditions in the mangrove ecosystem in Sembilang National Park, South Sumatra, Indonesia. Biodiversitas 25: 4603-4612.* Mangrove ecosystems play an important role in the global carbon cycle, but the Soil Organic Carbon (SOC) stock in these systems was not well-documented in some areas, including in Sembilang National Park (SNP), South Sumatra Province, Indonesia. This study aimed to estimate the SOC values of the mangrove ecosystem under different habitat conditions/management zones in the SNP area, namely natural mangroves, restored ponds, mudflats, human settlements, and post-fire forests. Soil samples were collected at depth intervals of 0 to 50 cm from the five different habitat conditions. Soil samples were then analyzed using the loss-of-ignition method for estimating the SOC stock. Mangrove density was assessed using the Normalized Difference Vegetation Index (NDVI) method. Statistical analyses of Kruskal-Wallis and Dunn's post-hoc tests with a significance threshold of 0.05 were used to examine differences in SOC stocks across habitat types. The result showed that the average SOC in the mangrove ecosystem in the SNP area was 177.26±60.20 Mg C ha^{-1}. Natural mangroves had the highest SOC value with 220.98 Mg C ha^{-1} followed by settlements (174.18 Mg C ha^{-1}), mudflats (160.87 Mg C ha^{-1}), and post-fire forests (156.84 Mg C ha^{-1}), while restored pond had the lowest with 114.07 Mg C ha^{-1}. Significant differences in SOC values were found among habitat conditions according to the Kruskal-Wallis test ($p = 0.01<0.05$), but only between natural mangroves and restored ponds were statistically significant based on post-hoc analysis (Dunn's, $p = 0.01<0.05$). This result demonstrated that land use changes (as in the case of ponds) affect SOC in the mangrove ecosystem, implying the importance of conserving the remaining natural mangroves and restoring the degraded mangrove habitats (e.g. pond, post-fire area) in the SNP area. This study suggests that an effort should be considered to integrate soil carbon into green economic plans, especially the mangrove conservation in the Banyuasin coastal wetlands.

Keywords: Blue carbon, coastal wetlands, conservation, habitat comparison, soil organic carbon

INTRODUCTION

Mangrove ecosystems are crucial for coastal environments as they provide important ecological services, such as protecting shorelines, providing habitats for various species, and cycling nutrients (Song et al. 2023; Uddin et al. 2023). Another significant contribution of mangroves is their capacity to sequester substantial amount of carbon (often so-called blue carbon) in both biomass and soil, contributing significantly to carbon storage and climate change mitigation efforts (Aye et al. 2023; Sharma et al. 2023). Mangroves are highly efficient in sequestering carbon from the atmosphere through the photosynthesis process and can accumulate carbon in biomass and sediments (Nehren and Wicaksono 2018; Mahmoudi and Pourebrahim 2022; Awad et al. 2023). The carbon stored in mangrove sediments are estimated to account for more than half of the ecosystem's carbon stocks (Trettin et al. 2021; Ouyang et al. 2024).

Indonesia, as one of the world's largest mangrove areas, holds a crucial position in global carbon dynamics and climate change mitigation efforts (Amelia et al. 2023). This is reflected in the extent of Indonesian mangroves, covering approximately 3.4 million hectares, which constitutes more than 20% of the total global mangrove area (MoEF 2021). Despite the significance of carbon stocks in mangrove ecosystems, a great number of studies have been focused on above-ground carbon in the form of tree biomass. Yet, Soil Organic Carbon (SOC) in mangrove ecosystems has often been overlooked, likely due to the logistical difficulties in data collection. The data on soil organic carbon in mangrove ecosystems in Indonesia are still patchy, including in Sembilang National Park (SNP).

Sembilang National Park is a conservation area located in the Banyuasin and Musi Banyuasin Districts of South Sumatra Province, Indonesia, and spans an area of approximately 202,896.31 hectares (MoEF 2020). Established in 2003, the park features a diverse array of wetland ecosystems, including mangroves (44%), back swamps (42%), freshwater and peat swamp forests (9%), mudflats (2.5%), fishponds (1.5%), and sandy beaches (1%) (MoEF 2020). SNP is renowned for its role as critical habitat for endangered species, such as the Sumatran tiger (*Panthera tigris* subsp. *sumatrae* Pocock, 1929), the Sumatran elephant (*Elephas maximus* subsp. *sumatranus* Temminck, 1847), estuarine crocodiles (*Tomistoma schlegelii* Müller, 1838), Malayan Giant Terrapin (*Orlitia borneensis* Gray, 1873), and Storm's stork (*Ciconia stormi* W.Blasius, 1896) (MoEF 2020). Irrawaddy dolphins have also been sighted in the waters surrounding the park (Fauziyah et al. 2022). Additionally, the mangrove areas within SNP serve as a potential habitat for Asian horseshoe crabs, marine organisms protected under Indonesian law (Fauziyah et al. 2019, 2022). These coastal and estuarine ecosystems contribute to SNP's rich biodiversity, underscoring its importance as a vital conservation area in the region.

Despite its importance for biodiversity conservation, the mangrove area of SNP has decreased by 4.5% during the period 2014-2019 (Febrianto et al. 2022). The main causes of mangrove loss and degradation are mainly anthropogenic factors, including the establishment of aquaculture and agriculture, coastal development, settlement, pollution, and climate change (Feller et al. 2017; Bhowmik et al. 2022; Akram et al. 2023). Land use change in the SNP area certainly has an impact on the mangrove ecosystem including soil organic carbon.

The understanding of soil organic carbon dynamics is crucial to inform ecosystem sustainability and health (Kumar et al. 2024). Despite the critical importance of mangrove ecosystems in sequestering carbon, there is a notable gap in detailed, localized data on SOC within these environments (Chen et al. 2023; Passos et al. 2023). Previous studies have extensively covered carbon stocks in terrestrial ecosystems (Kusumaningtyas et al. 2019; Suharnoto et al. 2022; Dharmawan et al. 2023), yet the unique carbon sequestration potential of mangrove soils remains underexplored (Sharma et al. 2023) including in the SNP area. Currently, existing research on the SNP area relates to mangrove carbon stocks in some forest zones (Manuri et al. 2011), carbon stock on *Bruguiera* spp. (Sarno et al. 2020), and mangrove carbon uptake through the photosynthesis process (Ulqodry et al. 2020). However, research related to the assessment of SOC stocks across different land uses in the SNP region is limited. This condition could hamper the understanding of the spatial variability and overall capacity of these habitats to store organic carbon. Moreover, the absence of detailed information makes it difficult to formulate focused conservation approaches and policies that optimize the potential of mangrove ecosystems to sequester carbon. It is challenging to formulate conservation plans and policies that optimize the capacity of mangrove ecosystems to store carbon without detailed and accurate data.

This study aimed to measure SOC stocks under various habitat conditions/management zones in the mangrove ecosystem in Sembilang National Park. Management zones investigated included natural mangroves in the Jungle Zone, restored pond in the Utilization Zone, post-fire area in the Rehabilitation Zone, mudflat in the Traditional Zone, and human settlement in the Special Zone. We expected that by properly evaluating SOC stocks in several habitat conditions and land management within SNP, this investigation could fill the knowledge gap and offer crucial insights into the ecological importance of conserving mangrove soil.

MATERIALS AND METHODS

Study area

This research was carried out in Sembilang National Park, South Sumatra Province, Indonesia in 2020-2023 (Figures 1 and 2). This park comprises six zones following the management system of conservation in Indonesia, namely Jungle Zone (JZ), Rehabilitation Zone (RZ), Special Zone (SZ), Traditional Zone (TZ), Utilization Zone (UZ), and Core Zone (CZ). In this study, each zone represented different habitat conditions, i.e. both CZ and JZ represented pristine/natural mangrove habitats, RZ represented rehabilitation area after fire, SZ represented settlement, and UZ represented restored ponds, while TZ represented mudflats habitat. Some areas in the CZ are habitats for estuarine crocodiles locally called Senyulong (*T. schlegelii*) and Sumatran tiger, both of which are included in the endangered category on the IUCN Red List. Therefore, this zone was excluded as a sampling location due to safety concerns.

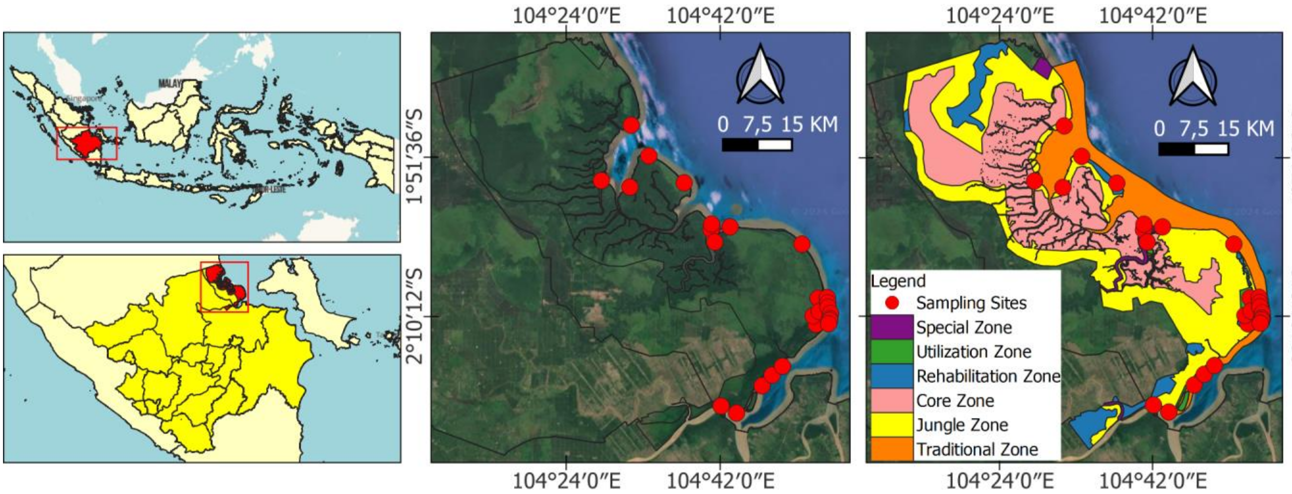

Figure 1. Study area map and the sampling sites in Sembilang National Park, South Sumatra Province, Indonesia

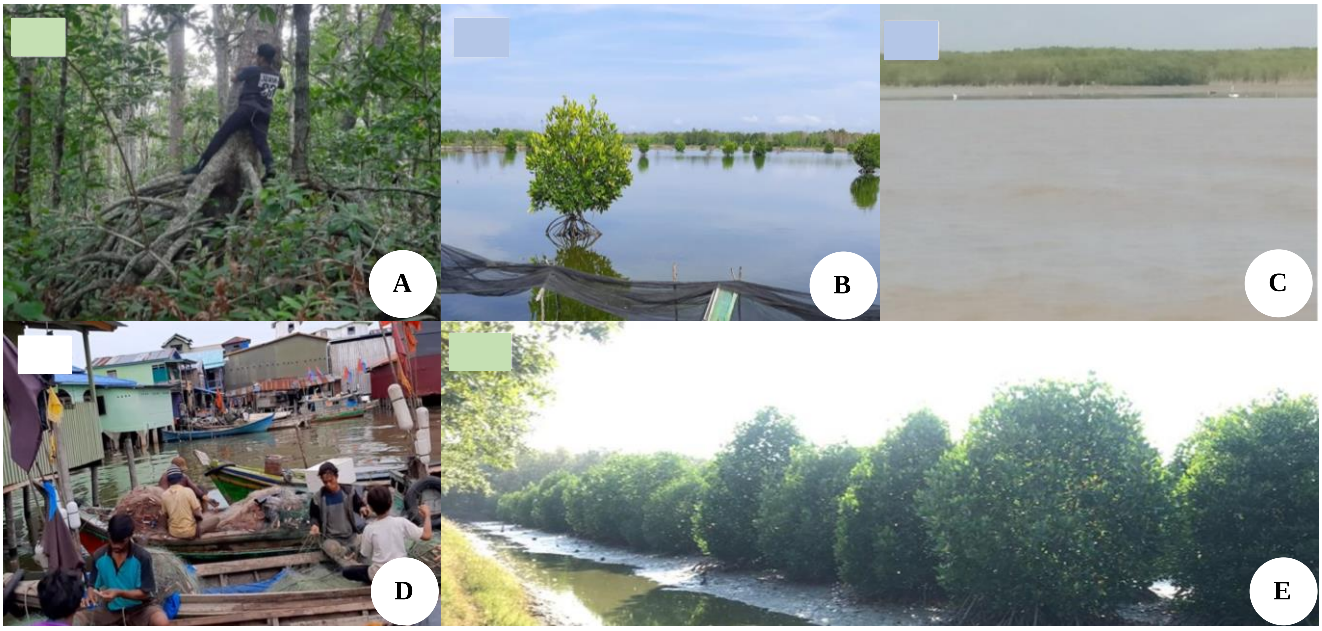

Figure 2. The image examples of the sampling site conditions: A. Jungle Zone; B. Utilization Zone; C. Traditional Zone; D. Special Zone; and E. Rehabilitation Zone. The Core Zone was not included in this study as it was not part of the sampling locations

Sampling procedures

A sampling of mangrove vegetation and soil was conducted at 28 stations located across 5 zones (Table 1), namely: (i) JZ (11 stations) represented pristine mangrove habitat and were located in Betet Island, Ngirawan River, Kacangwar River, Batang River, Banyuasin River, and Lalan River; (ii) RZ (2 stations) represented fire rehabilitation and were located in Alanggantang Island; (iii) SZ (2 stations) represented settlement and were located in Sembilang River; (iv) UZ (5 stations) represented restored pond and were located in Solok Buntu Resort; and (v) TZ (7 stations) represented mudflat habitat and were located near Barong River.

Soil sampling

Referring to the previous study by Kauffman and Donato (2012), accurate SOC measurements must include three parameters, namely SOC concentration, soil bulk density, and soil depth. At present, there is no globally standardized protocol for soil carbon stock analysis (Fest et al. 2022), and the majority of published research conducted soil sampling at a depth of 0-30 cm (Olson and Al-Kaisi 2015). Kauffman and Donato (2012) highlighted that many carbon valuations in upland forests were restricted sampling to the top 30 cm, because most soil carbon is stored in the topsoil horizons, and this is most exposed to land use change. In contrast, recent research in mangrove ecosystems has employed varying sampling depths. For instance, Eid et al. (2020) sampled down to 50 cm, Awad et al. (2023) reached 40 cm, while Breithaupt et al. (2023) and Diana et al. (2023) extended their sampling to depths of 100 cm and 150 cm, respectively.

In this study, soil sediment samples were randomly taken in each habitat using a sediment core tool. Considering the difficulties and costs associated with sampling, soil sampling was conducted at a depth of 0-50 cm. This depth was selected as it typically contains a significant proportion of total SOC due to higher organic matter inputs and active carbon cycling processes in the upper soil layers, making it a practical and representative sampling depth. Each soil samples obtained were stored in separate zip-lock bags, labeled, and weighed at its wet weight. These samples were kept cold (4°C) during transport to the laboratory and then air-dried for 24 hours to minimize organic matter decomposition and microbial growth. The dried samples were lightly ground, sieved through a 2 mm sieve, and used for soil carbon stock analysis.

Mangrove sampling

The line transect plot method was implemented to identify mangroves. This line transect was made by pulling a rope along 100 meters from the mangrove shoreline (estuarine zone) towards the landward margin (adjusting to conditions in the field) which consists of 2 or 3 transect plots measuring 30 × 30 meters.

Data analysis

Determining SOC stock

To estimate the organic carbon mass in soil, data on bulk density, SOC concentration, and soil sampling depth are necessary (Kauffman and Donato 2012; Howard et al. 2014). The calculations used in analyzing SOC stocks are as follows:

Bulk density. Upon returning from the survey, the soil samples in sealed bags were weighed, the lumps were broken up by hand, and then oven-dried to constant mass at a low temperature (60°C) for 48 hours. Thereafter, the sample was crushed or smoothed using a mortar until it achieved a homogeneous composition throughout the entire soil core (0-50 cm) before burning, and it was placed in a plastic bag. Three grams of this crushed sample were transferred to a porcelain crucible and put into a muffle furnace for burning at a temperature of 450°C for 4 hours, and then weighed again. Soil Bulk Density (SBD) was measured by dividing the oven-dried soil sample by the sample volume, as described in the following formula (Kauffman and Donato 2012; Howard et al. 2014):

$$SBD = \frac{Oven-dry\ sample\ mass}{Sample\ Volume} \quad (1)$$

Loss on Ignition (LOI). This LOI method was used to determine soil organic matter by combusting the soil samples at 450°C for 4-8 hours (Howard et al. 2014). Percent LOI was calculated as Bañolas et al. (2020):

$$\%\,LOI = \frac{dry\ mass\ before\ combustion - dry\ mass\ after\ combustion}{dry\ mass\ before\ combustion}\ x\ 100 \quad (2)$$

Carbon concentration percentage (% C). The % C estimation in the mangrove ecosystem was calculated referring to the relationship between % LOI and % C which was revealed by Kauffman and Donato (2012):

$$\%\,C = (0.415)\ x\ \%\,LOI + 2.89 \quad (3)$$

SOC stock. According to Kauffman and Donato (2012), total soil carbon mass per sampled depth was calculated as follows:

$$SOC = SBD * D * \%C \quad (4)$$

Where :
SOC : Soil organic carbon (Mg ha^{-1})
SBD : Soil bulk density (g cm^{-3})
D : Soil depth (cm)
%C : Concentration of soil carbon in percent

SOC stock in each habitat condition and land management. To determine the total SOC value in each habitat condition and land management, first, the average amount of SOC in each habitat was calculated. Afterward, the total SOC in each habitat was calculated as:

$$SOC_{ti} = \overline{SOC}_i * A_i \quad (5)$$

Where:
SOC_{ti}: Total soil organic carbon stored in the i^{th} habitat condition (management zone) (Mg)
A_i : Area of the i^{th} habitat (zone) condition
$\overline{SOC_i}$: Average SOC_i

Furthermore, the total SOC in the Sembilang National Park (SOC_t) was calculated as:

$$SOC_t = \sum_{i=1}^{5} SOC_{ti} \quad (6)$$

Where:
i : Habitat condition in Sembilang National Park
Numbers 1 to 5 : Habitat of mangroves, settlement, mudflat, burned area, and restored ponds, respectively

Converting to Carbon Dioxide Equivalence (CDE). The total SOC stock is converted to carbon dioxide equivalents (CO_2e) by multiplying the SOC stock by 3.67 which is the ratio of molecular weights between CO2 (44) and C (12) as shown in the following formula:

$$CDE = SOC_{ti} * 3.67 \quad (7)$$

Where:
CDE : Carbon Dioxide Equivalent (CO_2e) storage in soil
3.67 : Ratio of molecular weights between CO_2 and C

NDVI analysis

In this study, mangrove density was assessed using the Normalized Difference Vegetation Index (NDVI) method. This approach differentiates vegetative cover from other surfaces by comparing the absorption of red wavelengths by chlorophyll with the reflection of Near-Infrared (NIR) wavelengths, a characteristic feature of green vegetation (Huyen et al. 2022). The NDVI for Sentinel-2A imagery is determined by calculating the difference between Band 8 (NIR) and Band 4 (Red), divided by their sum, as shown in the following equation (Arfan et al. 2024):

$$NDVI = \frac{NIR-Red}{NIR+Red} = \frac{B8-B4}{B8+B4} \quad (8)$$

This calculation yields NDVI values ranging from -1 to 1. Higher positive values indicate denser, healthier vegetation, while values closer to zero or negative suggest sparse vegetation or non-vegetative surfaces.

Statistical analysis

All statistical analysis was performed using SPSS ver. 21. The Shapiro-Wilk test was used to check the normality of the data set. Since the data did not indicate a normal distribution, Kruskal-Wallis and Dunn's post hoc tests with a significant threshold of 0.05 were applied for analysis in statistical significance between the soil carbon stock across the habitat conditions. These tests were performed for data that could not be normally distributed (Martín-López et al. 2023).

RESULTS AND DISCUSSION

Mangrove species composition

This study recorded 12 mangrove species in the SNP, consisted of nine major mangroves including *Avicennia alba* Blume, *Avicennia marina* (Forssk.) Vierh., *Bruguiera gymnorhiza* (L.) Lam., *Bruguiera parviflora* (Roxb.) Wight & Arn. ex Griff., *Ceriops tagal* (Perr.) C.B.Rob., *Ceriops decandra* (Griff.) Ding Hou, *Rhizophora apiculata* Blume, *Rhizophora mucronate* Lam., *Sonneratia caseolaris* (L.) Engl.; two minor mangroves (i.e. *Excoecaria agallocha* L. and *Xylocarpus granatum* J.Koenig); and one associated mangrove (*Acrostichum aureum* L.) (Table 1). Based on habitat condition, there were 7 mangrove species in natural/pristine habitat (JZ) including *R. apiculata*, *R. mucronata*, *E. agallocha*, *B. parviflora*, *C. tagal*, *Ceriops decandra*, and *A. alba*. Two species were found in post-fire rehabilitation area (RZ), namely *S. caseolaris* and *A. aureum*. Furthermore, *R. apiculata* and *X. granatum* (2 species) were in settlement area (SZ) while in the restored pond (UZ) recorded 4 species, i.e. *A. marina*, *E. agallocha*, *R. apiculata*, and *B. gymnorhiza*. No mangrove plant was recorded on the mudflat (TZ). Based on IUCN Red List, the status of all mangrove species found is categorized as Least Concern except *C. decandra* which has near threatened status. The NDVI values in 2023 ranged from 0.318 to 0.431 with mean NDVI values of 0.401, 0.365, 0.410, and 0.376 for the JZ, RZ, SZ, and UZ sites, respectively.

Table 1. Mangrove species found in various habitat conditions in Sembilang National Park, South Sumatra Province, Indonesia

Zone/habitat/station	Latitude	Longitude	Species	NDVI	IUCN red list
Jungle Zone/Natural mangrove				**0.401**	
Station 2 (Sembilang River)	104°41'32" E	1°59'24" S	*Excoecaria agallocha*	0.321	LC
			Rhizophora apiculata		LC
			Ceriops decandra		NT
Station 11 (Batang River)	104°41'32" E	1°59'24" S	*Rhizophora apiculata*	0.421	LC
Station 12 (Sembilang River)	104°51'40" E	2°02'45" S	*Rhizophora mucronata*	0.409	LC
Station 14 (Kacangparang River)	104°43'03" E	1°60'44" S	*Rhizophora apiculata*	0.430	LC
Station 15 (Ngirawan River)	104°31'41" E	1°55'05" S	*Rhizophora apiculata*	0.390	LC
Station 16 (Betet Island)	104°28'09" E	1°54'20" S	*Ceriops tagal*	0.406	LC
Station 24 (Banyuasin River)	104°31'55" E	1°48'52" S	*Bruguierra parviflora*	0.426	LC
			Rhizophora apiculata		LC
Station 25 (Banyuasin River)	104°48'24" E	2°17'02" S	*Bruguierra parviflora*	0.415	LC
			Rhizophora apiculata		LC
Station 26 (Banyuasin River)	104°49'07" E	2°16'00" S	*Avicennia alba*	0.400	LC
			Bruguierra parviflora		LC
Station 27 (Lalan River)	104°43'55" E	2°21'28" S	*Bruguierra parviflora*	0.400	LC
Station 28 (Lalan River)	104°42'12" E	2°21'38" S	*Bruguierra parviflora*	0.395	LC
Rehabilitation Zone/Post-fire forest				**0.365**	
Station 1 (Alanggantang island)	104°33'30" E	1°51'26" S	*Sonneratia caseolaris*	0.380	LC
Station 13 (Alanggantang island)	104°37'02" E	1°55'35" S	*Acrostichum aureum*	0.350	LC
Special Zone/Settlement				**0.410**	
Station 3 (Sembilang River)	104°41'58" E	1°60'53" S	*Rhizophora apiculata*	0.390	LC
			Xylocarpus granatum		LC
Station 4 (Sembilang River)	104°40'36" E	2°00'04" S	*Rhizophora apiculata*	0.431	LC
Station 5 (Sembilang River)	104°41'12" E	2°01'30" S	*Rhizophora apiculata*	0.410	LC
Utilization Zone/Restored pond				**0.376**	
Station 6 (Solok Buntu Resort)	104°53'36" E	2°08'04" S	*Excoecaria agallocha*	0.416	LC
Station 7 (Solok Buntu Resort)	104°54'24" E	2°11'55" S	*Avicennia marina*	0.415	LC
Station 8 (Solok Buntu Resort)	104°53'51" E	2°11'06" S	*Rhizophora apiculata*	0.350	LC
			Bruguierra gymnorhiza		LC
Station 9 (Solok Buntu Resort)	104°52'45" E	2°10'07" S	*Avicennia marina*	0.380	LC
Station 10 (Solok Buntu Resort)	104°53'25" E	2°10'37" S	*Bruguierra gymnorhiza*	0.318	LC
Traditional Zone/Mudflat					
Station 17 (Barong)	104°54'34" E	2°08'59" S	None		None
Station 18 (Barong)	104°54'09" E	2°09'36" S	None		None
Station 19 (Barong)	104°54'07" E	2°09'07" S	None		None
Station 20 (Barong)	104°54'04" E	2°10'50" S	None		None
Station 21 (Barong)	104°54'34" E	2°10'27" S	None		None
Station 22 (Barong)	104°54'49" E	2°11'39" S	None		None
Station 23 (Barong)	104°54'34" E	2°11'02" S	None		None

Note: LC: Least Concern; NT: Near Threatened; NDVI: Normalized Difference Vegetation Index

Soil Organic Carbon (SOC) stocks

In this study, SOC stocks ranged from 92.21-296.30 Mg C ha^{-1} with an average of 177.26 Mg C ha^{-1} (Figure 3). The highest value of SOC stock was obtained at station 11 in the natural/pristine mangrove habitat (JZ), while the lowest was at station 7 in the restored pond (UZ). The data distribution in the JZ habitat appears bimodal; however, the result of the Kruskal-Wallis test ($p = 0.059$) indicated no significant differences in SOC stocks between the northern and southern stations.

Average SOC stocks in each habitat condition are presented in Figure 4. The natural mangrove habitat (JZ) had the highest average estimated SOC stocks (220.98 Mg C ha^{-1} or equivalent to 810.26 tCO_2e ha^{-1}), while the lowest average was in the restored pond with 114.07 Mg C ha^{-1}, or equivalent to 418.26 tCO_2e ha^{-1}. Statistically, the distribution of SOC stock was significantly different across habitat conditions (Kruskal-Wallis, $p = 0.01<0.05$), with natural mangrove is significantly higher and restored pond is significantly lower (Dunn's, $p = 0.01<0.05$).

When extrapolated across all areas of Sembilang National Park, excluding the Core Zone, total carbon dioxide equivalents (CO_2e) stored in the soil in the area of 267,592.41 Ha was 174,084,918 (650.56 ha^{-1}), as shown in Table 2. The highest value of CO_2e occurred in the natural mangrove habitat, amounting to 86,806,784 (810.26 ha^{-1}). On the other hand, the lowest value occurred in the restored pond habitat, reaching 1,120,991 (418.26 ha^{-1}).

Discussion

The multi-habitat conditions of SOC stock valuation in this study address knowledge gaps in the mangrove ecosystems management in the coastal area of South Sumatra Province, especially in Sembilang National Park (SNP). The estimates of SOC stock were provided for five habitat conditions of management zone in the park, except the core zone which was not possible due to safety reasons. The mangrove species in these zones were also observed.

The results indicated that the mangrove species in the studied area were dominated by *R. apiculata*, and this finding was consistent with a previous study conducted by Ulqodry et al. (2020), which found the genus *Rhizophora* dominated mangrove ecosystem in the SNP area. The near-threatened species (*C. decandra*) was found, implying that the presence of this species is quite essential due to it being the condition of a major mangrove that grows in tidal areas. Naturally, the critical mangrove populations are small in number due to their specific habitat and limited distribution (Wijayaningsih and Rani 2017). It is also important to know the distribution and ecological condition of endangered mangroves because it can be used for implementing the conservation program (Dharmawan et al. 2017).

The largest number of mangrove species was found in the Jungle Zone (JZ) which was composed with natural mangrove vegetation. Meanwhile, the Rehabilitation Zone experienced wildfires in 2015 (MoEF 2020), resulting in the loss of various plants and animals. The pioneer species of mangroves (*A. aureum* and *S. caseolaris*) were found in this habitat. Both species are growing rapidly in disturbed primary forests (Eddy et al. 2019) and are useful for mangrove restoration and conservation programs (Le and Van Le 2024). Meanwhile, in the restored pond under the Utilization Zone (UZ), JICA has carried out mangrove replanting using natural regeneration, enrichment, and new planting (Wijayaningsih and Rani 2017). Unfortunately, the 12 mangrove species found in this study were fewer than the 49 and 14 species reported by MoEF (2020) and Ulqodry et al. (2020), respectively. However, most of the species found in this study (9 of the total species) were consistent with those reported by Ulqodry et al. (2020). This finding suggests a potential decline in the number of mangrove species over the last decade.

The research findings highlight variations in SOC stored in different habitat conditions. Another study by Silvius et al. (2018) in Sembilang National Park found that peatland, which covers around 31% of the total area, constituted a large carbon store estimated at approximately 164 million tons. This peatland area is situated within the Core Zone of the park. In our current study, natural mangroves in the Jungle Zone and restored ponds in the Utilization Zone respectively had the highest and lowest SOC stocks, indicating that each habitat condition has a different capacity for storing carbon (Carpenter et al. 2023). The lower SOC observed in the restored pond compared to the natural mangrove vegetation may be attributed to its land-use history. Since 1995, this area has been utilized for aquaculture by immigrants from Lampung Province (Nurlia et al. 2020), leading to disturbances in soil structure and organic matter accumulation, critically reducing soil carbon storage. In contrast, the natural mangrove with its dense vegetation and undisturbed soils maintains higher SOC levels. Although JICA implemented a restoration program in the Utilization Zone between 2010 and 2015 to improve soil quality and health (Wijayaningsih and Rani 2017), the cumulative effects of previous land use may still impact SOC in this habitat, as indicated by lower NDVI values compared to the JZ site. Additionally, while the mudflat habitat in the study sites serves as a stopover for migratory birds (MoEF 2020), its role in SOC was not significantly different from the other habitats (settlement, post-fire forest, and restored pond), suggesting that factors such as vegetation cover and soil condition are more influential in determining SOC stocks.

The result of this study indicated significant variation in SOC stock across different zones, where various mangrove species were present. The high SOC in these zones is primarily derived from mangrove vegetation, as indicated by the increased concentrations of lignin phenol and amino sugar in restored areas, highlighting the importance of plant-derived residues in carbon sequestration (Qin et al. 2024). Critical factors such as tree biomass, total nitrogen, and pH are possible to significantly influence the carbon storage potential of mangrove soils, as reflected in the differences between JZ and other habitats observed in this study. Specifically, the zones dominated by *Rhizophora* species showed higher SOC stocks, likely due to their more extensive root systems and greater capacity to trap sediment, strengthening the finding by Qin et al. (2024) that optimal tree biomass and pH levels promote enhanced carbon accumulation.

Table 2. The value of carbon dioxide equivalents (CO_2e sink) under different habitat conditions of mangrove ecosystem in Sembilang National Park, Indonesia

Habitat/Zone	Area (ha)	CO_2e per Ha	Total CO_2e
		Ton	Ton
Natural mangrove (JZ)	107,134.48	810.26	86,806,784
Post-fire forest (RZ)	17,632.41	575.06	10,139,694
Settlement (SZ)	3,983.54	638.65	2,544,088
Restored pond (UZ)	2,680.13	418.26	1,120,991
Mudflat (TZ)	52,762.53	589.85	31,121,978
Total	267,592.41	650.56	174,084,918

Note: The Core Zone was not observed in this study

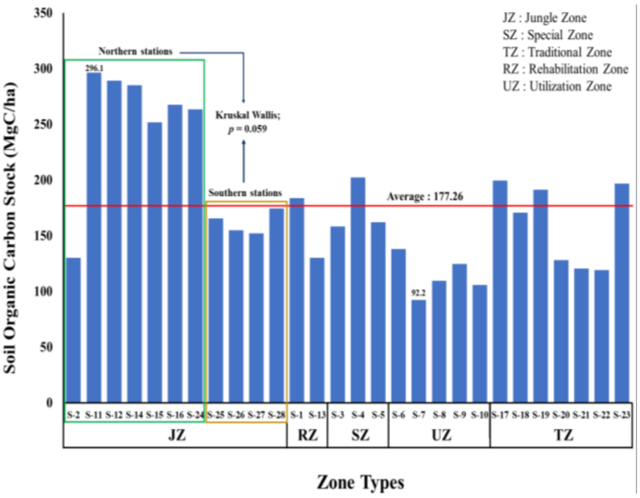

Figure 3. Variability in the Soil Organic Carbon (SOC) stocks (Mg C ha^{-1}) at each station under different habitat conditions in Sembilang National Park, South Sumatra, Indonesia. Although the data distribution in the Jungle Zone appears bimodal, Kruskal-Wallis test results (p = 0.059) indicate no significant differences in SOC between the northern and southern stations

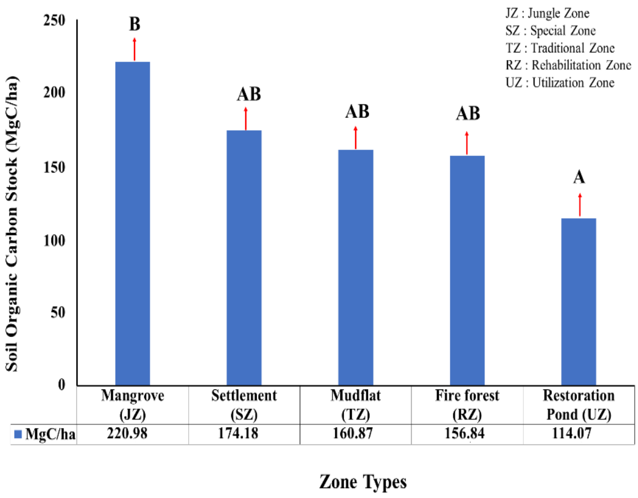

Figure 4. The average Soil Organic Carbon (SOC) stocks under different habitat conditions of mangrove ecosystem in Sembilang National Park, Indonesia. The similar uppercase letters represent no statistical difference between habitat conditions based on Kruskal-Wallis test ($p = 0.01<0.05$) and followed by Dunn's test to restored pond (Utilization Zone) and natural mangrove (Jungle Zone) which detected as significantly different (Dunn's, $p = 0.01<0.05$)

On the other hand, low SOC is not only influenced by tide effects but also by anthropogenic activities and intrinsic soil characteristics (Gandaseca et al. 2023). This is particularly evident in the JZ sites compared to other zones (TZ, UZ, SZ, and RZ), where greater anthropogenic disturbances have likely reduced carbon storage potential. Suello et al. (2022) noted that younger mangrove sites, as those undergoing restoration, tend to receive a higher input of allochthonous carbon (externally supplied suspended particulate matter), whereas older mangrove stands, such as those in JZ sites, accumulate more autochthonous carbon (on-site biomass carbon input). In this study, the highest SOC was recorded in the zones dominated by *R. apiculata* (Table 1 and Figure 3), likely due to their extensive root system that efficiently traps sediment. While *Rhizophora* species provide superior protection against storm surges (Méndez-Alonzo et al. 2015), they also play a crucial role in capturing both allochthonous and autochthonous carbon through upstream and tidal currents (Alongi 2014). Additionally, mangroves contribute to the direct sequestration of atmospheric CO$_2$, emphasizing their dual function in both carbon storage and CO$_2$ sequestration. The concept of CO$_2$ equivalence may still apply, as this stored carbon would otherwise contribute to atmospheric emissions if released elsewhere. However, for carbon trading purposes, it is essential to differentiate between carbon stored from direct atmospheric CO$_2$ sequestration and transported carbon from other ecosystems. As a result, the higher SOC stocks in the JZ sites, particularly in the southern JZ, may be attributed to their more favorable tree biomass and pH levels compared to other zones, although the dominance of allochthonous carbon in these areas warrants further examination.

For natural mangrove habitat in Jungle Zone, the estimate of SOC stock (220.98 Mg C ha^{-1}) was lower than in Bregasmalang of Central Java (Sugiatmo et al. 2023) and in the Mahakam delta of East Kalimantan (Diana et al. 2023) with values reaching 671.25 Mg C ha^{-1} and 1120 Mg C ha^{-1}, respectively. Meanwhile, in the post-fire forest habitat, the SOC stocks obtained (156.84 Mg C ha^{-1}) were lower than research in Ngurah Rai Forest Park, Bali which reached 617.88 Mg C ha^{-1} (Irawati et al. 2021). In the restored pond, the estimated SOC stock (114.07 Mg C ha^{-1}) was higher than that at the silvo-fishery pond area in Deli Serdang Regency, North Sumatra with 14.53 Mg C ha^{-1} and 13.6 Mg C ha^{-1}, respectively (Harefa et al. 2022). However, this result was lower than research in the silvo-fishery and ponds areas of Central Java (Sugiatmo et al. 2023) which reached 680 Mg C ha^{-1} and 688.81 Mg C ha^{-1} respectively, including at shrimp ponds in the Mahakam delta, East Kalimantan (Arifanti et al. 2019) which reached 486 ± 55 Mg C ha^{-1}. In terms of SOC stocks in mudflat habitats, the estimated result (160.87 Mg C ha^{-1}) was higher than the previous studies in Bintuni Bay of Papua (Sasmito et al. 2020), and in Bahrain of Arabian Gulf (Naser 2023) which reached 62 Mg C ha^{-1} and 81.56 Mg C ha^{-1}, respectively.

Overall, the average SOC stock observed in Sembilang National Park (165.39 ± 34.34 Mg C ha^{-1}) was lower than the average SOC stock in Indonesia which reached 420.1420.1 Mg C ha^{-1} (Alongi 2020), and in Bregasmalang of Central Java which reached 671.87 Mg C ha^{-1} (Sugiatmo et al. 2023). This was also lower than the global average SOC stock which reached 565.4565.4 Mg C ha^{-1} (Alongi 2020), the Persian Gulf with 612.6 Mg C ha^{-1} (Mahmoudi et al. 2022), and Sri Lanka with 643.6-1,253.6 Mg C ha^{-1} (Cooray et al. 2021). Several factors may contribute to the lower SOC stocks in SNP compared to other regions. The mangroves in SNP may be younger and less diverse, particularly in restoration areas, leading to lower biomass accumulation. Ulqodry et al. (2020) highlighted that the mangroves in SNP are relatively young, with an average age of around 14 years, which may explain the lower biomass and subsequently reduced carbon storage. Furthermore, anthropogenic activities and environmental pressures, such as land conversion and disturbances in upstream areas, may have affected carbon sequestration processes. Unfortunately, these factors were not directly observed during the survey, limiting the ability to draw definitive conclusions about their specific contributions to the lower SOC stock. These considerations, combined with the specific soil characteristics in SNP, likely contribute to the lower SOC stock compared to other mangrove ecosystems in Indonesia and globally.

According to Ouyang and Lee (2020), variations in SOC stocks in mangrove forests were influenced by geography, climate, and environmental factors. In this study, these factors may vary significantly across different habitat conditions, including natural mangroves (JZ) and other zones. For example, differences in salinity, forest condition, and mangrove condition can lead to notable variations in SOC stocks within SNP. Additionally, Carnell et al. (2022) revealed that the older mangrove stands (17 and 35 years old) had double the total carbon stocks and soil sequestration rates compared to the youngest mangrove stand (13 years old). This finding suggests that the age of mangroves in different habitats within SNP could be a critical factor influencing carbon storage, with the older mangrove stand likely contributing more to SOC stocks than younger ones. By understanding these relationships, the management and conservation strategies for mangrove habitats in SNP can be better informed.

Similar to SOC stocks, the CO_2e value also varied. The potential for CO_2 sequestration of the mangrove ecosystem provides economic opportunities for local people in Banyuasin coastal communities, which have the potential to generate financial income through trading carbon derived from mangrove conservation. Moreover, any future increase in carbon prices (assumed price of US$5 t^{-1} CO_2e) could hugely expand the scope of financially feasible mangrove carbon projects, and their financial returns, including their climate change mitigation potential (Zeng et al. 2021). Meanwhile, Smith et al. (2018) stated that CEADIR calculated the value of stored carbon and predicted future carbon stock per hectare of mangrove forest at four carbon price levels, namely $0, $8, $15, and $25 per metric ton of CO_2e. With enhancing momentum to emerge a green economy, mangroves play a role and have potential in climate change. The soil-based carbon economy establishment, in this expanding financial space, is likely to generate a paradigm shift that can accelerate climate change mitigation, and attain net benefits for soil health as well as provisioning soil ecosystem services (Keenor et al. 2021). Valuation of carbon pools is one way to disseminate to the public the urgency to promote conservation as a way of mitigating the climate change impacts (Bañolas et al. 2020).

The novelty of this study lies in its detailed examination of SOC stocks across multiple habitat conditions within the SNP area, an approach that has not been previously undertaken in this park. The findings of this study play an important role in encouraging effective conservation policies, highlight the importance of mangrove ecosystems in global carbon sequestration efforts, and emphasize the need for targeted restoration activities. Consequently, this study contributes significantly to a better understanding of the SOC variation in mangrove ecosystems and their broader environmental and economic implications. In addition, to optimize the carbon storage capacity of mangrove ecosystems, more exact and data-based conservation policies and plans are required. The comprehensive data on SOC stocks across different habitats in this park is useful as a basis for developing more effective and efficient conservation policies. Although the insightful findings obtained from this study, several limitations should be acknowledged to appropriately interpret the results. These include (i) Logistical and temporal constraints limited the sampling scope, resulting in a restricted number of soil samples being taken from various habitat conditions; (ii) The study lacked to take into consideration any temporal and seasonal fluctuations in soil carbon stocks, which may have an impact on mangrove ecosystems' capacity to store carbon; and (iii) The findings might have been impacted by methodological limitations, such as the accuracy and precision of soil sampling and carbon measurement procedures.

In conclusion, the SOC stored in the different habitat conditions representing management zones in Sembilang National Park varied. Natural mangroves in the Jungle Zone produced the highest value in SOC stock, while the lowest was at the restored pond in the Utilization Zone. Statistically, the distribution of SOC stock was significantly different across the habitat conditions (Kruskal-Wallis, $p = 0.01<0.05$), particularly between the natural mangrove and the restored pond (Dunn’s, $p = 0.01<0.05$). The findings have significant implications for the possible application of mangrove planting techniques as a conservation action of carbon offset, especially in the restored habitats. Hence, an effort should be considered to integrate the SOC stock into green economic plans, especially the mangrove conservation in the Banyuasin coastal wetlands. More research is required on other variables that affect the SOC stock, including microbiological activity in the soil, surface elevation changes, vertical accretion, tidal patterns, and soil properties.

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