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The Assessment of Peat Physico-Chemical Properties and Carbon Stocks in Resak Tambahan Peat Swamp Forest, Pahang

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ABSTRACT

Conserving tropical peat forests with high carbon density is among the most cost-effective strategies for addressing global climate change. However, large areas of these forests have historically been impacted by land-use changes, logging, and other human activities, leading to substantial carbon emissions into the atmosphere. This study quantified the physico-chemical properties and soil carbon stocks in a total of nine (9) different compartments representing three (3) different categories of forest; which were high, medium and low density forest located in the district of Rompin, Pahang in order to assess the differences between them. Collected samples were analysed for the physical characteristic; bulk density, total porosity, moisture content and chemical properties; ash content, loss of ignition and organic carbon content. The results showed minimal variation, with most parameters exhibiting similar trends across all densities. Consistency in pH, bulk density, moisture, organic carbon content, and loss on ignition indicates that, despite varying forest densities. The soil carbon stock for the high, medium and low density forests were 329.48 ± 62.25 (C t/ha) 328.50 ± 64.71 (C t/ha) 326.46 ± 48.79 (C t/ha), respectively. Statistical analysis by using ANOVA followed by multiple mean comparison showed no significance difference were observed among the carbon stock value between the three categories of forest. Comprehensive understanding of the variability of the peat properties within the studied area is essential for developing effective strategies for their conservation and sustainable management.

Key words: peat forest, climate change, fibrous, hemic, sapric

INTRODUCTION

Peatlands are a type of wetland that play a crucial role in water management strategies due to their unique characteristics and hydraulic properties. Understanding these aspects are essential for effective water management and environmental conservation. In the intricate tapestry of Earth's ecosystems, this environment hold ecological importance and climate-regulating potential as tropical peat swamp forests. The unique and delicate ecosystems, found in the heart of tropical regions, play a pivotal role in supporting biodiversity, sequestering carbon, and maintaining the overall health of our planet. As our understanding of the interconnectedness of ecosystems deepens, the significance of these lush and waterlogged landscapes becomes increasingly evident. The tropical peat swamp forests are characterised by their waterlogged, acidic, and nutrient-poor soils, creating an environment where organic matter decomposes exceedingly slowly. This unique condition allows the accumulation of vast quantities of peat a carbon-rich substance derived from partially decayed plant material. Peat accumulation is a natural carbon sink, effectively locking away large amounts of carbon dioxide, a key greenhouse gas responsible for global warming.

Despite their ecological significance, tropical peat swamp forests face an array of threats that jeopardise their existence. Human activities, such as logging, agriculture, and drainage for development purposes, have led to widespread deforestation and degradation of these fragile ecosystems. This compromises the biodiversity they harbour and releases significant amounts of stored carbon into the atmosphere, exacerbating the global climate crisis. Land-use change in tropical peatlands has been identified to increase during the past few decades, and in 2007 approximately 60 % of the peat swamp forest in south-east Asia had been impacted by logging (Miettinen & Liew, 2010). A major concern in relation to this rapidly advancing land-use change has been the transformation of large parts of the peatland ecosystems into C sources of global significance (Hooijer *et al.,* 2010, Page *et al*., 2011). Tropical peatlands store 69.6 – 129.8 Gt C, which is equal to 19% of global peatland C stock. Mismanagement of the area will lead to the release of greenhouse gases (GHGs), contributing to a significant amount of CO_2 (Sjögersten *et al.,* 2014), CH_4 and N_2O (Leifeld and Menichetti, 2018, Cooper *et al.*, 2020).

In Pahang, very limited data were observed on the carbon stock content and the peat characteristics of its tropical peatlands. Understanding the carbon stocks in peatland forests helps prioritize areas for conservation and restoration. Peatlands with high carbon content are particularly valuable and should be protected from activities that could lead to carbon release, such as deforestation, drainage, or agricultural conversion. For degraded peatlands, carbon stock assessments can guide restoration efforts by identifying areas where rewetting or reforestation could enhance carbon sequestration and contribute to ecosystem recovery. This will assist the stakeholders and government agencies in developing policies to reduce the national greenhouse gas emissions.

Continual assessment of carbon stocks in peatland forests is important for monitoring changes over time, especially in response to land use changes, climate change, or restoration activities. Long-term data collection enables researchers to study trends, refine models, and improve predictions of carbon dynamics in peatlands, contributing to a deeper understanding of their role in the global carbon cycle. The research was conducted with the following objectives; (1) To investigate the status of physico-chemical characteristics of peat in Resak Tambahan peat swamp forest across three forest categories characterized by high, medium, and low canopy densities and (2) To quantify the total underground carbon stocks in the Resak Tambahan peat swamp forest across the same forest categories (high, medium, and low canopy densities). The data and information gathered from this study can contribute to the national forest inventory and serve as a foundation for establishing baseline data on forest carbon emission levels. Additionally, it can support foundational research for conservation efforts aimed at preserving peatland ecosystems, particularly in areas with varying forest densities.

MATERIALS AND METHODS

Study site and soil sampling

The study site is situated within the Resak Tambahan Forest Reserve (RTFR), located in the forest district of Rompin, Pahang. The RTFR is part of the South-East Pahang Peat Swamp Forest (SEPPSF) complex, which also comprises other peat swamp forest reserves. The study site is dominated by mixed peat swamp forest, characterized by distinct vegetation associations. Within the Resak Tambahan Forest Reserve (RTFR), these associations are commonly represented by the dominant species *Durio carinatus, Gonystylus bancanus, and Horsfieldia crassifolia.* (UNDP/GEF 2003). The study area coordinates lie between 584500 E to 598500 E and 327500 N to 342700 N, covering about 12,657.97 ha of area (Figure 1).

Soil samples were collected based on three (3) different categories of forest densities, which were; high, medium and low. For each forest category, three different forest compartments representing three replicates (high; SCH 1, SCH2, SCH3, medium; SCM1, SCM2, SCM3 and low; SCL1, SCL2, SCL3) were selected as the sampling the points (**Figure**

1). In each compartment, 6 sampling points were identified and peat samples were collected by using peat augers.

A minimum of 50 cm depth of peat profile were taken vertically to ensure the profile is not disturbed prior to profiling analysis. In total, 54 soil samples were collected in 9 different forest compartments. The sampling points were modified according to Kauffman *et al*. (2011) where plots were established 100 m apart along a 600m transect as depicted in **Figure 2**. The physical profiles of the peat were initially described in the field and later transferred to the laboratory for detailed analysis of their physical and chemical properties (**Figure 3**).

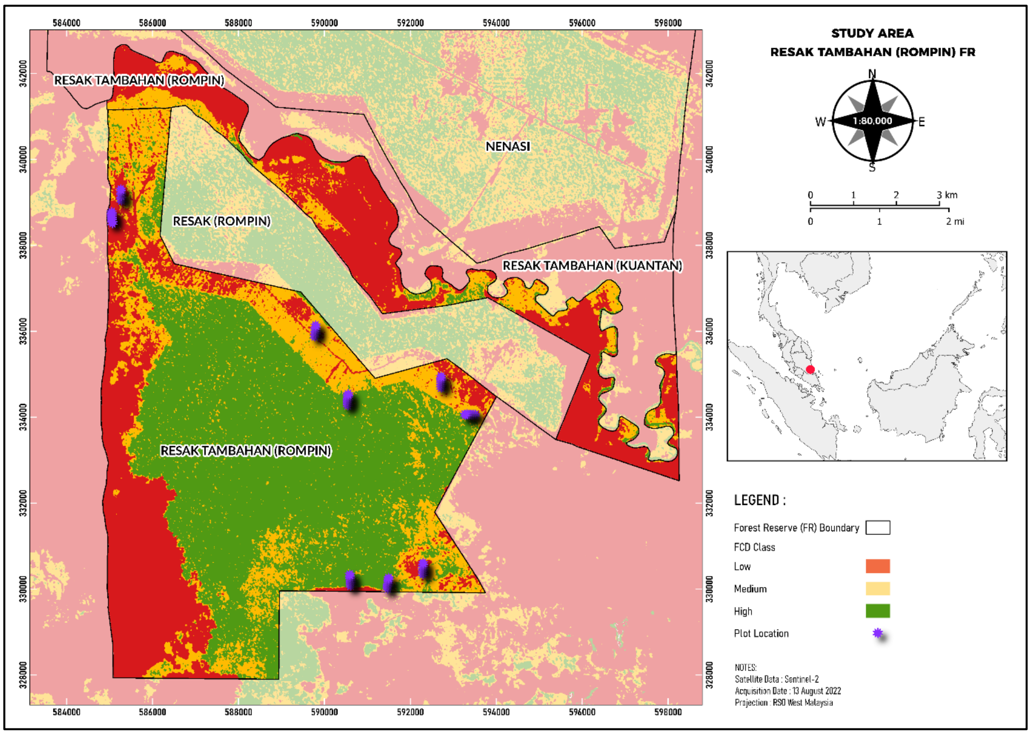

Figure 1. Location of study site in Resak Tambahan Forest Reserve, Pahang

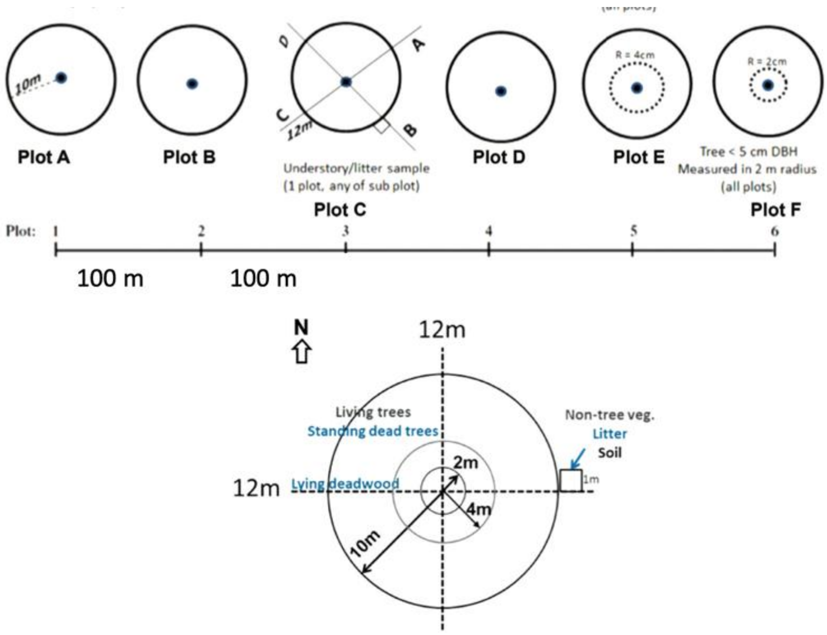

Figure 2. The plot transect and sampling points layout in the Resak Tambahan FR peat swamp forest

Figure 3. Soil sampling conducted at 50 cm depth in the field and sample storage

Laboratory analysis

Moisture content (%), bulk density (g/cm^3), organic content (%) and ash content (%) were determined according to the ASTM standard D2974-87. Moisture content (%) was calculated by subtracting oven-dried mass from the original wet mass and expressing as a percentage of oven-dried mass. For bulk density analysis, peat samples were collected by using a core ring method based on ASTM D2978. The sample was extruded from the sampling cylinder, then a representative specimen was cut from it. The length, diameter and dry mass of the specimen were measured, and bulk density was calculated by dividing the mass of the specimen by its volume. Peat pH analysis was performed in accordance with British Standard 1377:1990 to determine the acidity or alkalinity of the peat. A 1:5 (v/w) solution-to-soil ratio was prepared, shaken at 1800 rpm for 30 minutes, allowed to settle or filtered, and the pH was measured using a laboratory bench pH meter (Mettler Toledo, USA).

The determination of cation exchange capacity (CEC) was conducted using a modified ammonium acetate leaching method, as described by Schollenberger and Simon (1945). In this procedure, 1 g of peat soil was leached with 60 mL of 1M ammonium acetate (NH4OAc). The mixture was then centrifuged at 1800 rpm for 30 minutes. Following centrifugation, the soil samples were washed with 96% ethanol, then subjected to a shaking extraction using 100 mL of potassium sulfate (K_2SO_4). The resulting filtrate was analyzed using the Auto Analyzer Model AA500 (Seal Analytical, Germany) to determine the CEC.

For ash content determination, the Standard Test Methods (ASTM D2974-87) for moisture, ash, and organic matter in peat and other organic soils were applied. Oven-dried samples were ignited in a muffle furnace at 440°C until they were completely ashed, with no further mass change observed after additional heating. The ash content (%) was calculated as the mass of the residue after ignition expressed as a percentage of the oven-dried sample mass. Organic carbon content (%) was then estimated by subtracting the ash content (%) from 100 and dividing the result by a conversion factor of 1.724.Carbon stock in the study area were calculated using the data of area of each peat depth (Ai), the average thickness of the peat in each thickness class (hi) and the average data for BD and Corg for each peat layer and peat area. Thus, the carbon stocks were calculated using the following equations (Chen *et al*., 2007, Zhang *et al*., 2013).

$$C_{stock} = \sum (A_i * h_i * BD * C_{org})$$

Total nitrogen content were determined using high temperature combustion method using LECO carbon analyser TruMac (LECO Corporation, Michigan). The samples were transferred into the combustion chamber of the LECO analyzer and were combusted between 900°C and 1200°C.

RESULTS AND DISCUSSIONS

Peat physical properties

Information on the physical properties as a basis for understanding water holding capacity of peat soils is important for peatland restoration efforts, including hydrological restoration and revegetation of drained peatlands. Bulk density is a good indicator of any peat disturbance caused by compression (Golubev & Whittington, 2018). Any changes in bulk density were reported to alters the hydrological properties of peat soils. From the study, the bulk density of peat soil across high, medium, and low-density forest did not showed any significant variation, with value of 0.13 ± 0.02 g/cm³, 0.14 ± 0.03 g/cm³, and 0.13 ± 0.03 g/cm³, respectively ($p<0.05$) (**Table 1**). The bulk density varies significantly across different peat types: fibric, hemic, and sapric. Fibric peat, being the least decomposed, usually has the lowest bulk density, while sapric peat, the most decomposed, has a higher value. A fully decomposed peat showed a smooth texture with lower volume of pores. The bulk density of fibric type of peat is usually found to be less than 0.1 g/cm^3 (Gunawan *et al*., 2023). These results were comparable to the peat study conducted by Melling *et al*. (2008) in the peat swamp forest Loagan Bunut National Park and Alan forest with bulk density value of 0.16 g g/cm^3 and 0.12 g g/cm^3, respectively. The analysis revealed that total porosity in high, medium, and low-density forests consistently exceeded 90%.

Table 1: Physical properties of peat in high, medium and low forest density of Resak Tambahan peat swamp, Pahang

Soil Parameter	High Density Forest Mean (n=18)	Medium Density Forest Mean (n=18)	Low Density Forest Mean (n=18)
Bulk Density (g/cm^3)	0.13 ± 0.02 ^{a}	0.14 ± 0.03 ^{a}	0.13 ± 0.02 ^{a}
Total porosity (%)	95.18 ± 0.85 ^{a}	94.74 ± 1.31 ^{a}	94.92 ± 0.73 ^{a}
Moisture Content (%)	555.15 ± 86.99 ^{a}	613.41 ± 120.27 ^{a}	363.41 ± 120.27 ^{b}
Peat degree of decomposition	Sapric	Sapric	Sapric

Peat soils typically exhibit high porosity due to the accumulation of organic matter, which decomposes over time, creating significant pore spaces. These values can vary depending on factors such as the degree of organic material decomposition, the presence of fibrous materials, and the extent of soil compaction. Moisture content was significantly lowest in low-density forests (363.41 ± 120.27%) and higher in medium-density (613.41 ± 120.27%) and high-density forests (555.15 ± 86.99%) ($p<0.05$). The reduced moisture content in low-density forests can be attributed to a decline in forest canopy cover. In medium and high-density forests, denser tree canopies mitigate the direct impact of rainfall on the forest floor. This canopy interception slows water flow, allowing more time for infiltration and enhancing water storage within the peat. Moreover, the root systems of trees and vegetation play a vital role in maintaining peat structure, preventing collapse, and preserving its water retention capacity.

These roots also improve water retention by increasing soil porosity, further enhancing the peat's ability to hold moisture.

From the findings, it suggests that the forest density, whether high, medium, or low, does not significantly influence the bulk density of peat soil in these areas. The lack of significant difference in bulk density across different forest densities could be attributed by several factors. Firstly, the similarities may indicate that the degree of peat decomposition is consistent across the different forest types as in this study the category of peat were sapric. This could suggest uniformity in the age of peat deposits and the nature of the organic material. Additionally, similar environmental conditions such as moisture levels and microbial activity that influence decomposition rates within the same area could also be the factors of similar value found.

Other soil properties, such as soil moisture content, organic matter content, and soil porosity, which are known to influence bulk density, are also similar across the forest density gradients. Peat soils, due to their high organic matter content and porosity, typically have low bulk densities. If these characteristics are consistent across the study sites, it would explain the observed lack of significant variation in its bulk density value. Nevertheless, the findings suggest that bulk density in the study peatland is relatively stable across varying forest densities in the studied area. This stability could be reflective of uniform conditions of peat formation and decomposition, consistent forest impacts on the soil structure, and similar organic matter content and soil moisture levels.

Effective peatland conservation requires a thorough understanding of the relationships between bulk density, moisture content, porosity, and the decomposition state of peat. Peatlands with low bulk density typically exhibit higher porosity and moisture content, which enhance their ability to retain water and sustain the hydrological conditions vital for peat formation and preservation (Harisuseno and Novrianti, 2024). Less decomposed, fibric peat is characterized by higher moisture content and porosity, whereas more decomposed, sapric peat tends to have lower porosity and diminished moisture retention capacity. The advanced decomposition of sapric peat results in extensively broken-down organic material, which reduces its structural integrity and ability to retain water. Furthermore, this state often impedes water flow due to decreased hydraulic conductivity (Rezanezhad *et al*., 2010). From a management perspective, maintaining high water levels is essential to preserve peat moisture, stabilize its structure, and prevent oxidative decomposition. Drainage should be minimized to avoid peat subsidence, as sapric peat is particularly prone to rapid degradation when dried. Excessive drainage accelerates peat mineralization and oxidation, leading to increased carbon dioxide emissions and further degradation of peatlands (Hallema *et al*., 2015).

By evaluating these parameters, conservation efforts can be tailored to maintain the hydrological balance, prevent further decomposition, and enhance the resilience of peatlands against environmental changes and anthropogenic pressures. Effective management requires maintaining high moisture levels and preventing the transition from fibric to sapric states, thereby preserving peatland ecosystems' carbon storage and biodiversity functions.

Peat chemical properties

Table 2 presents the mean values of the analyzed peat which include the measurements of pH, CEC, ash content (%), loss of ignition (%) (LOI) and organic content (%). According to Law and Selvadurai (1968), organic soils were categorised based on its loss of ignition value (LOI) which are, organic clay (20–35 %), muck (35–65 %) and peat (>65 %). Nevertheless, based on Paramananthan *et al.* (1984) classification of peat also were also done based on the observation of peat thickness; shallow (50–100 cm), moderate (100–150 cm), deep (150–300 cm) and very deep (>300 cm). From the study, the samples from the top 50 cm depth of the three different forest categories showed all the samples were categorised as peat as level of LOI were more than 65% as describe by Paramanthan *et al.* (1984). The LOI found in high density forest showed the highest average value of 83.92 ± 9.07% , followed by low density forest with value of 83.86 ± 5.97%. Medium category forest showed and average value of 81.28 ± 5.38%. However, statistical analysis by using ANOVA followed by multiple mean comparison (Duncan) showed no significance of different can be observed among the value ($p<0.05$).

The average pH of peat soil in high, medium, and low-density forests was 3.17 ± 0.11, 3.20 ± 0.10, and 3.19 ± 0.29, respectively, with no significant differences observed among the forest categories. These pH values indicate that the peat soils in the study area fall within the acidic range, a characteristic commonly associated with tropical peatlands. The consistently acidic pH across different forest densities aligns with the well-documented properties of peat soils in tropical regions. Tropical peatlands are naturally acidic due to high decomposition rates, which are accelerated by the warm and humid conditions of the tropics (Husni *et al*., 1995). This rapid decomposition leads to the accumulation of organic acids, such as acetic, formic, and citric acids, which contribute to the soil's acidity (Adeleke et al., 2017). The pH values recorded in this study are comparable to those reported in other studies, such as in Kota Samarahan (pH 3.57; Afip and Jusoff, 2019) and Klias (pH 3.0; Sapar *et al*., 2022). Additionally, the presence of pyritic materials (iron sulfides) beneath the peat layers may further influence soil acidity. When exposed to air through drainage or natural processes, these materials oxidize to form sulfuric acid, significantly lowering the soil pH. This phenomenon is particularly relevant in disturbed peatlands or areas where the water table has been altered, allowing oxygen to penetrate deeper soil layers.

The cation exchange capacity (CEC) of peat were found high, ranging from 22.93 to 25.85 $cmol_{(c)}$/kg. Peatlands are known for their high organic matter content, which generally contributes to a higher CEC compared to mineral soils. Various studies have reported CEC values for peat that can range widely, often depending on the type of peat, its decomposition stage, and the environmental conditions. According to Melling (2016), unlike mineral soils, the high CEC in peat is not due to the presence of basic cations like potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na) but is attributed to the dissociated carboxyl groups, which release H^+ ions, thereby increasing the acidity of the peat.

Table 2: Chemical properties of peat in high, medium and low forest density of Resak Tambahan peat swamp, Pahang

Soil Parameter	High Density Forest Mean (n=18)	Medium Density Forest Mean (n=18)	Low Density Forest Mean (n=18)
pH	3.17±0.11 ^{a}	3.20±0.10 ^{a}	3.19±0.29 ^{a}
CEC ($cmol_c$/kg)	22.93±1.99 ^{a}	25.04±12.34 ^{a}	25.85±14.04 ^{a}
C/N ratio	70.24±16.36^a	62.54±20.04 ^{a}	58.52±17.85^b
Ash content (%)	16.08±9.08 ^{a}	18.72±5.38 ^{a}	16.14±5.97 ^{a}
Loss of Ignition (%)	83.92±9.07^a	81.28±5.38 ^{a}	83.86±5.97 ^{a}
C organic (%)	48.77±5.27 ^{a}	47.47±3.12 ^{a}	48.64±3.47 ^{a}

Ash content is a key parameter for determining the mineral content in peat. It reflects the proportion of inorganic materials, including minerals such as silica, calcium, magnesium, potassium, and phosphorus. Generally, higher ash content indicates a higher concentration of these minerals. In the study, all forest categories had ash content values exceeding 10%. The lowest average ash content was observed in high-density forests, recorded at 16.08 ± 9.08%, while the medium-density forests showed the highest average ash content at 18.72 ± 5.38%. According to ASTM D2974, peat with an ash content exceeding 15% is classified as high. This elevated ash value often indicates increased decomposition, as the organic matter breaks down and the proportion of inorganic material becomes more pronounced. The peat collected in in the study peatland were in sapric state of decomposition which cause it to have higher ash content compared to less decomposed peat (e.g., fibric peat). Higher ash content implies lower organic material, which reduces peat quality, especially for uses where organic matter content is a critical factor (e.g., agricultural or horticultural applications). Statistical analysis by using ANOVA followed by multiple mean comparison showed no significant differences can be observed among the value ($p<0.05$).

The result from this study showed that the carbon content (%) were found the highest in high density forest with mean value of 48.77±5.27%, followed by low and medium density forest with mean value of 48.64±3.47% and 47.47±3.12%, respectively. However, statistical analysis by using ANOVA followed by multiple mean comparison showed no significant of differences can be observed among the value. As mentioned in above discussion, the categories of peat type were the same in all of the sampling points and compartment which is sapric, a well decomposed type of peat. This explained the less variability found in the carbon content value throughout the study site. A study done in Sarawak reported that the C content were around 52.3 to 57.0%, which is comparable to this study (Melling, 2016). Tropical peat were recorded to have an average carbon content of 56.0% (Hu *et al.,* 2018) and the carbon content of South-east Asian peat were found to be is in the range of 41.6 to 62% (Page *et al.,* 2011).

The average carbon-to-nitrogen (C/N) ratio in a peatland forest, ranging from 58.52 to 70.21, indicates a high level of carbon relative to nitrogen in the peat soil. This elevated ratio suggests that the organic matter in this peatland is relatively rich in carbon compared to nitrogen. The results were slightly higher compared to study done in Jalan Kebun Peat Research Station, West Selangor, where the C:N ratio were reported as 39.90% (Joseph *et al.,* 1974) and by Melling (2016), which found C/N ration ranging from 28.2 – 41.6%. In peatlands, such high C/N ratios are typical and reflect the slow decomposition rates of plant material, which leads to the accumulation of carbon-rich peat. This slow decomposition is due to the waterlogged conditions that limit microbial activity, resulting in a higher retention of carbon and a lower proportion of nitrogen. Overall, the high C/N ratio in this peatland forest underscores the role of these ecosystems in carbon storage and their potential impact on the global carbon cycle.

Determination of carbon stocks

This study collected soil samples for carbon stock determination up to 50 cm depth from the land surface. A peat soil is define as an area containing at least 50 cm peat depth from the land surface. From the observation during the sampling, all of the samples collected in each point showed at least 50 cm depth of peat as in **Figure 4**.

Figure 4. Samples of peat showing a minimum of 50 cm length of peat profile

Based on the carbon stock calculation, the average soil carbon content at a depth of 50 cm in the studied peat swamp forest was as follows: 330.37 ± 61.02 C t/ha for high-density forest, 328.50 ± 64.70 C t/ha for medium-density forest, and 326.46 ± 48.79 C t/ha for low-density forest (**Table 3**). **Figure 5** presents a comparison of the carbon stocks across all nine compartments, which include samples collected from high-density (SCH1-3), medium-density (SCM1-3), and low-density (SCL1-3) forest categories. The soil carbon stock values in the peat swamp forest showed minimal variation, with the highest mean value recorded in the medium-density forest. Statistical analysis using ANOVA followed by Duncan's multiple mean comparison revealed no significant differences in carbon stock among the forest categories **(**$p > 0.05$**).**

Table 3: Mean value of carbon stock (t/ha) in peat of high, medium and low forest density of Resak Tambahan peat swamp, Pahang

	Forest category		
	High Density Forest	**Medium Density Forest**	**Low Density Forest**
	Mean (n=18)	**Mean (n=18)**	**Mean (n=18)**
C stock (t/ha)	330.37±61.02^{a}	328.50±64.70^{a}	326.46±48.79^{a}

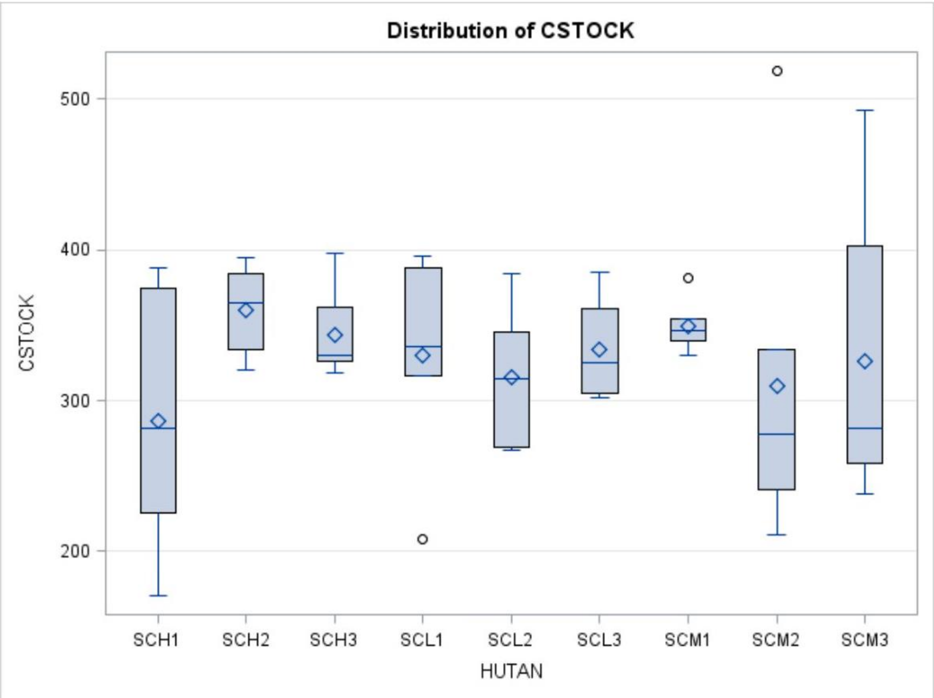

Figure 5. Overview of carbon stock (t/ha) across compartments with high, medium, and low forest density in a peat swamp forest in Pahang.

Several studies on carbon content has been reported in this country and Indonesia (**Table 4**). The soil carbon stock in this study site were observed to be lower compared to study done by Novita *et al.* (2021) in Berguruh, Indonesia, but almost similar to previous study done in Pahang. In South-east Asia, the average of peat carbon store were reported to be ranged from 252 to 3528 t C/ha in few countries (Page *et. al.*, 2011).

Table 4: Studies related to soil carbon content reported in Malaysia and Indonesia

Soil Carbon Stock (t/ha) (50cm depth)	Location	Source
588	Secondary PSF in Tatau District, Sarawak	Osumanu *et al.* 2012
553	Beguruh, Indonesia	Novita *et al.,* 2021
409.87	Sungai Bebar Peat Swamp Forest, Pekan, Pahang	Ismail *et al.,* 2017
414.19	Sungai Merchong Peat Swamp Forest, Pekan, Pahang	Ismail *et al.,* 2017

CONCLUSION

The analysis of the physico-chemical characteristics and carbon stocks in the Resak Tambahan Forest Reserve (RTFR) peat swamp forests, categorized by high, medium, and low forest density, has provided valuable insights into the carbon dynamics of these ecosystems. The study revealed minimal variation in most parameters, with consistent trends observed across all density categories. This consistency implies that peat swamp forests in this region experience similar environmental conditions and nutrient dynamics, underscoring their collective importance for carbon sequestration and ecosystem stability. The carbon stock estimates also showed no significant differences among high-density (326.85 C t/ha), medium-density (328.49 C t/ha), and low-density forests (326.46 C t/ha). These findings suggest that forest density in the study area may not play a significant role in influencing the variation of peat physico-chemical properties and its carbon stocks. Furthermore, the study confirmed that the peat in the Resak Tambahan Forest Reserve falls within the sapric category, indicative of a highly decomposed peat layer with minimal variability in peat profiling. These results offer valuable insights to the scientific community and hold practical implications for conservation and sustainable forest management. Understanding the physico-chemical properties of peat enables forest managers and stakeholders to make informed decisions that enhance peatland ecosystem services, such as biodiversity conservation, carbon sequestration, and hydrological regulation. Conservation efforts, including interventions like rewetting and the introduction of specific vegetation species, are essential for restoring and preserving ecological balance. In summary, this study not only advances our understanding of carbon stocks in peat swamp forests but also lays a foundation for continued research and action to promote sustainable environmental practices.

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