Assessment of soil carbon stocks in several peatland covers in Central Kalimantan, Indonesia

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Abstract. Changes in the soil carbon (C) stocks of degraded peatlands due to drainage, fire, or conversion of forest cover have not been studied much. This study aims to determine the characteristics of soil C stocks in degraded peatland covers due to logging and fire. The research was carried out on peatlands located in three villages representing peatland cover conditions in the form of primary/pristine peat swamp forest, logged-over forest, and post-fire peatland. Peat samples from each type of peatland cover were analyzed to determine the bulk density (BD) and C concentration. The results showed that peatland on the logged-over forest has the highest BD (0.135 gr cm$^{-3}$) compared to the other sites. Based on the distribution of peat depth, the lowest BD was mainly found at the surface peat layers and increased significantly with the depth of peat. The C concentration with the mean value of 57.6% showed no significant differences among the three locations and at different depths. Soil C stocks in the upper one-meter depth were 621, 779, and 606 Mg ha$^{-1}$ in the peat swamp forest, logged-over forest, and post-fire peatland, respectively. The total soil C stocks were ultimately determined by the peat thickness in the area.

1. Introduction

Peatlands, some people call them organic soils, bogs, fens, or mires, are land that is at least 80% dominated by peat soil formed from plant debris that has partially decomposed and accumulated over thousands of years under waterlogging [1-2], which has created anaerobic conditions causing slow decomposition [3]. Based on its taxonomic keys, peat soil is classified as histosol, and based on the composition of the constituent material, it is included in organic soils [4].

Although peatlands cover only about 3% of the world's land area, they globally have essential roles in storing 10% of freshwater and 30% of terrestrial organic carbon [5]. The structure of peat soil with 90% of average porosity acts as a hydrological buffer for the surrounding area, with the ability to control flooding, drought, and seawater intrusion [6-7]. The amount of carbon storage in peat soils is estimated at 650 billion tonnes or more than half the amount of carbon in the atmosphere [2].

Based on its distribution, peatlands can be found over boreal, temperate, and tropical landscapes. Tropical peatland differs from the others in terms of climatic conditions, constituent materials, and vegetation cover. Tropical peat is formed in the environment of high temperature and rainfall with the main constituent ingredient of woody vegetation, and its natural land cover is tropical rain forest [8-9]. This condition causes tropical peatlands; although their area is only 12%, their carbon deposit reaches 20% of the world's peatlands [10]. The largest tropical peatland area is in Southeast Asia (24 million ha), and 87% of them are in Indonesia, mainly on the islands of Sumatra, Kalimantan, and Papua, with
a predicted total soil carbon stock of 57.37 Gton [11-12]. This soil carbon stock value reaches ten times the carbon in the biomass on the peat surface [13].

However, this area of peatland has continued to experience degradation, especially since the beginning of 2000. The fastest tropical peat degradation occurred in Southeast Asia due to socio-economic pressures, characterized by drainage activities in tropical peat forests for timber use, agricultural land, and plantations. Peatland conversion through drainage has a high risk of burning and is evidenced by the increasing intensity of peat fires [11, 14-16]. In Indonesia, peatlands in Central Kalimantan region are among the most degraded ones. The most extensive degradation was caused by the failure of the Mega Rice Project (MRP) through the clearing of one million hectares of peatland, which is equipped with canals up to 30 meters wide and a total length of about 4000 km to drain the peat [3, 17].

With increasing attention to the conservation and management of tropical peat carbon reserves in various land uses and the prevention of greenhouse gas emissions, the importance of soil carbon stock data at a detailed spatial distribution is still very much needed [18]. Soil carbon stocks on peatlands can be predicted through various approaches [17]. However, peat degradation due to land cover conversion, fire, and drainage will affect the physical properties of peat, such as peat bulk density, and probably change the C concentration of the peat [7, 14]. Therefore, the value of bulk density and carbon concentration that corresponds to the peatland conditions should be used to obtain a more accurate predictive value of soil carbon stocks to obtain a more accurate predictive value of soil carbon stocks. However, these data in various land covers still lack [11], so more data through field surveys and laboratory measurements are needed for accuracy predictions [18]. Therefore, this research objective was to determine the characteristics of soil C stocks in degraded peatland covers due to logging and fire.

2. Materials and Methods

2.1. Research sites

This research was located around 20 km from Palangka Raya, the capital of Central Kalimantan Province (Figure 1). Fieldworks were conducted in three land cover types: primary peat swamp forest, logged-over forest, and post-fire peatland. Observations on the primary peat swamp forest were carried out in Danau Tundai Village, Sebangau District. This area is located in block E as a part of the ex-Mega Rice Project (ex-MRP) and is covered by relatively intact peat swamp forest. During the big fire in 1997, only a small pristine forest area burned [3]. The Logged-over forest site was represented by the peatland area in Kalampangan Village, laid between the Kahayan and Sebangau rivers and this area is a part of block C of ex-MRP. In addition, the post-fire peatland site was located in Tanjung Taruna Village, Jabiren District. This site is a part of block B of the ex-MRP and has experienced repeated fires, among others, in 1997 and 2002.
2.2. Peat sampling

For the three types of peatland cover, five random sampling points were assigned in each peatland cover type. Samples were taken using a Russian peat borer (Eijkenkamp Soil & Water, The Netherlands) up to one-meter depth. Each sample point was taken at two steps, the first take is for a depth of 0-50 cm, and the second is for a depth of 50-100 cm. Therefore, each sampling resulted in a 50 cm length peat core (530 cm$^3$ of volume), and then it is divided into 10 cm segments so that a sampling point with one-meter depth resulted in 10 sample segments, and each of them has 106 cm$^3$ volume. Thus, for all land cover types, 150 samples were obtained. Each sample segment was bagged and sealed to keep its moisture.

2.3. Laboratory analysis

Each sample segment was analyzed in the Soil Laboratory of Forest Research and Development Center to obtain soil bulk density (BD) and soil carbon concentration (CC) values. BD was determined by the core method according to the International Standard ISO 11272: 1998 guidelines. The values were obtained from the comparison between the dry mass (g) and the volume of the peat sample (cm$^3$) [19-20]. Carbon concentration was analyzed using a Sumigraph NC analyzer (Sumica Bunseki Center Co.Ltd., Tokyo). This elemental analysis applies high-temperature combustion succeeded by gas...
chromatography for carbon detection [21]. Compared to other methods, the elemental analysis has the highest accuracy compared to the Walkley-Black method, and the lost on ignition (LOI) method [21-23], especially on soils with high organic content [21, 24].

2.4. Assessing C stocks
The C stocks in a certain peat area depend on peat volume (m³) and soil carbon density (kg C m⁻³). The carbon density has resulted from peat bulk density (g cm⁻³) multiplied by the carbon concentration (%) [25]. The peat depth used in the C stocks prediction is derived from the peat thickness class data in the study area accessed online from the Indonesian Peat Restoration Agency [26]. In this study, the soil carbon density was measured only to a depth of one meter, while for the subsequent depths, the same density value assumption was used.

2.5. Statistical analysis
The two-way analysis of variance (ANOVA) at a 95% confidence level was performed to assess the possible effect of peatland cover types, peat depth segments, and their interactions on bulk density, carbon concentration, and carbon stock. Duncan's multiple range test (DMRT) would be conducted if the result showed a significant effect. All statistical analyses were conducted using SAS 9.0 software [27].

3. Results and Discussion
3.1. Bulk density
In general, the BD values for all peat samples ranged from 0.02 to 0.19 gr cm⁻³ with a mean value of 0.12 ± 0.03 g cm⁻³. This range value is similar to other studies in Central Kalimantan, such as in the Sebangau area and in block C ex-MRP, which obtained BD values of 0.02 - 0.18 g cm⁻³ [11]. The analysis results of variance and DMRT show significant differences in BD values on different land covers. The BD values in the logged-over forest site were significantly higher for each depth segment except for the 70-80 cm segment, as seen in Figure 2. The lowest BD was found in post-fire land, although the peat swamp forest showed the lowest value if observed in some depth segments. This was confirmed by the DMRT results, which were not significantly different between these two sites.

![Figure 2. Soil bulk density in each land cover and depth segment.](image)
Based on the vertical distribution, BD values in the surface peat segment tend to be lower than in the deeper layers. Therefore, the lowest BD values were found in the first three surface segments, and the highest values were found in the lowest three segments, as shown in Table 1.

| Depth (cm) | Soil bulk density (g cm\(^{-3}\)) * |
|-----------|-----------------------------------|
| 80-90     | 0.137 a                           |
| 70-80     | 0.136 a                           |
| 90-100    | 0.130 a                           |
| 40-50     | 0.120 ab                          |
| 30-40     | 0.120 ab                          |
| 60-70     | 0.118 ab                          |
| 50-60     | 0.118 ab                          |
| 20-30     | 0.113 ab                          |
| 10-20     | 0.103 bc                          |
| 0-10      | 0.086 c                           |

* the values followed by the same letters indicate no significant difference at \( p \leq 0.05 \)

On tropical peatlands, BD is an important soil characteristic in influencing ecological processes [28]. Apart from being used in calculating soil carbon stocks and the number of carbon emissions in peat fires, the bulk density value is also used in determining some of the hydrological properties of peat [8]. Naturally, the BD value of peat depends on its constituent material, degree of decomposition, hydrological condition, and mineral content. However, the degradation of peatlands tends to increase the BD of peat which adversely affects its hydrological function [29]. Various mechanisms that can increase BD peat include draining the peat due to the construction of canals, opening forest canopies, fires, or compaction of various heavy equipment activities on the peat surface [30].

### 3.2 Carbon concentration

Carbon concentration obtained from the three sites, as shown in Figure 2, ranges from 53.25% to 57.99%, with a mean value of 57.60 ± 0.69%. The variance analysis resulted in insignificant carbon concentration values from the differences in land cover and peat depth segments. This condition is common where the diversity in C concentration is usually lower than the diversity in BD [11]. Although with relatively lower values, similar results have been measured on peat in Jambi Province with the land cover of intact forest, drained logged forest, and oil palm plantation. The C concentrations as measured by the elemental analysis method were 52.2, 53.1, and 53.7%, respectively. The opposite was seen in the difference of BD mean between intact forest cover (0.12 g cm\(^{-3}\)) and oil palm plantation (0.15 g cm\(^{-3}\)), while the maximum BD values were 0.19 and 0.33 g cm\(^{-3}\), respectively [21].
Figure 3. Soil carbon concentration in each land cover and depth segment.

The C concentration is usually higher at the surface than at the base layer due to the influence of mineral soil content in the transitional layer, especially on peat with high BD [13]. In this research, the C concentration range is included in the range resulting from several studies in Central Kalimantan between 41.6% and 62.0%, while lower values are usually found at the bottom bordering with the mineral substrate [11, 31-32].

3.3. Soil carbon stocks

The calculation of soil carbon stock was carried out in two stages, firstly, soil carbon stocks for a depth up to one meter, which was summed from the soil carbon stocks of each segment, and the second was the prediction of total soil carbon stocks for the whole peat thickness. As presented in Table 2, the calculation results show that differences in land cover significantly affect soil carbon stock. Peatlands with logged-over forest cover have the largest soil carbon stocks in both calculation stages, while soil carbon stocks in peat swamp forest and post-fire land show an insignificant difference. Peat swamp forest has higher carbon stocks up to one-meter depth than in post-fire land, but because peatlands in post-fire land have thicker peat, the total soil carbon stock was higher.

Table 2. Soil carbon stock prediction.

| Land cover type     | Soil bulk density (g cm⁻³) * | Soil carbon concentration (%) | Soil carbon stocks up to 1 m depth (Mg ha⁻¹) * | Peat depth (cm) | Total soil carbon stocks (Mg ha⁻¹) * |
|---------------------|-------------------------------|-------------------------------|-----------------------------------------------|----------------|-------------------------------------|
| Peat swamp forest   | 0.113 ± 0.031 b               | 57.25 ± 1.66                 | 621.33 ± 116.70 b                             | 150            | 931.99 ± 175.04 b                   |
| Logged-over forest  | 0.135 ± 0.032 a               | 57.61 ± 0.64                 | 778.66 ± 113.41 a                             | 325            | 2530.64 ± 368.59 a                  |
| Post-fire land      | 0.106 ± 0.035 b               | 57.37 ± 2.78                 | 605.85 ± 80.72 b                              | 208            | 1260.16 ± 167.90 b                  |

*the values followed by the same letters indicate no significant difference at p ≤ 0.05

The carbon stock variability in this research was due to the significant differences in the BD values. Changes in land cover from peat swamp forest to shrubs or fern also affect peat BD through changes in root morphological conditions and soil characteristics [29, 33]. Deforestation tended to increase BD up to 24% compared to natural forest conditions. However, the increase in BD is getting worse to 56% if deforestation is accompanied by canal construction [3]. The three land cover types of peatlands still
show high soil carbon stocks, especially when compared to the carbon stocks of mineral soils. Nevertheless, though degraded peatlands show an increase in BD and soil carbon stocks, they are prone to fires if they are not restored and managed sustainably. The fire that occurred in a peatland area with a high soil carbon stock will also result in higher soil carbon emissions.

4. Conclusion

Primary peat swamp forest, logged-over forest, and post-fire peatland significantly have different soil bulk densities, and the values ranged from 0.02 to 0.19 gr cm\(^{-3}\) with a mean value of 0.12 ± 0.03 g cm\(^{-3}\). Logged-over forest has the highest BD (0.135 gr cm\(^{-3}\)) significantly compared to the other sites. Based on the distribution of peat depth, the lowest BD was mainly found at the surface peat layers and increased significantly with the peat depth. The C concentration with the mean value of 57.6% showed no significant differences among the three locations and at different depths. Based on BD and C concentration, soil C stocks in the upper one-meter depth were 621, 779, and 606 Mg ha\(^{-1}\) for the peat swamp forest, logged-over forest, and post-fire peatland, respectively. Logged-over forest significantly has the highest soil C stocks either up to one-meter depth or based on calculated predictions of the total peat depth (2530.64 ± 368.59 Mg ha\(^{-1}\)).

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**Authors’ contribution**
All authors contributed equally to this work as the main contributor.