Available online at:
http://journal.unila.ac.id/index.php/tropicalsoil
DOI: 10.5400/jts.2024.v29i1.23-32

Dynamics of Tropical Peatlands Characteristics and Carbon Stocks as Affected by Land Use Conversion and Ages of Land Use in Riau Province, Indonesia

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Received 06 September 2023, Revised 10 October 2023; Accepted 17 October 2023

ABSTRACT

The dynamics and patterns of relationships between the characteristics of Indonesian tropical peat involving a function of time (ages of land use) in the context of land conversion have yet to be widely reported. The effects of tropical peatland use change are generally discussed regarding C emissions, with the limited literature identifying dynamic soil characteristics as these changes occur. This study used a survey method. We identified the physical, chemical, and C stock characteristics of peat in forest locations, oil palm plantations with a land use age of 0-5 years,>5-10 years,>10 years, and agricultural land with a land use age of 0-5 years and >5-10 years to find out the dynamics of soil characteristics. Land use changes from peat swamp forests to oil palm plantations and agricultural land, and the longer age of land use results in an increase in BD (especially at the top layer), ash content, pH, Total-N, total-P_2O_5, total-K_2O, but there was a decrease in water content, fiber content, Organic-C, E400/E600, and soil C stocks. The alignment of economic, social, and ecological interests was directed to water and land management by regulating the area's hydrological system and increasing peat stability.

Keywords: Carbon stock, land management, physical-chemical characteristics, tropical peatland

INTRODUCTION

The diversity of tropical rain forests located in areas of organic matter deposits, high rainfall, reinforced by suitable topography and geology, and anoxic conditions that inhibit microbial activity cause peat to form because the accumulation rate of organic matter was more significant than the decomposition rate. Peatlands are carbon-dense areas that provide various ecosystem and economic-social services but are currently threatened by anthropogenic activities. Peatlands are easily damaged, so their use must be in the context of constructive-adaptive development (Fernandes et al., 2018). Information on the dynamics of peat soil characteristics and C stocks is crucial to designing effective conservation and management policies because Indonesia's tropical peat has a wide distribution and plays a vital role in sustaining life.

The largest peatland area in Indonesia is on Sumatra Island, which is 6,741,870 ha. Riau has the largest peatland, 3.57 million ha or 60% of Sumatra's peat area (Ritung et al., 2019). Peatland use changes into cultivation areas, production forests, and other use areas occur every year. Forest land has consistently decreased, while non-forest use has relatively increased.

The conversion of peat swamp forests to other uses is a crucial driver of a decrease in the groundwater level and an increase in the oxygenation zone. Drainage and land use changes cause an increase in soil temperature and soil microbial activity (Maslov and Maslova, 2020), reduced soil C due to emissions, as well as in the form of dissolved Organic-C, which can be identified using a spectrophotometer at a wavelength of 350 nm (Sudadi et al., 2023). However, knowledge about the dynamics of peat soil characteristics and C stocks from various stages of land conversion involving the function of time (age of land use) in plantation and agricultural development still needs to be minimally reported. Most researchers only focus on binary comparisons between forests and certain types of land use.

The utilization of peatlands is essential for sufficient food, bioenergy, and economic growth, especially for developing export commodities (Kurniawan and Managi, 2018). However, the utilization of peatlands is faced with a dilemma of socioeconomic interests for agricultural production and the interest in maintaining environmental quality. Sustainable agriculture requires a technically implemented system to be economically feasible, socially acceptable, and environmentally friendly under productive, competitive, and efficient conditions. This study aims to identify the dynamics of peat's physical and chemical characteristics, calculate soil C stocks, and examine the relationship between these parameters due to land use changes and the age of land use. This information is needed to prepare land management directions and save degraded land.

MATERIALS AND METHODS

Study Sites

The research was carried out from December 2022 to May 2023 on several types and ages of peat land use in Siak and Kampar Regencies, Riau Province, Indonesia (Figure 1).

Field Sampling

The research was carried out using a survey method. The determination of the location for field observations was guided by the results of the overlay of land and soil unit maps, topographical Indonesian maps, land use maps, and peat thickness maps using the Geographic Information System technique. Soil sampling locations were determined purposively based on differences in type and age of land use with a combination of terrain techniques based on land physiography. The number of soil samples at each observation location was determined based on the peat ecosystem function criteria. The diversity factor was determined based on the peat maturity to the state of the rhizosphere and fluctuations in the groundwater level, namely at a layer of 0-50 cm (fluctuations in the water level change in a short/intensive period; daily-monthly), and layers >50-100 cm (fluctuations water level changes over a relatively long period; yearly).

Peat cores using a gouge auger model Eijkelkamp (Netherlands) with a drill blade length of 50 cm, drill tube outer diameter of 6 cm, and sample diameter of 5.2 cm. Drilling was carried out from the top layer of peat to the substratum layer. Information on the maturity of the peat in the field in each profile was identified qualitatively by squeezing soil samples from the palms of the hands (Agus et al., 2011). At each location, soil samples were taken at four points and two layers of peat thickness. In total, there were 48 undisturbed soil samples and 48 disturbed soil samples taken from

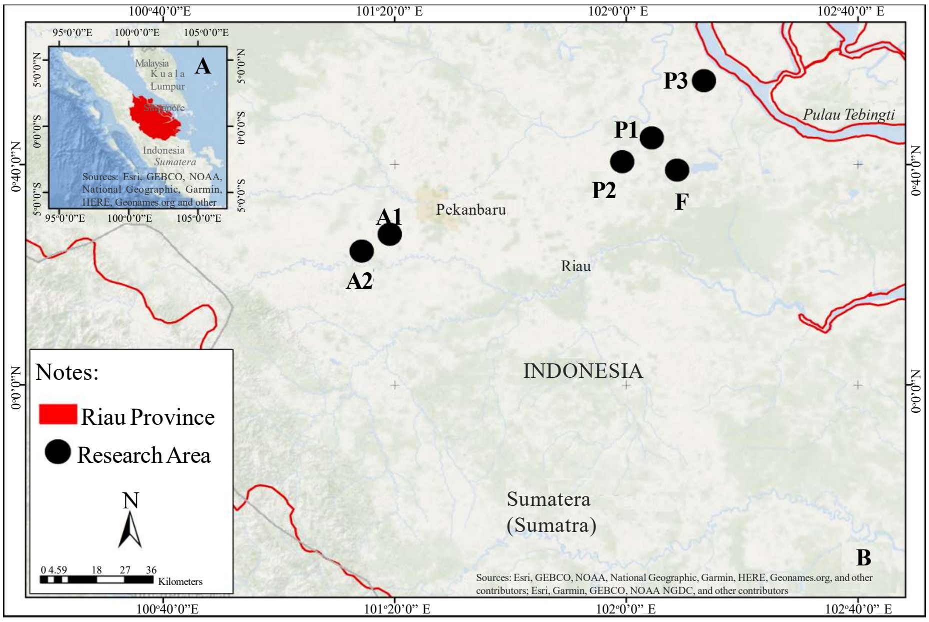

Figure 1. A (inset): Riau Province. B: Location of observation on several types and ages of land use; F (forest); P1 (oil palm plantations aged 0-5 years); P2 (oil palm plantations aged >5-10 years); P3 (oil palm plantations aged >10 years); A1 (agricultural land aged 0-5 years); A2 (agricultural land aged >5-10 years).

six observation locations. Next, soil samples were divided into several sub-samples according to the laboratory analysis needs.

Laboratory Analysis

A total of 384 soil sub-samples were analyzed for 11 observation parameters. Bulk density (BD) and water content were analyzed using the gravimetric method. Fiber content was analyzed using the syringe method (Agus et al., 2011). The ratio of fulvic acid and humic acid to determine the degree of peat humification (E400/E600) was analyzed by extraction method $Na_4P_2O_7$ 0.025 M and spectrophotometry (Kaila, 1956; Tan and Giddens, 1972). Organic-C and ash content were analyzed using the Loss on Ignition method. pH H_2O and pH KCl were analyzed using a pH meter (1:5). Total-N was analyzed using the Kjeldahl method. Total P_2O_5 and total K_2O were analyzed by extraction method 25% HCl.

Estimation of Carbon Stocks

Carbon stocks are calculated by a mathematical equation (Agus et al., 2011):

C stock (Mg ha^{-1}) = Σ(BD*Org-C*Ai*hi); where Ai is peatland area (ha), hi is peat thickness (m), BD is bulk density (g cm^{-3} or Mg m^{-3}), and org-C is organic-C (g kg^{-1}). The dynamics of C stocks due to changes in land use and the age of land use were calculated on the top 1 m of peat thickness, where aerobic decomposition begins due to groundwater level fluctuations and is in the rhizosphere area of cultivated plants. If forced to compare C stock for the entire thickness of the peat layer as usual, the resulting data will have too much bias due to variations in peat thickness that are not comparable between land uses.

Data Analysis

The general linear model, analysis of variance, and followed by the Tukey HSD post hoc test were used to identify differences in peat physicochemical characteristics and their interactions between land use classes (F, P1, P2, P3, A1, A2) and peat layer classes [I (0-50 cm) and II (>50-100 cm)]. The relationship pattern between observation parameters was analyzed using Principal Component Analysis (PCA). PCA was conducted to evaluate further the relationship between soil characteristics, land use, and C stocks. To predict the strength of the relationship between parameters examined using simple linear regression and Pearson correlation. Land spatial data was processed with Geographic Information System techniques using Arc. GIS 10.8 and statistical analysis were processed with IBM SPSS 25.

RESULTS AND DISCUSSION

Land Management and Crop Productivity

Forest land use represented the condition of peat in its natural state and had not received human intervention. Oil palm land use represented the condition of peat that had been opened and used for cultivation. Aerobic conditions in the surface layer characterized peat characteristics in oil palm plantations to a depth of 40-60 cm. Construction of drainage channels with a width of ±1-1.5 m and a depth of ±1 m. The status of oil palm plantations owned by the people/community with non-intensive management and fertilization. Fertilization was not routinely applied in a year (0-1 times). The fertilizers and doses given were urea 280 kg ha^{-1} yr^{-1}, TSP 140 kg ha^{-1} yr^{-1}, phonska 100 kg ha^{-1} yr^{-1}, and dolomite 400 kg ha^{-1} yr^{-1}. The productivity of smallholder oil palm plantations was around 13-17 Mg ha^{-1} yr^{-1}. There were three locations of oil palm plantations identified, namely oil palm plantations on cleared peatlands aged 0-5 years (P1; 24 months), >5-10 years (P2; 96 months), and >10 years (P3; 168 months).

The agricultural land (food/horticulture) represented the condition of peat, where management was more intensive than oil palm plantations. The planting system carried out by farmers was a rotation between food crops and horticulture. The main crop cultivated was pineapple. The drainage channels were constructed with a width of ±0.5-1 m and a depth of ±0.3-0.8 m. Two locations for food/horticulture planting were identified, namely food/horticulture land that had been cleared 0-5 years (A1; 24 months) and >5-10 years (A2; 96 months). Fertilizer applications for one application include manure 7-10 Mg ha^{-1}, urea 300 kg ha^{-1}, TSP 150 kg ha^{-1}, KCl 250 kg ha^{-1}, and ash 150 kg ha^{-1}. Fertilization was conducted 2-3 times a year. Pineapple productivity reached 18-25 Mg ha^{-1} yr^{-1}.

General Characteristics of the Research Location

The research location was mainland peat, where rainwater comes from, and the Siak and Kampar Rivers, which flank the hydrological unit. The peat formation process at the study site was influenced by a wet tropical climate with rainfall of

Table 1. Land morphology characteristics.

Location	Peat thickness (m)	Groundwater level (cm)	Maturity level 0-50cm	Maturity level >50-100cm	Substratum	Drainage
F	14.730 ± 0.963	-5.5 ± 0.424	Fibric	Fibric	Clay deposits	Natural
P1	5.148 ± 0.412	-56.95 ± 3.196	Fibric	Fibric	Clay-sand deposits	Artificial
P2	3.808 ± 0.387	-43.75 ± 2.472	Hemic	Hemic	Clay deposits	Artificial
P3	1.50 ± 0.315	-33.5 ± 1.445	Sapric	Hemic	Clay deposits	Artificial
A1	3.50 ± 0.073	-37.525 ± 0.974	Hemic	Hemic	Clay deposits	Artificial
A2	1.498 ± 0.110	-29.025 ± 1.646	Sapric	Hemic	Clay deposits	Artificial

2,000-3,000 mm yr^{-1} and was classified as type B in the Schmidt-Ferguson classification.

Forest land use (obstructed drainage) peat maturity level did not differ between the top and bottom layers. On the other hand, in the peatlands cleared for cultivation, the peat maturity continues to increase, both in oil palm plantations and agricultural land. The peat maturity of the top layer (0-50 cm) was dominated by hemic-sapric, while the peat maturity of the bottom layer (>50-100 cm) ranged from fibric-hemic (Table 1). The high peat maturity level of the top layer was because the top layer had higher aeration and was the locus of soil biochemical activity. Lignin oxidation mediated by lignin-degrading microbes characterized the degradation of peat material. Due to relatively drier soil conditions, these microbes were concentrated in developing and active in the top layer (Hijri et al., 2022).

Peat thickness and groundwater level (GWL) varied for each land use (Table 1). The data presented was the condition of the field when the research was conducted. The initial peat thickness from each observation location was not identified due to data limitations. The initial peat thickness might have been different. The highest peat thickness was found in location F (14.730 ± 0.963 m), and the lowest was found in A2 (1.498 ± 0.110 m). The GWL at the study site was relatively shallow; the minimum average was +5 cm, and the maximum was -60.5 cm, with an overall average of -37 cm. The highest GWL was found in P1 (-56.95 ± 3.196 cm), and the lowest was found in F (-5.5 ± 0.424 cm). A negative (-) value for GWL indicates that the groundwater table was below the peat surface.

Dynamics of Peat Physical Characteristics

The BD of the top layer was higher than that of the bottom layer in all land uses. BD of peat increased with more intensive land management and the longer the age of land use (the highest was on agricultural land (A2) and oil palm plantations (P3), respectively in the top layer). The increase in BD was significant, especially in the top layer of peat (Table 2). The high BD on agricultural land was suspected due to intensive land management, such as tillage, fertilizing, adding ash, applying mineral soil to peat, harvesting activities, and heavy equipment that puts pressure on peat compaction. The increase in BD was also thought to be due to the accumulation of particulate organic matter concentrated near the water's surface, concomitant with compaction due to the aerobic decomposition of peat.

The bottom layer, where maturation predominates, was fibric, which contains higher OH-phenolic groups, was polar, and had a remarkable ability to bind water. Fibric peat contained higher cellulose than sapric. Cellulose was hydrophilic, so it could bind more water, so the water content of the bottom layer was higher than that of the top layer. It was also due to the change in peat maturity from fibric to a higher level of maturity, causing a decrease in the pore space between peat particles so that the peat's water-holding capacity is reduced in the top layer (Rezanezhad et al., 2016). The highest water content was found in location F (438.26 ± 4.16 g kg^{-1}), and the lowest was found in location A2 (144.34 ± 1.52 g kg^{-1}). The top layer, which was relatively lower in water content, allowed the activity of microorganisms to decompose the peat material. Simultaneously, this process would reduce the fiber content of the peat. As we saw, in cultivated peatland, the fiber content was lower than the condition of the forest. The highest fiber content was found in location F (82.89 ± 1.43 %), and the lowest was found in location A2 (11.06 ± 0.32 %) (Table 2).

Dynamics of Peat Chemical Characteristics

The ratios of fulvic acid and humic acid (E400/E600), Organic-C, pH H_2O, pH KCl, ash content, total-N, total-P_2O_5, and total-K_2O differed significantly between land uses (Table 2). The ratio of fulvic acid and humic acid (E400/E600) continues to decrease as land use changes and the age of

Table 2. Physical and chemical characteristics of peat between land uses.

Soil characteristics		Location F	P1	P2	P3	A1	A2	*P-value*
BD	I*	0.112 ± 0.005	0.113 ± 0.001	0.128 ± 0.001	0.136 ± 0.003	0.127 ± 0.002	0.151 ± 0.001	<0.001
(g cm^{-3})	II	0.124 ± 0.001	0.111 ± 0.003	0.099 ± 0.003	0.094 ± 0.002	0.091 ± 0.006	0.061 ± 0.003	
Water content	I	438.26 ± 4.16	359.48 ± 1.95	284.04 ± 3.17	197.98 ± 4.62	262.98 ± 6.36	144.34 ± 1.52	<0.001
(g kg^{-1})	II	442.63 ± 2.44	448.43 ± 0.82	456.57 ± 0.44	460.95 ± 0.31	463.37 ± 0.54	530.71 ± 0.50	
Fiber	I	82.89 ± 1.43	48.40 ± 0.75	43.44 ± 0.49	39.10 ± 0.61	44.92 ± 0.25	11.06 ± 0.32	<0.001
content (%)	II	84.02 ± 0.29	86.00 ± 0.35	88.12 ± 0.14	90.73 ± 0.35	89.92 ± 0.40	92.15 ± 0.49	
E400/E600	I	10.49 ± 1.19	8.13 ± 0.33	5.25 ± 0.19	3.77 ± 0.45	7.56 ± 0.22	2.71 ± 0.33	<0.001
	II	11.14 ± 0.66	8.86 ± 0.20	6.91 ± 0.73	5.82 ± 0.22	8.43 ± 0.20	4.61 ± 0.81	
Organic-C	I	56.82 ± 0.21	55.16 0.47±	53.20 ± 0.07	47.78 ± 0.13	53.86 ± 0.18	45.39 ± 0.66	<0.001
(g kg^{-1})	II	57.84 ± 0.03	56.92 ± 0.02	53.84 ± 0.03	52.73 ± 0.11	54.90 ± 0.13	51.23 ± 0.12	
Ash content	I	2.04 ± 0.36	4.91 ± 0.81	8.29 ± 0.12	17.63 ± 0.22	7.14 ± 0.30	21.74 ± 1.14	<0.001
(g kg^{-1})	II	0.28 ± 0.06	1.87 ± 0.04	7.18 ± 0.04	9.09 ± 0.20	5.36 ± 0.22	11.68 ± 0.21	
pH	I	3.37 ± 0.03	3.46 ± 0.04	3.62 ± 0.01	3.68 ± 0.03	3.59 ± 0.01	3.89 ± 0.11	<0.001
H_2O	II	3.31 ± 0.01	3.43 ± 0.03	3.54 ± 0.04	3.62 ± 0.02	3.7 ± 0.03	3.65 ± 0.01	
pH	I	2.46 ± 0.03	2.53 ± 0.08	2.76 ± 0.04	2.85 ± 0.04	2.72 ± 0.03	2.92 ± 0.13	<0.001
KCl	II	2.26 ± 0.02	2.35 ± 0.03	2.55 ± 0.03	2.60 ± 0.01	2.43 ± 0.04	2.64 ± 0.02	
Total N	I	0.78 ± 0.03	0.86 ± 0.03	0.93 ± 0.02	1.02 ± 0.11	0.88 ± 0.02	1.06 ± 0.05	<0.001
(g kg^{-1})	II	0.75 ± 0.02	0.81 ± 0.01	0.88 ± 0.02	0.91 ± 0.03	0.83 ± 0.01	0.95 ± 0.03	
Total P_2O_5	I	318.69 ± 9.03	347.51 ± 10.5	372.22 ± 5.01	394.42 ± 8.52	368.92 ± 7.74	426.74 ± 19.3	<0.001
(mg kg^{-1})	II	296.41 ± 4.39	315.29 ± 6.23	358.64 ± 3.94	374.00 ± 8.05	334.68 ± 11.1	396.54 ± 9.15	
Total K_2O	I	105.78 ± 1.18	124.66 ± 2.98	158.14 ± 1.38	175.29 ± 5.89	133.63 ± 3.45	201.28 ± 3.44	<0.001
(mg kg^{-1})	II	99.75 ± 2.14	113.10 ± 3.00	137.70 ± 4.45	156.14 ± 5.30	121.78 ± 4.70	173.53 ± 5.39	

Note*: I (layer 0-50 cm); II (layer >50-100 cm). P-value < 0.001 indicates that the difference is significant at the level of $\alpha = 5\%$

land use increases. E400/E600 values indicate the degree of peat humification. Dominant concentrations of fulvic acid indicated a peat humification level that had not yet developed further. In contrast, dominant concentrations of humic acid indicated a peat humification level that had advanced further. The lower the E400/E600 value, the more humified the peat was (Sim et al., 2017). The E400/E600 value of the top layer, which was lower than the bottom layer, indicates that the top layer had a higher level of humification, and the peat was more mature than the bottom layer. The lowest E400/E600 values were in A2 and P3, and the highest was in F, both in the top and bottom layers. Decreasing E400/E600 showed a pattern in line with decreased water content, fiber content, organic-C, and increased pH and ash content (Figure 2).

pH analysis showed negatively charged soil (pH H_2O > pH KCl). Soil pH was classified as acid-very acid in all land uses. The highest pH H_2O and

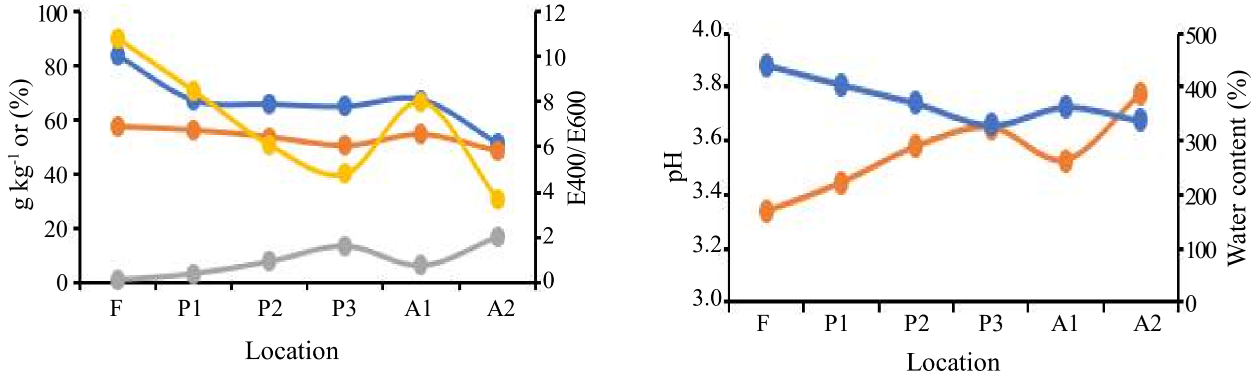

Figure 2. (A) Dynamics of E400/E600 (—), Organic-C: (—), fiber content: (—), and ash content: (—) between land uses. (B) Dynamics of pH (—) and water content (—) between land uses.

pH KCl were found in location A2, with details of pH H_2O 3.89 ± 0.11 and pH KCl 2.92 ± 0.13. Meanwhile, the lowest value was found in location F, with details of pH H_2O 3.37 ± 0.03 and pH KCl 2.46 ± 0.03. The high acidity of peat is due to the hydrolysis of organic acids, which are dominated by fulvic and humic acids (Nurhayati et al., 2022). Organic materials that have undergone decomposition have reactive groups such as carboxyl (–COOH) and phenol (C_6H_4OH), which predominate in exchange complexes that can dissociate and produce large amounts of H ions. Agricultural land (A2) had the highest pH compared to other locations. Intensive land management, amelioration, and drainage reduced soil acidity.

Soil Organic-C differed significantly between land uses, highest in the forest (F) and lowest in the agricultural land (A2). The decrease in water level resulted from making drainage on the peatland, so O_2 availability increased, stimulated the activity of soil microorganisms, and triggered the decomposition of peat material. Farmers generally provide urea on the land. Adding fertilizers containing N increases the diversity of soil microbiota (Lau et al., 2022). Nitrogen enrichment in soil contributes to C decomposition. Respiration of microorganisms, oxidation of peat matter, mineralization, and loss of organic matter matrix were apparent effects of clearing and management mainly due to drainage and fertilization (Leifeld et al., 2020).

The highest value of ash content, Total-N, total-P_2O_5, and total-K_2O, was found in agricultural land (A2), and the lowest was found in forest (F). The top layer's ash content and total macronutrients were higher than the bottom layer. The top layer was decomposed more intensively than the bottom layer (Nursanti et al., 2023). Oxidation of methane, sulfide, ferrous, ammonium, and manganese materials and accelerated oxidation of organic matter produced simpler compounds besides nutrients (Maftuah et al., 2016). Changes in the physical and chemical characteristics of peat are due to land clearing and management, resulting in changes to the area's hydrology. This situation affects the level of peat decomposition and the effect of the fertilizer applied (Kruger et al., 2015).

Below Ground Carbon Stocks

The function of peatlands as a C store can become a source of emissions if natural peat forests are cleared for cultivation. Potential emissions come from an increase in the rate of soil C mineralization due to several treatments, such as drainage or land fires. This study found the highest soil C stock in forests and the lowest in agricultural land (A2). Carbon stocks from highest to lowest follow the sequence F > P1 > P2 > A1 > P3 > A2 (Table 3).

The peat decomposition level increased following drainage and land conversion into oil palm plantations and agricultural land, as indicated by differences in the physical and chemical properties of peat between land uses (Table 2), thus affecting soil C stocks. For the same layer thickness (1 m), there was a significant difference in C stocks between forest land use (F), oil palm plantations (P1; P2; P3), and agricultural land (A1; A2). This study's predicted C stock of 1 m peat thickness ranged from 500.614 ± 7.35 Mg C ha^{-1} (A2) to 677.128 ± 17.43 Mg C ha^{-1} (F). Reduced soil C stock was due to the increased respiration of microbial heterotrophs in peatlands (Lupitasari et al., 2021). It was exacerbated by uncontrolled fluctuations in groundwater level, resulting in proliferation and increased microbial communities. Kurnianto et al.'s

Table 3. Predictions of C stock between observation locations.

Location	C stock (1 m depth) (Mg C ha^{-1})
F	677.128 ± 17.43 e
P1	629.304 ± 8.94 d
P2	605.707 ± 12.61 cd
P3	570.662 ± 8.70 b
A1	593.881 ± 21.91 bc
A2	500.614 ± 7.35 a

Note: Numbers followed by the same letter are not significantly different according to the Tukey HSD test at the level of α = 5%.

(2015) modeling showed that C loss was a real thing that happened after peat was converted for agricultural cultivation and plantations. The simulation of C loss due to peatland conversion was around 1,400 Mg C ha^{-1} for 100 years. Therefore, it is crucial to apply appropriate land management techniques to reduce the degradation of cultivated peatlands.

Interrelationships between Land Use, Peat Characteristics, and Carbon Stocks

Principal Component Analysis (PCA) and regression analysis showed the changing pattern and the strength of the relationship between research parameters. PCA detected two main gradients of variation in the physical and chemical characteristics of the peat concerning land use and layer depth (Figure 3). The total diversity that PCA can explain was 94.467%, with details of component 1 (X) 71.031% and component 2 (Y) 23.436%. The proximity between objects showed changes and differences in physical and chemical characteristics that were increasingly significant as the age of land use increased. This study showed a direct solid relationship (positive correlation) between water content, fiber content, Organic-C, and E400/E600 but a negative correlation with BD. The PCA biplot shows that soil C stock had a closer relationship with BD than other soil characteristics. Agus et al., (2011) found that C stock was more determined by BD variations than Organic-C.

This study also showed a strong direct relationship between ash content, pH, Total-N, total-P_2O_5, and total-K_2O, which were positively correlated and, on the other hand, were negatively correlated with water content, fiber content, Organic-C, and E400/E600. The strength of the relationship is explained more fully in Figure 4. Decreased water content and increased BD indicated increased decomposition and mineralization, resulting in nutrient accumulation (Frank et al., 2014).

Management Recommendations

The conversion of peatlands to oil palm plantations and agricultural land was economically profitable and socially acceptable, but ecologically significant changes in soil characteristics occurred. An indicator of sustainable management, namely soil C stocks (Suratman et al., 2020), decreases with increasing time and management intensity, indicating that sustainability still needs to be fulfilled. Efforts to minimize peatland degradation are directed at land and

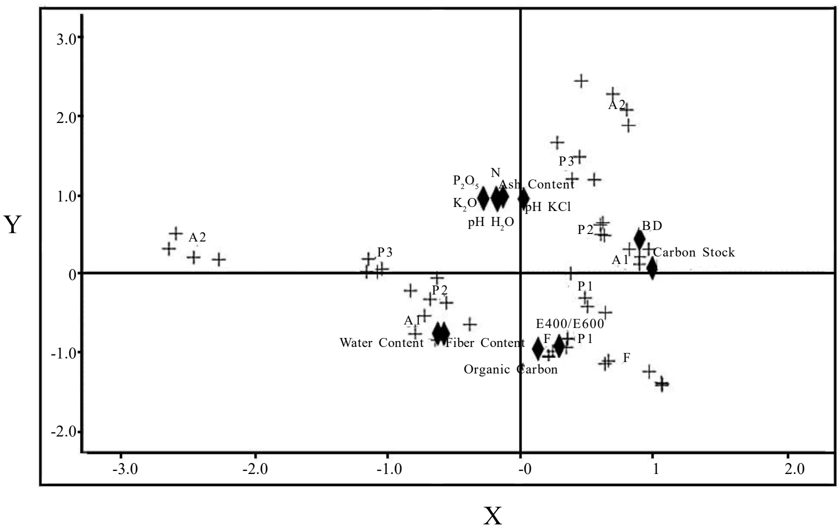

Figure 3. The PCA ordination diagram summarizes the variations and relationships between land use conversion, chemical-physical characteristics, and C stocks of peat soils.

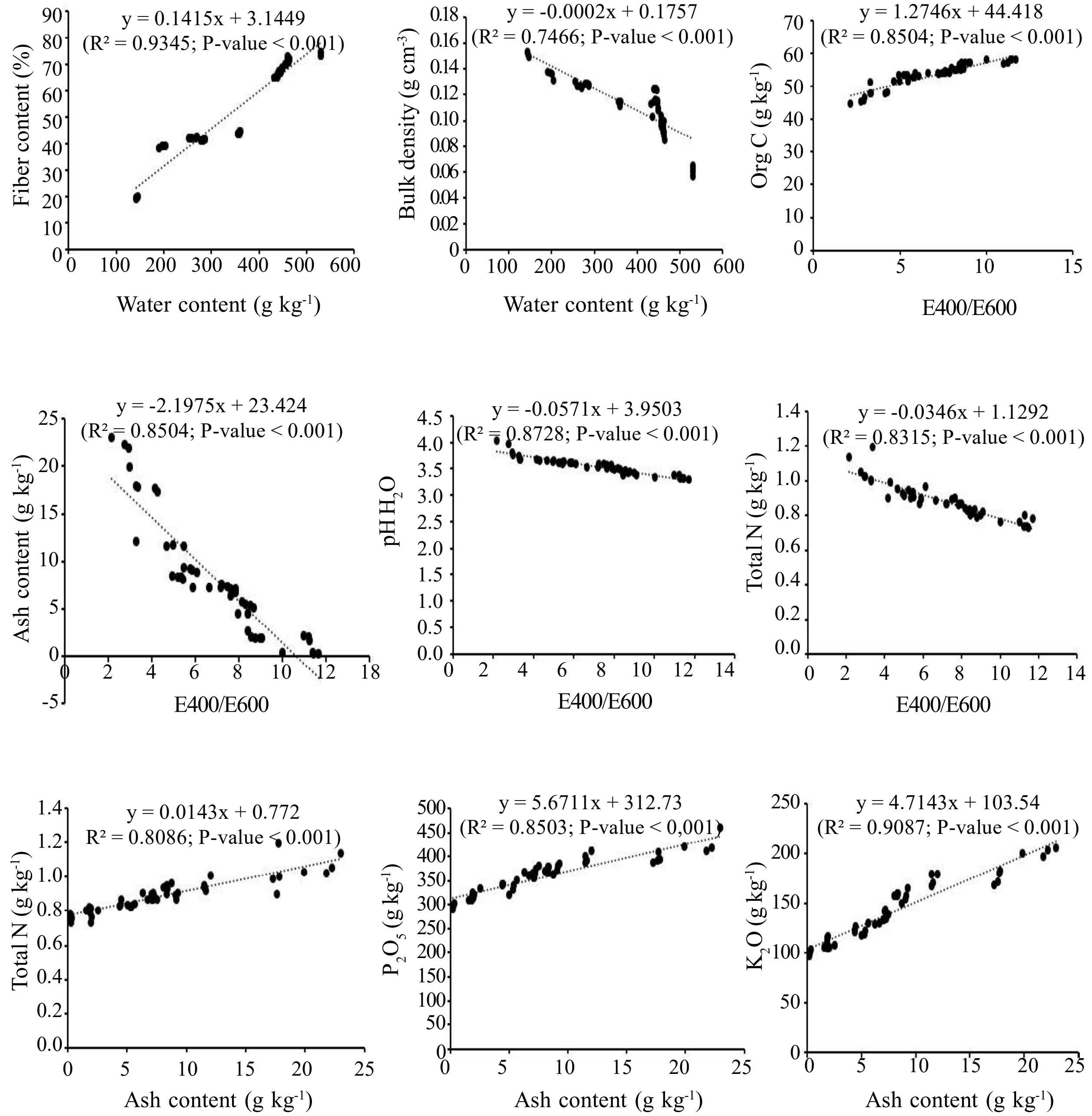

Figure 4. Linear regression analysis between soil characteristics.

water management through regulating water management and increasing peat stability. Water management is essential because the dynamics of the groundwater level stimulate changes in the physicochemical characteristics of peat (Basuki et al., 2021). Increasing peat stability must also be done to make it more stable against decomposition (Suratman et al., 2020). Good water and fertilization management are needed to support the successful development of agriculture on peatlands (Suwardi, 2019).

Developing peatlands for agriculture requires a macro-drainage network to control the water system in one area and a micro-drainage to control the water system at the field level. This water management also functions to prevent fires on peatlands (Nurzakiyah et al., 2016). An essential component in regulating peatland water management is the control structure in the form of a canal blocking each waterway so that fluctuations during the rainy and dry seasons can be controlled (Maftuah et al., 2016). Maintaining a groundwater level as shallow as possible according to plant needs, drought, compaction, and peat subsidence can be minimized. However, it must remain within the limits of plant tolerance to inundation. Oil palm plantations require micro-drainage of ±40-60 cm (Adhi et al., 2021) and food/horticultural crops ±40-50 cm from the surface for optimal plant production (Hairani and Noor, 2020).

Increasing the stability of peat material is also essential to reduce the sensitivity of land degradation. Amelioration with mineral soils with high Fe content or ameliorants containing polyvalent cations can increase peat stability and reduce the adverse effects of phenolic acids (Septiyana et al., 2017). The addition of microelements is needed to form chelates and complexes with organic matter from peat soils through organocation-metal bonds, making them more stable against decomposition. Maftuah et al. (2016) suggested adding Cu 25 kg ha^{-1} yr^{-1}, $MgSO_4$ 7 kg ha^{-1} yr^{-1}, $ZnSO_4$ 25 kg ha^{-1} yr^{-1}, sodium molybdate 0.5 kg ha^{-1} yr^{-1} and borax 0.5 kg ha^{-1} yr^{-1}. If fertilization only adds macro elements without being followed by microelements, peat decomposition increases (Moore, 2019). Therefore, regular and balanced fertilization between macro and micronutrients is needed in peatlands.

Finally, paying attention to the area and location of peat that needs to be maintained to reduce peatland damage is necessary. Agricultural development on peatlands must also follow Article 9 paragraph (2) of the Minister of Environment and Forestry Regulation RI Number P.14 of 2017. At least 30% of the peat hydrological unit must be maintained as natural peatland (protection function). Upstream peat areas, river banks, the peat dome (>3 m), and its surroundings, which have deep peat, need to be maintained so that land is not cleared for cultivation. This area functions as a buffer zone for the surrounding area.

CONCLUSIONS

Conversion of peat swamp forests into oil palm plantations and agricultural lands changes peat's physical and chemical characteristics. Increasing land use age and land management intensity resulted in decreased water content, fiber content, Organic-C, E400/E600, and soil C stocks. Ash content, pH, Total-N, total-P_2O_5, and total-K_2O are positively correlated and, on the other hand, are negatively correlated with water content, fiber content, organic-C, and E400/E600. The use of peat for cultivation needs to meet the ecological sustainability aspect. The alignment of economic, social, and ecological interests in peat areas is directed to water and land management through regulating water management and increasing peat stability.

ACKNOWLEDGMENTS

Thanks to Lembaga Pengelola Dana Pendidikan (LPDP) from the Ministry of Finance Republic Indonesia for granting the scholarship and supporting this research.

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