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Structural characteristics and degradability of soil organic matter in Malaysian peat soils under sago palm cultivation

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Abstract: To understand the sensitivity of soil organic carbon (SOC) in peat soils planted with sago palm to increases in pH, temperature, and solar irradiation, four soil samples collected from two sago palm gardens (SGs) in Mukah, SG1 and SG2, and a SG and a neighboring forest in Talau, Sarawak, Malaysia, were subjected to laboratory incubation experiments. ^{13}C nuclear magnetic resonance spectra were obtained to characterize the SOC of each soil. Three soil sample treatments: control (native pH (3.3－4.2), 25°C), neutral pH (pH 7, 25°C), and higher temperature (native pH, 35°C), were incubated for 91 days under aerobic conditions. The rate of production of carbon dioxide was determined at intervals of 7－14 days. A photodegradation experiment was conducted using Talau soil samples at 650 W m^{-2} for seven days. Two Mukah SG soils were characterized by an enrichment of alkyl C. In the Talau SG soil, both *O*-alkyl C and alkyl C were dominant, while aromatic C, followed by *O*-alkyl C, was dominant in the Talau forest soil. The rate of SOC mineralization in the control treatment was higher in the order of Mukah SG1, Mukah SG2, and two Talau soils, suggesting an enhancement of the decomposability of SOC under sago palm cultivation in association with the transition in C composition. The total amount of SOC mineralized in the neutral pH treatment in three of four soils was 1.4－3.2 times larger than that in the control treatment, although the amount may still be underestimated because CO_2 dissolved in soil water has not been evaluated. Higher temperature treatment also enlarged the amount of SOC mineralized to 1.6－3.1 times that of the control treatment in all soils. After seven days of irradiation, SOC decreased by 4－16% of the initial, suggesting that photodegradation is a possible mechanism of significant C loss in shallow surface soil.

Keywords: pH, photodegradation, sago palm, soil organic matter decomposition, temperature, tropical peat soil

Introduction

In parallel with the growth of the world's population, the demand for agricultural products for food, feed, and fuel is also increasing. To meet these demands, it is necessary to use land and soils that are unsuitable for crop production. Among them are peatlands and peat soils, which are characterized by a high groundwater level that could flood even the land surface during the wet season, low pH, low soil bulk density, high organic matter, and low nutrient content in soil. Although peatlands are mainly distributed in the subarctic and cool temperate regions, there are also 90–170 Mha in the tropics and ca 21 Mha in Southeast Asia (Ribeiro et al., 2020). In Malaysia and Indonesia, the sago palm (*Metroxylon sagu*) has long been cultivated in peat soils as a starch crop (Yong et al., 2018). An advantage of cultivating sago palms in peatland is that they can grow even under submerged conditions due to the development of aerenchyma in the roots (Nitta, 2015), although minimal drainage is actually provided.

The vast accumulation of soil organic carbon (SOC) in tropical peat soils is attributed to the high productivity of tropical peat swamp forests and the slow rate of organic matter decomposition in saturated conditions (Hoyos-Santillan et al., 2016). The decomposition of SOC in tropical peatland is also impeded by strong acidity and poor nutrient status (Dommain et al., 2011). Environmental conditions, such as temperature, groundwater level, and pH, are likely to play key roles in determining the rate of SOC decomposition and greenhouse gas fluxes (Jungkunst and Fiedler, 2007; Couwenberg et al., 2010; Jauhiainen et al., 2014; Girkin et al., 2020). The flux of carbon (C) in a peatland ecosystem is also modified by a change in the land use, in which intensive drainage resulting in an enhanced oxygen supply to the soil may accelerate SOC decomposition by soil organisms (Austin et al., 2018; Hergoualc'h and Verchot, 2011). Simultaneously, the input of C is generally reduced in cultivated lands as compared with forests (Chimner and Ewel, 2004; Hergoualc'h and Verchot, 2014).

According to Dommain et al. (2018), conversion to oil palm or *Acacia* plantations dramatically changes tropical peatlands from C sinks to C sources, and the conditions will continue for a century to millennia. Miettinen et al. (2017) estimated that 44% and 34% of C emissions from peatlands in Peninsular Malaysia, Sumatra, and Borneo were derived from lands used for industrial plantations and smallholder crop production, respectively. Hooijer et al. (2012) estimated that the oxidation of peat SOC is responsible for 75% to more than 90% of the cumulative subsidence in tropical peatlands under agricultural use after drainage. Increased carbon dioxide (CO_2) fluxes during the early years after the establishment of a sago palm plantation in an Indonesian peatland was reported by Watanabe et al. (2008). On the other hand, CO_2 flux does not necessarily correlate with the lowering of the groundwater table (Berglund and Berglund, 2011; Hergoualc'h and Verchot, 2011; Watanabe et al., 2009), suggesting the complex effects of environmental variables on the C cycle in a tropical peatland.

In the agricultural use of peatland, an increase in soil temperature and solar radiation intensity during the period when plant growth is insufficient to shade the soil's surface and that after harvest may also accelerate SOC decomposition (Jauhiainen et al., 2014). Previous studies have shown that a 10°C increase causes an increase in soil respiration of 1.5 to 4 times (Q_{10} = 1.5–4) in temperate and tropical peat soils with some exceptions (e.g., Hirano et al., 2009; Kim and Verma, 1992; McKenzie et al., 1998; Silvola et al., 1996). The Q_{10} values for burned sites in Central Kalimantan were small, 1.2–1.4 (Hirano et al., 2014), while those reported for fallow agricultural sites in the same region were as high as 2.2–35 (Jauhiainen et al., 2014). There is no information for sago palm soils. Although there are no reports in which the photochemical degradation of tropical peat was investigated (Rutledge et al., 2009), it is well known that considerable amounts of dissolved organic matter, in particular dark-colored humic substances, in aquatic ecosystems are degraded photochemically (Brinkmann et al., 2003; Moran et al., 2000). As such, the chemical structure of the SOC accumulated is important for evaluating the response of SOC to environmental changes induced by land use change. Sangok et al. (2017) found a maximum threefold difference in total CO_2 flux during a three-year period among the three soil samples collected from different phasic communities of a tropical peat swamp forest when those were buried in an oil palm plantation. They attributed the difference in the rate of SOC decomposition among the three soils to differences in SOC composition as estimated by ^{13}C nuclear magnetic resonance (NMR), i.e., SOC abundant in oxygen (O)- or nitrogen (N)-substituted alkyl C, derived mainly from polysaccharides and proteinaceous materials, is sensitive to changes in environmental conditions.

Fertilizer application and liming as common

practices to improve soil conditions (Funakawa et al., 1996; Kakuda et al., 2015) also may affect the decomposition of SOC by enhancing soil microbial activity (Comeau et al., 2016), although such a practice is not common in smallholder sago palm gardens (Jong et al., 2006). On the other hand, improved plant production supplies a larger amount of organic matter to the soil (Haynes and Naidu, 1998), which could reduce the rate of the decomposition of inherent SOC. Watanabe et al. (2009) did not find significant differences in CO_2 fluxes in peat soils growing sago palms with different amounts and composition of chemical fertilizers applied in a field experiment, even in a treatment where the plant height was taller than the other treatments. There have been few studies on the effect of liming on the decomposition of SOC (Biasi et al., 2008; Murayama and Bakar, 1996).

The objective of this paper is to evaluate the influence of environmental changes on the rate of SOC decomposition in the tropical peat soils used for sago palm production. For this purpose, SOC in peat soils where sago palms are cultivated was characterized using ^{13}C NMR spectroscopy, and the response of SOC decomposition to the changes in pH and temperature was examined in a laboratory incubation experiment. The C loss and structural change of SOC due to photodegradation were also investigated using a solar simulator.

Materials and methods

Soil samples used

Soil samples were collected in August 2015 from two sago palm (*Metroxylon sagu*, Rottb.) gardens (SGs) owned by local farmers in Mukah, Sarawak, Malaysia (Watanabe et al., 2016), SG1 (2°52'04.4"N, 112°08'28.2"E) and SG2 (2°49'48.5"N, 111°54'27.9"E), a sago palm field in the Sungai Talau Peat Research Station (2°49'38.9"N, 111°55'31.1"E), and a neighboring mixed peat swamp forest (2°49'43.8"N, 111°55'44.3"E) in Talau, Sarawak (Fig. 1). The peat layer was 75 cm thick at the Mukah SG1 site, approximately 2.8 m thick at the Mukah SG2 site, and ca 12 m thick at the Talau site. Drainage canals were provided around an area including the Mukah SG2 site (groundwater table ranging from ca 50 cm to above the land surface), while the Mukah SG1 site was not drained (groundwater table ranging from ca 5 cm to above the land surface). At the two Mukah sites, sago palms have been cultivated for roughly 30 years, but precise records did not exist. The number of sago palms at the SG1 site was ca 500 plants ha^{-1} with 60% in the rosette stage, while that at the SG2 site was ca 800 plants ha^{-1} with more than 90% in the rosette stage. At the Talau site, sago palm cultivation started in 2007 after land preparation in 2006 (Yong et al., 2018). The number of sago palms at the Talau SG site was 144 plants ha^{-1}, and 1–2 kg of chemical fertilizer containing N:P:K = 12:12:17 has been top-dressed for ca 70 ha three times a year in March, July, and November. Groundwater levels at both the Talau SG and forest sites were maintained at 20–40 cm. Drainage canals were found ca 50 m from the sampling site.

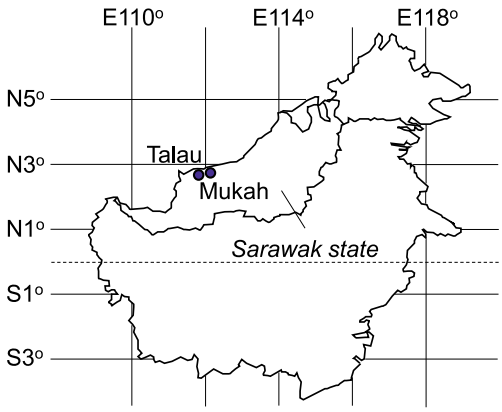

Fig 1. Location of peat soil sampling sites in Sarawak, Malaysia

Soil samples were collected from a depth of 0–25 cm using a peat auger, Model 04.09 (Eijkelkamp, Giesbeek, The Netherlands). Four samples from each site were combined to make a composite sample and stored at 4°C before use. An aliquot of the samples was freeze-dried, sieved (< 2 mm) to remove large debris, and ground to < 0.5 mm. The pH was recorded for a soil suspension in water mixed at 1:10 (w/v), almost equivalent to 1:2.5 (w/v) for a dried peat soil,

on a pH meter (D-72 Horiba, Tokyo). Total C and N contents were determined using an elemental analyzer (Flash 2000, ThermoFisher Scientific, San Jose, CA, USA). Ash content was determined by combusting the soil samples at 550°C for 4 h.

Measurement of ^{13}C NMR spectra

A 30 mg freeze-dried fine sample was placed in a 4 mmϕ zirconia sample tube, and ramp cross-polarization/magnetic angle spinning (CPMAS) ^{13}C NMR spectra with phase-adjusted spinning sidebands (PASS) (Ikeya and Watanabe, 2016) were recorded at 176 MHz on an ECA 700 spectrometer (JEOL, Tokyo, Japan). The operation conditions were as follows: contact time, 1.0 ms; spinning rate, 9 kHz; recycle delay, 1.0 s; and number of data accumulation, 1560–6240. The chemical shift was relative to tetramethylsilane (0 ppm) and adjusted with hexamethylbenzene (17.36 ppm). The spectra were divided into five regions of 0–45 (saturated alkyl C), 45–110 (alkyl C substituted with O or N, abbreviated *O*-alkyl C), 110–160 (aromatic C), 160–190 (carboxyl C), and 190–220 (ketone C) ppm, and cumulative signal intensities in each region relative to the total were regarded as the relative abundance of each C group.

Biodegradation of SOC

The moist soil samples were sieved (< 2 mm), and the water content was regulated at 85% using ultrapure water. Ten g of each soil sample was placed in a 100 mL Erlenmeyer flask and capped with a W-shaped butyl rubber stopper. Then the air inside the flasks was replaced with CO_2-free air, and the soils were incubated for 91 days under dark conditions. The following three treatments were prepared: 1) control, soil samples were incubated at 25°C; 2) neutral pH, the pH of soil samples was adjusted to 7 with $Ca(OH)_2$ before putting in a flask and then incubated at 25°C; and 3) higher temperature, soil samples were incubated at 35°C without pH modification. During incubation, CO_2 concentration in the headspace was determined at an interval of 1 week (until day 36) or 2 weeks (after day 36) using a gas chromatograph equipped with a thermal conductivity detector (GC14B, Shimadzu, Kyoto, Japan). The rate of CO_2 production on day n was obtained by dividing the difference in the amount of CO_2 in the headspace between day n and the previous measurement day, m, by n - m.

Photodegradation of SOC

Freeze-dried soil samples were used. One hundred mg of each soil sample was spread on a petri dish (inner diameter, 35 mm; soil thickness, 1.5 mm), moistened with ultrapure water, and irradiated continuously by Xenon lamp (wavelengths, 300–800 nm) at 650 W m^{-2} at 30°C for seven days in a solar simulator (Suntest XLS+, Atlas, Linsengericht, Germany) in three replicates. This treatment corresponds to 21 days in conditions of average solar radiation in Malaysia, where the mean daily irradiation is between 4.7 and 6.5 kWh m^{-2} (Petinrin and Shaaban, 2015), and the average annual sun hours of 2220 h is between 4 and 8 hours per day (Mekhilef et al., 2012). Soil water content was regulated at 80% by weighing soils and supplementing ultrapure water on days three and five. To reduce the rate of water loss, distilled water in a glass bottle was also placed in the solar simulator. After seven days of solar irradiation, the sample weight and total C content were determined. ^{13}C CP/PASS NMR spectra of the Talau soils after solar irradiation were also obtained.

Statistical analyses

The significance of the difference in the amounts of C mineralized during the incubation experiment between the different treatments of each soil and between soil samples subjected to the same treatments was determined using ANOVA and Tukey's Honestly Significant Difference test. Relationships between the amount of C mineralized and the chemical properties of the soil and SOC were evaluated using regression analysis.

Table 1. pH, total C, total N, and ash contents of peat soil samples used

Sample name	pH	Total C (g kg^{-1})	Total N (g kg^{-1})	C/N ratio	Ash content (g kg^{-1})
Mukah SG1	4.2	383	8	48	417
Mukah SG2	3.4	572	13	44	21
Talau SG	3.6	528	17	31	12
Talau forest	3.3	525	18	29	18

SG, Sago palm garden.

Results

Characteristics of SOC in peat soil samples

Table 1 shows the pH, total C, total N, and ash contents, and the C/N ratio of the peat soil samples. Soil pH ranged from 3.3 to 4.2, and ash content ranged from 12 to 417 g kg^{-1}, with the Mukah SG1 soil that has a shallow peat layer having the highest values. Total C content ranged from 383 to 572 g kg^{-1}. Total N content ranged from 8 to 18 g kg^{-1}, and the C/N ratio tended to be smaller in the Talau soils (29–31) than in the Mukah soils (44–48).

The ^{13}C NMR spectra of the soil samples are shown in Fig. 2. Major peak maxima were recorded at 27–30 (methylene C in long alkyl chains), 53–55 (methoxy C), 70–73 (secondary alcohol C), 102–103 (acetal C), 112 (aromatic C next to that substituted by O), 127–133 (aromatic C-C/C-H), 150–152 (aromatic C-O), and 171–172 (carboxy C) ppm for the whole samples. Relative intensities of the major signals were various among them, in particular between the Talau and Mukah soils. The methylene C signals at approximately 28 ppm were predominant in the Mukah SG soils, while the secondary alcohol C signals at 71–73 ppm and aromatic C signals at 129 ppm were also strong in the Talau soils. These variations are reflected in their C composition as presented in Table 2. Alkyl C was most abundant in Mukah SG soils and accounted for 43% of the total C, while that in the Talau soils was 23–29% and similar to % *O*-alkyl C, 26–31%. The % aromatic C was in the range of 20–36% with the highest in the Talau forest soil. The % carboxy C and % ketone C ranged from 10–14% and 2–5%, respectively, for all soil samples. As such, the differences in the C composition of the SOC depending on land use type were not observed.

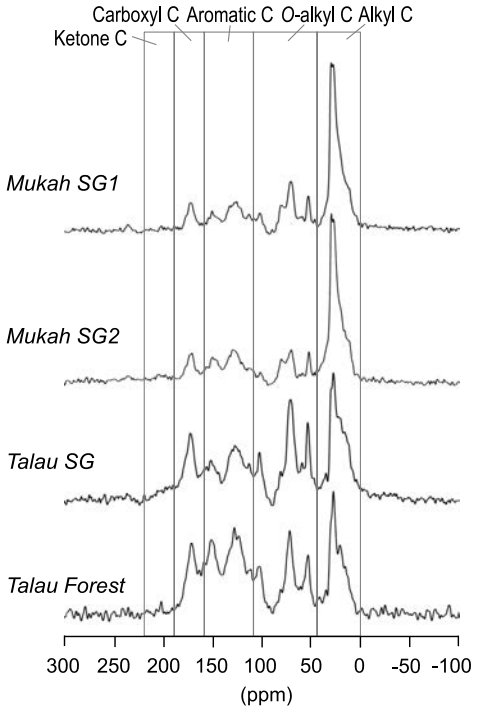

Fig 2. ^{13}C CP/PASS NMR spectra of peat soils collected from sago palm gardens in Mukah and Talau as well as a neighboring forest in Talau

Rate of decomposition of SOC in tropical peat soil under higher pH or higher temperature

Figure 3 shows the variations in the rate of CO_2 production during the 91-day period of incubation. Control treatment of Mukah SG1, SG2, and Talau forest soils showed the largest rate of CO_2 production on day seven, the first measurement day, and the rate

Table 2. C composition of peat soils from sago palm gardens and a neighboring forest

Sample name	% alkyl C (0–45 ppm)	% *O*-alkyl C (45–110 ppm)	% aromatic C (110–160 ppm)	% carboxyl C (160–190 ppm)	% ketone C (190–210 ppm)
Mukah SG1	42.5	24.5	19.5	9.8	3.7
Mukah SG2	43.3	19.9	21.6	10.5	4.7
Talau SG	29.2	30.9	24.3	11.3	4.3
Talau forest	22.5	25.7	35.9	13.7	2.2

SG, Sago palm garden.

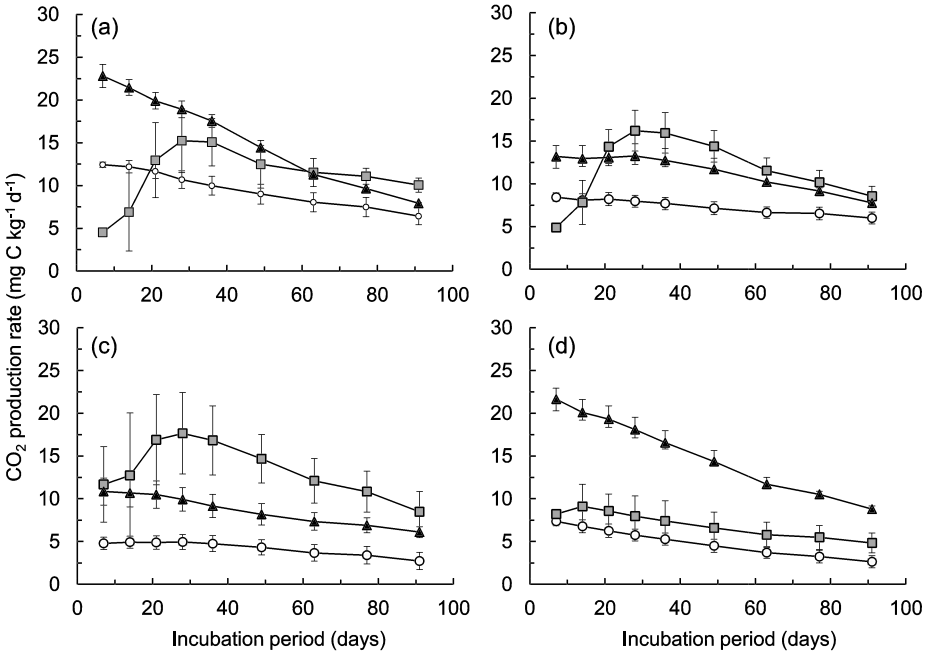

Fig 3. CO_2 production rate of peat soils collected from sago palm gardens and a neighboring forest: (a) Mukah SG1, (b) Mukah SG2, (c) Talau SG, and (d) Talau forest
Error bars indicate the standard deviation ($n = 3$).
Open circles, control treatment; gray squares, neutral pH treatment; closed triangles, high temperature treatment.

then decreased gradually. The rate of CO_2 production in the Talau SG soil was similar during the first 36-day period and then decreased slightly. The total amount of C mineralized was higher ($P < 0.05$) in the order of Mukah SG1 soils, 823 mg C kg^{-1} dry soil; Mukah SG2 soils, 636 mg C kg^{-1} dry soil; and Talau SG and forest soils, 365–418 mg C kg^{-1} dry soil (Table 3).

The rate of CO_2 production in the neutral pH treatment (Fig. 3) showed a pattern of variation different from those of other treatments. The specific pattern was conspicuous in the Mukah soils, where the rate of CO_2 production was the lowest on day seven and then increased until around day 28. After that, the rate of CO_2 production gradually decreased but was still larger than or similar to those in the higher temperature treatment on day 91. Although the Talau SG soil also showed a similar tendency, the rate of CO_2 production on the first measurement day was higher than that of the control treatment. The initial increase in the rate of CO_2 production in the neutral pH treatment was ambiguous in the Talau forest soil, although it still tended to be larger than that in the control treatment.

Total amount of C mineralized in the neutral pH treatment ranged from 599–1176 mg C kg^{-1} dry soil

and was significantly larger ($P < 0.05$) than that in the control treatment of the respective soils except for the Mukah SG1 soil (Table 3). Among the four soil samples incubated at pH 7, the amount of C mineralized was smaller in the Talau forest soil, 599 mg C kg^{-1} dry soil (Table 3). However, the increased level relative to the control treatment, 1.4 times, was within the range of the other soils, 1.1–3.2 times.

Higher temperature treatment enhanced CO_2 production in all of the soils throughout the incubation period (Fig. 3). In the Mukah SG1 and Talau forest soils, the rate of CO_2 production was the largest on the first measurement day, 21.6–22.8 mg C kg^{-1} d^{-1}, and decreased almost constantly. On the other hand, the Mukah SG2 and Talau SG soils, where the rate of CO_2 production on day seven was smaller, 10.9–13.2 mg C kg^{-1} d^{-1}, than those of the Mukah SG1 and Talau forest soils, showed no reduction in the CO_2 production rate during the first month. The total amount of C mineralized in the high temperature treatment, 991–1319 mg C kg^{-1} dry soil, was larger than that in the control treatment for all soils (Table 3). The total amount of C mineralized was larger ($P < 0.05$) in the order of Mukah SG1 and Talau forest soils, 1303–1319 mg C kg^{-1} dry soil; Mukah SG2 soil, 991 mg C kg^{-1} dry soil; and Talau SG soil, 747 mg C kg^{-1} dry soil (Table 3). The relative increase was considerably similar, 1.6–2.1 times, except for the Talau forest soil where the difference between the two treatments reached 3.1 times.

Sensitivity of SOC in tropical peat soils to solar irradiation

Table 4 shows the % C loss of the Mukah and Talau soils and the C composition of the Talau soils after seven days of irradiation. The % C loss ranged from 4.0 to 15.7%. The C composition of the Talau soils as estimated from ^{13}C CP/PASS NMR analysis (Fig. 4) showed a slight decrease in the relative abundance of *O*-alkyl C, i.e., from 31% (Table 2) to 27% in the SG soil and from 26% to 21% in the forest soil. On the contrary, % aromatic C (SG soil) or % carboxy C (forest soil) increased.

Discussion

Comparison of the rate of SOC decomposition under control conditions

The amount of CO_2 produced in the control treatment during the incubation experiment (Table 3) did not differ between the Talau SG and forest soils. The higher N content and lower C/N ratio have been thought to be beneficial for SOC decomposition

Table 3. Cumulative amount of peat soil C mineralized during a 91-day period of incubation

Soil sample		Control tr.	Neutral pH tr.	High temperature tr.
Mukah SG1	(mg C kg^{-1} dry soil)	823 ± 61† Ab‡	912 ± 175 ABb	1319 ± 30 Aa
	(mg kg^{-1} C)	2.18 ± 0.23 Ab	2.45 ± 0.61 ABb	3.43 ± 0.11 Aa
Mukah SG2	(mg C kg^{-1} dry soil)	636 ± 44 Bb	1036 ± 98 Aa	991 ± 65 Ba
	(mg kg^{-1} C)	1.14 ± 0.11 Bb	1.82 ± 0.24 ABa	1.75 ± 0.16 Ca
Talau SG	(mg C kg^{-1} dry soil)	365 ± 55 Cc	1176 ± 225 Aa	747 ± 74 Cb
	(mg kg^{-1} C)	1.02 ± 0.23 Bb	3.26 ± 0.89 Aa	2.10 ± 0.29 BCab
Talau forest	(mg C kg^{-1} dry soil)	418 ± 38 Cc	599 ± 58 Bb	1303 ± 54 Aa
	(mg kg^{-1} C)	0.80 ± 0.11 Bc	1.16 ± 0.16 Bb	2.49 ± 0.14 Ba

SG, Sago palm garden. † Mean value ± standard deviation (n = 3).

‡ Values followed by different capital letter differ among soil samples of same treatment at $P < 0.05$ and those followed by different letter in lower case differ among three treatments of the same soil at $P < 0.05$.

Table 4. Carbon loss from peat soils and C composition of Talau soils after seven days of solar irradiation

Sample name	C loss (%)	% alkyl C (0–45 ppm)	% *O*-alkyl C (45–110 ppm)	% aromatic C (110–160 ppm)	% carboxyl C (160–190 ppm)	% ketone C (190–210 ppm)
Mukah SG1	10.3±4.6†	N.D.	N.D.	N.D.	N.D.	N.D.
Mukah SG2	4.0±0.2	N.D.	N.D.	N.D.	N.D.	N.D.
Talau SG	15.7±2.0	27.9	26.5	26.8	14.3	4.5
Talau forest	8.6±3.1	22.8	20.6	33.8	19.4	3.4

S.G., Sago palm garden. N.D., Not determined.

† Mean value ± standard deviation (n = 3).

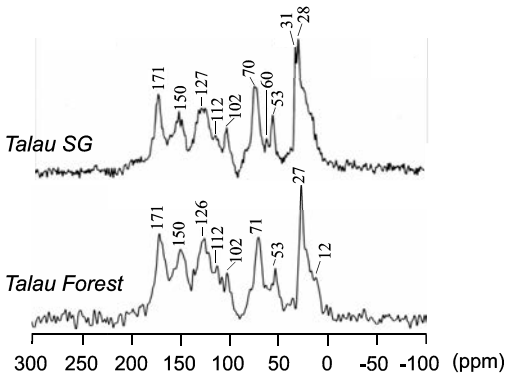

Fig 4. ^{13}C CP/PASS NMR spectra of Talau sago palm garden and forest soils after seven days of solar irradiation

(Córdova et al., 2018). However, 29 of the C/N ratio in the Talau forest soil was likely still insufficient to promote it. No correlation between the C/N ratio and the rate of decomposition of SOC was also observed for peat profiles in Panama (Hoyos-Santillan et al., 2016). The lower content of the readily decomposable organic matter, as is suggested by a higher % aromatic C in the Talau forest soil (Table 2), may be a negative factor for SOC decomposition. The significant negative correlation between the amount of C mineralized and % aromatic C in the four soil samples in the control treatment (r = -1.00; $P < 0.005$) agreed with this. The difference in soil microbial activity between forest and SG soils is also a potential cause of the different rates of SOC decomposition, which should be confirmed in another study.

According to Sangok et al. (2020), it took ca 350 years for 25 cm of peat to accumulate in a mixed peat swamp forest in Maludam National Park, which is located in Sarawak. Assuming a similar rate of peat deposition, the majority of SOC in Talau SG soil was formed under forest vegetation, and it is considered that sago palm cultivation has altered the quality of soil organic matter (SOM) toward a higher aliphaticity (Table 2). The ^{13}C CP/PASS NMR spectra of the Mukah soils, with their longer history as sago palm gardens, suggest the further reduction of aromatic components that are resistant to microbial decomposition. Although we do not have analyzed data, a smaller supply of lignin from sago palms compared with woody plants in mixed peat swamp forest could be a cause of this change (Normand et al., 2021). As such, the replacement of SOC components under continuous use for sago palm cultivation could increase the rate of CO_2 production.

The % alkyl C/% O-alkyl C ratio has often been considered in association with the degree of decomposition of peat organic matter (Baldock et al., 1997; Krosshavn et al., 1992; Wright et al., 2011), in which the increase in the % alkyl C is interpreted as a result of the selective preservation of lipids, waxes, and resins or an accumulation of byproducts of microbial metabolism during SOC decomposition. On the contrary, the relative contents of polysaccharides and proteinaceous materials, major sources of *O*-alkyl C, were suggested to be indicators of the productivity of CO_2 (Normand et al., 2021; Sangok et al., 2017; Treat et al., 2014). As the % alkyl C/% *O*-alkyl C

ratio was higher in the Mukah soils than in the Talau soils, this parameter was not related to the amount of C mineralized in the present incubation experiment. Within the alkyl C region, the relative intensity of the signals of methylene C in long alkyl chains (26–29 ppm) is much higher in the two Mukah soils (Fig. 2). Thus, the degradability may also vary among the alkyl components. Microbial activity could be another cause of the variation in the rate of SOC decomposition among the soil samples, although there is no information on this aspect.

The amount of CO_2 produced during incubation was higher in the SG1 soil than in SG2 soils (Table 3), although the order of the total C content was opposite (Table 1). These results could be attributed to higher soil pH and ash content (Table 1) as well as a higher % *O*-alkyl C (Table 2) in the SG1 soil than in the SG2 soil. Higher soil pH and ash content, suggesting a greater amount of inorganic nutrients in soil, could increase microbial activity in peat soils. These suppositions were supported by the positive correlation between soil pH or ash content and the amount of C mineralized per unit weight of soil C for the four soil samples ($r = 0.96$–0.97; $P < 0.05$).

Effects of soil neutralization, temperature increase, and solar irradiation on SOC decomposition

Different from the control or higher temperature treatment, the rate of CO_2 production in the neutral pH treatment of three SG soils increased during the initial period of incubation (Fig. 3). This pattern might reflect the transition of the soil microbial community (Frostegård et al., 1993; Zhang et al., 2017). However, the rate of CO_2 production during the initial period based on changes in the headspace CO_2 concentration may be underestimated because CO_2 dissolved into the soil solution under neutral conditions, and the following release of H^+ from the carbonic acid formed might have affected the CO_2 concentration in the headspace. Although the difference from the control treatment was not significant in the Mukah SG1 soil caused by the large deviation among the replicates, larger total C mineralization, including the result for the Talau forest soil, suggests that an increase in pH induced by liming stimulates microbial activity and accelerates peat decomposition/C emission (Table 3). When a US peat soil from a depth of 1.5–2 m was incubated at 15°C under anoxic conditions, an increase in soil pH from ambient (≤ 4.5) to 5.5 also tended to increase the rate of CO_2 production (Kluber et al., 2020). Although their result was not statistically significant, an increase in the bacterial 16S rRNA gene abundance and a change in the microbial community structure were observed simultaneously. A smaller increase in soil pH from 4.9 to 5.3 in a Finnish peat soil due to liming did not increase the CO_2 emission from SOM in upland field conditions (Biasi et al., 2008). The greater effect of pH elevation on the rate of CO_2 production in this study probably was due to the fact that the pH was raised to neutral. For example, phenol oxidase activities continuously increase with an increase in pH toward neutral (Kang et al., 2018), which may encourage the mineralization of the lignin- or tannin-derived SOM through their depolymerization.

The positive effect of high temperature on the rate of the mineralization of SOC was observed in all soil samples irrespective of land use type. Q_{10} values were estimated to be 1.6–2.1. Girkin et al. (2020) reported values similar to ours, 1.3–1.5, for Panamanian and Malaysian (peninsula) peat soils collected from forests and intercropping. The absence of a significant difference in total SOC mineralization between forests and intercropping in their study agrees with the present result for the Talau soils. A wider range of Q_{10}, 0.85–2.4, was reported for forest peat soils in Sarawak (not Talau) when the water content in the soil varied (Maie et al., 2019), although those values are among the smaller ones reported for peat soils (Hirano et al., 2009; Jauhiainen et al., 2014; Kim and Verma, 1992; McKenzie et al., 1998). However, as Q_{10} is affected by temperature ranges used for obtaining Q_{10} and soil water content (Hirano et al.,

2014; Moore and Dalva, 1993; Silvola et al., 1996; Maie et al., 2019), it is possible that the temperature effect on SOC mineralization in sago palm soils is larger in the field.

Although the absolute or relative increase in the amount of C mineralized during incubation due to neutralization did not correlate with any of the soil or SOC parameters, there was a positive correlation (r = 0.98; P < 0.05) between the increase in the amount of C mineralized in the high temperature treatment relative to that in the control treatment and the % carboxy C. Since the % carboxy C also correlated positively (r = 0.99; P < 0.005) and negatively (r = -0.96; P < 0.05) with the % aromatic C and C/N ratio, respectively, the higher % carboxy C may be associated with the progression of decomposition and humification of peat SOM. If some of the SOM were mineralized due to the increase in microbial activity or the transition of the microbial community under high temperature, similar correlations could have been observed with the other parameters. As an alternative interpretation, this interesting observation may show that high temperature incubation brought about the abiotic decarboxylation of SOM.

The proportion of C that was lost in the photodegradation experiment, 4–16%, was much greater than the rate of biodegradation of SOC in any treatment, even though the cumulative irradiation in the experiments is roughly equivalent to that for three weeks in average conditions in Sarawak. This indicates that photodegradation should not be ignored as one of the processes involved in the degradation of peat SOM in the surface layer without vegetation cover. Although changes in the SOM structure before and after irradiation were not so drastic, the decrease in % *O*-alkyl C suggested that the biodegradability of SOM could also be changed through photodegradation. Thus, further validation is required to assess the long-term impact of photodegradation on the C dynamics in the surface soil.

Conclusions

The present study suggests that sago palm cultivation affects the rate of decomposition of SOM in tropical peat soils, which is further influenced by soil management practices that increase pH, temperature, and solar radiation intensity. Through the incubation experiment, interesting relationships between the rate of SOC mineralization or its enhancement due to increased temperature and soil or SOC properties could be detected, although those should be confirmed using a larger number of soil samples. Photodegradation as a potential mechanism of C loss in the surface layer of peat soils was indicated for the first time.

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