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Soil characteristics and CO_2 emissions of ex-burnt peatland in Kubu Raya District, West Kalimantan, Indonesia

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Abstract. *Astiani D, Widiastuti T, Latifah S, Simatupang D. 2020. Soil characteristics and CO_2 emissions of ex-burnt peatland in Kubu Raya District, West Kalimantan, Indonesia. Biodiversitas 21: 3691-3698.* West Kalimantan, Indonesia has a large extent of tropical peatland with total 1.74 million ha with only 44.5% of such areas remaining as peat forest, while the rests have been converted into plantations, agricultural lands, and shrubs. The conversion of peat forest often uses fires to clear the vegetation and is followed by building canal to drain the water. The lack of vegetation combined with drought soil trigger uncontrolled escaped fire, especially in the dry season or El-Nino events, which is likely to affect soil characteristics and emit carbon dioxide. The purpose of this study is to examine the changes in soil characteristics both physical and chemical properties and to investigate CO_2 emissions from peat soil post-fire. As a comparison, similar parameters were also assessed in non-burnt sites. The results showed significant differences in some peat soil characters both physically and chemically between ex-burnt and non-burnt peatland. The ex-burnt site had higher pH, available phosphorus and C/N ratio than those in the non-burnt site. Conversely, the total nitrogen and carbon contents, and cation exchange capacity were lower which is likely due to leaching. Peat fires also impacted physical characteristics of the soil such as increasing soil bulk density, reducing soil water content, soil temperature, especially in wet conditions. Carbon dioxide emissions in the ex-burnt site were considered higher than non-burnt site. These results could be brought out as a part of baseline data in managing ex-burnt peatlands to maintain a balance between carbon output and input and efforts on preventing peatland fires from becoming continuous carbon sources.

Keywords: Carbon sources, CO_2 emissions, peatland fires, peat characteristics, tropical peatlands

INTRODUCTION

Tropical peatland is a wetland ecosystem that contributes to substantial carbon sinks and sequesters a relatively large amount of carbon (Page et al. 2011; Astiani et al. 2017a). Tropical peatlands are sensitive to changes in water system, especially in the Ombrogen peatland, where water and nutrient intake is only sourced from rainfall. As such, they are susceptible to drought and fire once they are deforested and drained, often so-called degraded peatlands.

Changes in vegetation cover and hydrological regimes have devastating impacts on tropical peatlands (Taufik et al. 2017). Hydrological conditions determine the respiration rate of these gases from the soil (Chimner and Ewel 2004) and the reduction in water levels caused by deforestation and drainage results in peatland drought (Chimner and Cooper 2003; Li et al. 2007). These conditions cause CO_2 emissions from peatlands due to the increased availability of oxygen moving towards unsaturated peat where more active oxygen transport is available and increased aerobic respiration (Astiani et al. 2018a: 2018b). In addition, a decrease in water table levels causes an impact on draining peat layers, especially on the surface which can trigger fires (Dohong 2003).

The impacts of deforestation and drainage on degraded peatlands are amplified by climate change in the form of global warming. Prominent effects of global warming on wetland ecosystems mainly through the reduced rainfall and the increase in temperature which can accelerate the reduction in water content in peat soils, especially in deforested and degraded peatland due to being converted to other land uses. Global warming can also increase the frequency and intensity of El Niño events, which are the conditions of long dry months with no rainfall. The El Niño phenomenon affects physical condition by creating reduction in water supply in the tropical peatland, which decreasing peatland forest input on water, carbon, and nutrient (Astiani 2017b,c; Sowerby 2008). If drought continues, this condition can make peatlands become permanently dry and is a potential source of fuel for severe fires when ignited (Bellamy et al. 2005). As such, to tackle these problems some modifications on hydrological regime through canal blocking and rewetting might be required to restore degraded peatlands (Kwon et al. 2013; Budiharta et al. 2014).

West Kalimantan has 1.74 million hectares of tropical peatlands. These areas are at risk to be degraded due to the decrease in water level caused by drainage development. Making drainage or canal is often carried out when opening peat forests in West Kalimantan for the purposes of small-scale agriculture and commercial plantations. The construction of drainage network is aimed to dry the top layer of peat in order to grow the desired commodity. However, changes in hydrological conditions on peatlands affect the condition of some of the physical and chemical properties of the soil in the long run, and make it worse as climate variations are increasingly frequent. These changes can trigger peat fires which have impacts on increasing CO_2 emissions.

Fires in peatlands impact land characteristics, especially the surface of the land (Astiani et al. 2018b). In addition to the changes in micro-bodies due to the burning process that affects the speed of CO_2 emissions, it is also necessary to study the impact of fire on some physical and chemical properties of peat soils as well as the emission activities from post-burnt peatlands and provide a basis for their post-fire management. The study aimed to examine the impact of fires on several peat soil properties in degraded tropical peatland in Kubu Raya District, West Kalimantan, Indonesia. The study also investigated the rate of CO_2 emissions from peatland after burning. The results of the research are expected to provide baseline information for the sustainable management of ex-burnt peatlands in the region.

MATERIALS AND METHODS

Study area and period

The study was carried out in an area of partly ex-burnt peatland in Kuala Dua village, Kubu Raya District (Figure 1). The study was conducted for 12 (twelve) months from January to December 2019.

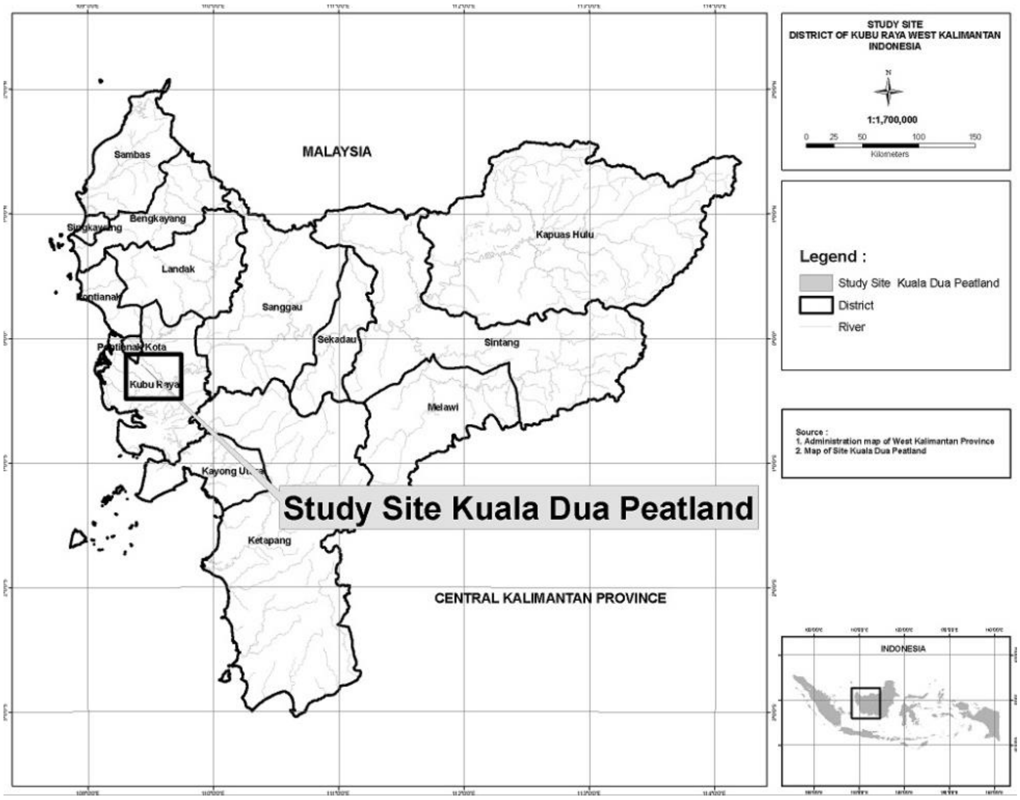


Figure 1. Map of the study area in an ex-burnt peatland in Kubu Raya District, West Kalimantan Province, Indonesia

Table 1. Description of research sites

Items	Description
Site coordinate	0º13' S and 109º 26 E
History of land use	Open peatland with small scale, traditional, mixed crop patches, with drainage canal and some part was ex-burnt and recently burnt areas
Peat depth	3.6-4.1 m
Peat sampling depth (cm)	0 - 40 cm
Mean water table of 2 years monitoring	74.2 ± 13.7
Water table at peat sampling in wet season (cm)	47.3 ± 2.3
Water table at peat sampling in dry season (cm)	88.2 ± 6.5
Mean rainfall y^{-1}	3227 mm ± 345 mm, without dry month, in 2015, 2018 impacted by ENSO with dry condition >3 months

Data collection

The study site was 3-5 months-burned peatland, which was affected by escaped fire from nearby agriculture practices. The fires impacted on the losses of peat layers in the average of 10.5 to 24.1 cm (Astiani et al. 2018b), less than the figure found by Ballhorn et al. (2009) with 30 cm depth. The prior management of the land was dominated by low input management of mixed farming owned by villages community. Vegetation succession post-fire was in the form of ferns and other shrubs, covering an area of 3-6 ha.

We collected samples of peat soils from the area in various environmental conditions especially groundwater level. For comparison, non-burnt soil samples were also inspected. The soil samples comparison was at similar 40 cm depths of each of ex-burnt and non-burnt sites. The tools used to collect soil samples were Russian Peat Borer and soil ring samplers. The measurement of CO_2 emissions used Licor-8100, which concomitantly measured soil temperature, volumetric water content, and humidity. Soil temperature was measured using gauges attached to the Licor. Solinst Levelogger was used to record water table levels. Except for CO_2 emission and microclimatic conditions which were measured twice a month for 12 months, all soil samplings were collected once at the beginning of soil emission measurement.

Peat sampling

Peat soils were purposively sampled to represent ex-burnt and non-burnt areas. Twenty-seven soil samples at 9 points were taken, three sample of each point and three sub-samples on each of the soil sample at a depth of 0-40 cm, were then be compiled into the 27 soil samples. At each sampling point, environmental conditions were measured. Soil samples were taken using a Russian peat borer by installing a peat swivel drill stem then connecting the extension rod. The soil samples were put into plastic bags and then labeled. The same method was repeated for as many soil samples as needed. The peat samples were then brought to soil laboratory at Tanjungpura University.

Carbon emissions assessment

The measurement of CO_2 emissions followed the method by Astiani et al. (2018a) in which emissions were obtained from the amount of CO_2 respiration from peat soils. CO_2 respiration data was then converted to the amount of CO_2 emissions in peatlands following Malhi et al. (2012) by separating the respiration activity of plant roots (autotroph respiration) from the peat decomposition process (heterotroph respiration, where the proportion of decomposition is ~ 48%). CO_2 respiration was measured using Licor 8100 Automated soil CO_2 flux system, using a 20 cm diameter collar made of PVC. CO_2 respiration from the soil was measured twice per month for dry and wet months so that the effect of the water on the peatlands can be ascertained. Based on preliminary measurement results, the average daily emission of CO_2 in tropical peat can be effectively represented by measurements of minimum daily CO_2 emission (6: 00-8: 00) and maximum (12: 00-14: 00) and then the results were averaged to obtain a value daily CO_2 emission.

Measurement of site conditions

Along with measurements of CO_2 respiration, several site environmental conditions were also recorded (i.e. soil surface moisture, ambient surface CO_2 concentration, groundwater vapor concentration, and soil temperature) on above soil surface (2-5 cm) on each point of soil sampling

Laboratory works and data analysis

Soil properties were analyzed at soil laboratory of Tanjungpura University to measure the organic C, pH, CEC, N and P contents, water content, and bulk density. Soil C, N, and P were determined using Spectrophotometer method. Soil pH was quantified from a 10 g soil sample placed within a beaker/flask with aquadest until 50 ml (for pH H_2O) and 50 ml KCl 1 M (for pH KCl) and then stirred for 30 minutes, and measured with calibrated pH meter. On both of ex-burnt and non-burnt sites, undisturbed soil samples were collected using the same corer for soil bulk density measurement. Soil samples were drained for 24 hours at ambient temperature, weighed for water holding capacity, oven-dried at 80^0C, and the dry weights were recorded. Soil bulk density was calculated using oven-dried mass per volume sample in g cm^{-1}.

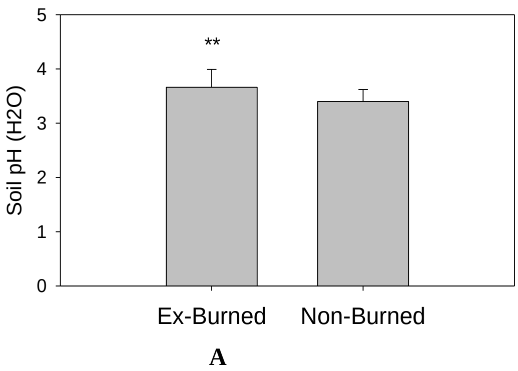
The estimation of soil CO_2 emissions and soil properties were presented as mean and SEs. The regression of CO_2 emission with continuous data available from site environment data, the figure, and statistical test of soil physicochemical properties were analyzed using SigmaPlot 12.3 version.

RESULTS AND DISCUSSION

Peat soil characteristics

Peat acidity (pH)

Peatland fires significantly increase soil pH ($P = <0.001$). This increase has an impact on accelerating peat weathering. In addition, the increase in the soil pH can affect physical, biological, and other chemical activities in peatlands. Changes in soil pH (H_2O) after fire increased by an average of 0.26 from 3.40 to 3.66 (Figure 2.A) while KCl pH increased from 2.7 to 3.0 (Figure 2.B). This significant increase in pH affects the solubility of existing nutrients. Increase in soil pH could be beneficial because it increases the solubility of some nutrients essential for the growth of vegetation after the fire, but on the other hand, the increase can accelerate the process of peat decomposition. An increase in pH can increase soil microbial activity and potential to increase peat decomposition (Moilanen et al. 2012).



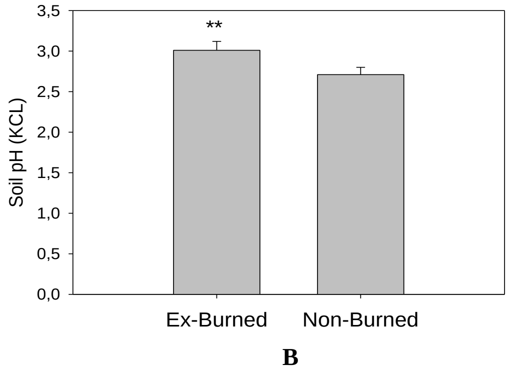


Figure 2. Soil acidity on ex-burnt and non-burnt areas: A. pH H_2O, and B. pH KCl. Columns with two stars symbol differ significantly at the 99% level of confidence

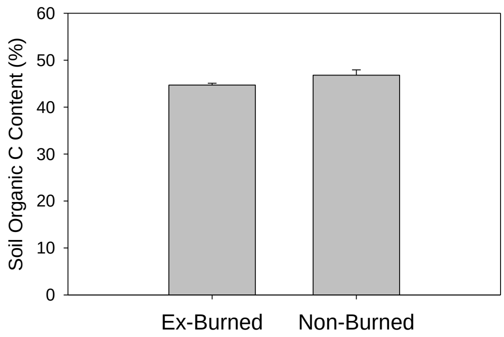


Figure 3. Soil organic C content (%) on ex-burnt and non-burnt peatland

Organic C content

Peat soils contain almost all organic matters, and for young peat classified as Tropofibrists, these can reach 98%. Among organic matters contained in peat soils is carbon. Peat fires can decompose organic C and change its shape from solid to CO_2 gas. Result shows that there is a significant reduction of the peat C on ex-burnt peat compared to non-burnt peat (Figure 3). The carbon content between non-burnt and ex-burnt was 46.8 ± 1.15 and 44.70 ± 0.38, respectively, meaning that there was a 2.1% decrease in organic C. Assuming that the carbon content of peat soil at 20 cm surface depth is around 117 tons C ha^{-1}, peat combustion due to fires could emit at least ~ 2.5 tons C or equivalent to 9 tons of CO_2 to the atmosphere. These results are in line with Astiani et al. (2018a).

Soil nitrogen

Total nitrogen content in peatlands is very important considering that some parts of peatlands in coastal areas and inland are less fertile Ombrogenous peat. This is due to limited nutrient sources that penetrate to the ecosystem which mostly through rainfall, or possibly from atmospheric deposition, peat surface and subsoil water flow (Kirk et al. 2015), symbiotic nitrogen fixation and nitrification, and other nitrogen transformation processes (Espenberg et al. 2018)

The natural N content in the studied area is relatively small to moderate in terms of soil fertility which was 1.83 ± 0.04%. Fire reduced significantly about 14% of the total N available ($P < 0.001$) (Figure 4.A). Fire reduced total Nitrogen after nine months of burning and the residual combustion on the surface of the peat was washed away.

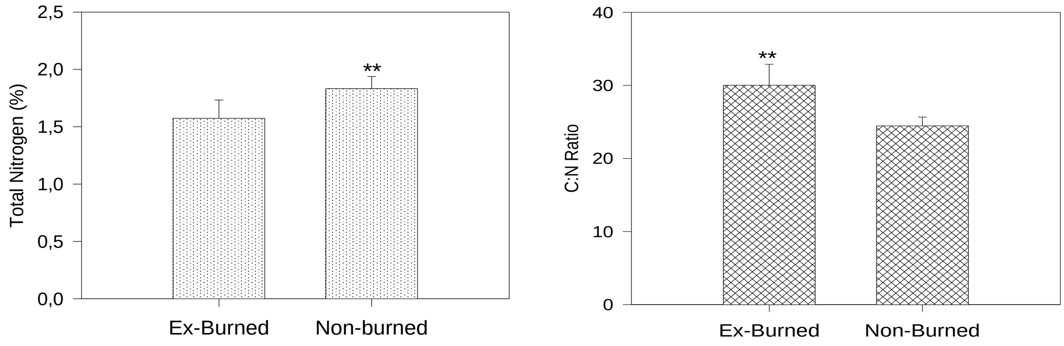
The loss of biomass during the burning peat is accompanied by volatilization of N, leaving remnants of biomass that are resistant in subsequent decomposition (Dikici and Yilmaz 2006). In degraded and burnt peatlands with lack of vegetation, the addition of elements C and N is low due to small amount of new litter, thus contributing to smaller N concentrations (Dikici and Yilmaz 2006; Takakai et al. 2006).

C/N ratio

Changes in carbon and nitrogen content after fire shifts the C/N ratio. The light decrease of C concentration and sharp decrease in nitrogen makes the ratio of C/N higher in the burnt area (Figure 4.B). The C/N ratio was higher by 23% after the occurrence of fires measured after 9 months. This result is also similar to van Beest (2019) which conducted similar analyses in peatland in temperate zone in Canada.

Available phosphorus

The addition of ash to peat surface during fires provides cation enrichment, but it will decrease after some time. However, from the results of this study, P concentrations were consistently available after 9 months of burning and were significantly higher than non-burnt (Figure 5). The mean available P (P_2O_5) in ex-burnt area (47 mg Kg^{-1}) is considered to be medium to high level in terms of soil fertility (Siswanto 2006). However, the concentration of P available for non-burnt was also high.



A **B**

Figure 4. A. Total Nitrogen content; B. Ratio C/N, on ex-burnt and non-burnt areas. Columns with two stars symbol differ significantly at the 99% level of confidence

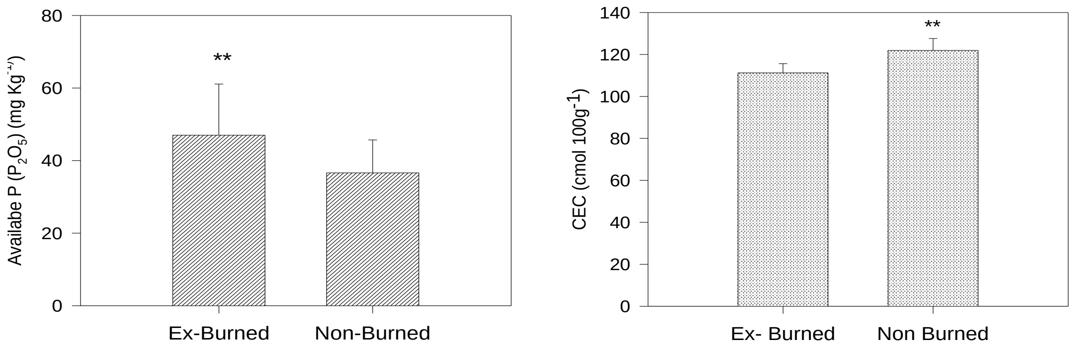


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Figure 5. A. Available phosphorus content; B.. Cation exchange capacity on ex-burnt and non-burnt areas. Columns with two stars symbol differ significantly at the 99% level of confidence.

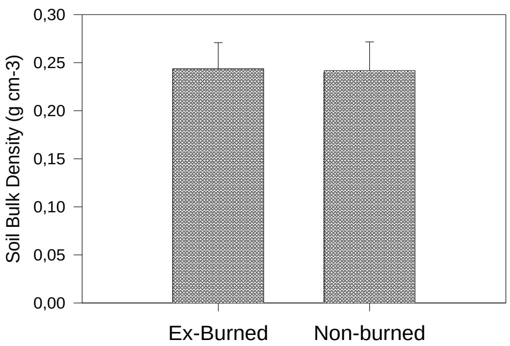


Figure 6. Peat soil bulk density on ex-burnt and non-burnt areas

Cation exchange capacity

Mean cation exchange capacity (CEC) was lower in ex-burnt peatland with 121.9 ± 1.9 meq 100g^{-1} compared to non-burnt with 111.2 ± 1.5 meq 100g^{-1}, suggesting average gap of 10 meq 100g^{-1} (Figure 7). Nonetheless, the CEC level of both ex-burnt and non-burnt were very high. Tropical peatlands in Indonesia usually have low fertility due to the very low mineral and other base ions content and availability. Immediately after fire, some of the remaining burned minerals are exposed and in an unstable position, because the roots of vegetation are absent or do not actively absorb through the mass flow, one of the mechanisms of nutrient uptake by plants. This condition causes some nutrients to be washed quickly by rainwater.

Soil bulk density

In general, after a fire, peat mass density usually increases, but the measurement results showed there is no significant difference between ex-burnt and non-burnt peatland with 0.242 and 0.244 g cm^{-3}, respectively (Figure 6).

Soil water content

Soil water content in peat is strongly related to water level. Therefore, the measurement of water contents was assessed in two different groundwater table conditions, both in the rainy and dry seasons. The average water content in the rainy season was higher than the dry season due to the relatively different groundwater table effects (See Table 1). Mean water content in the wet season in ex-burnt area was 416.8% ± 24.5%, higher ~ 57% compared to the dry season in the same area. The difference is relatively similar in non-burnt areas (Figure 7.A-B).

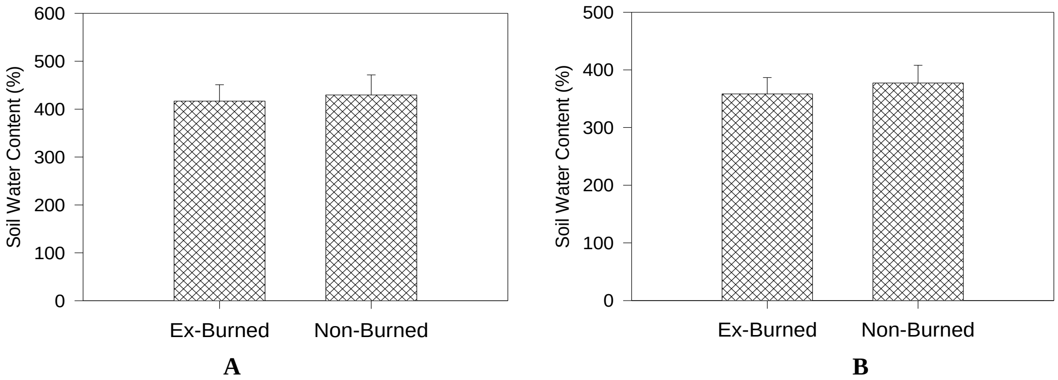


Figure 7. Water content (dry weight base): A. During wet season; B. During dry season

The condition of water content in ex-burnt and non-burnt areas did not differ significantly. This can be interpreted that the ability of peat material after burning to store water is not affected by fire events, suggesting that it has good properties in holding water, except in conditions where peat is exposed and permanently dry. The content of organic matter in peat is relatively very high and in condition of hemic to sapric peat both in the upper layer and in the lower layer exposed to fire, it shows the ability to hold significant amount of water.

The water content has a large effect on other physical characteristics of peat. High water level makes the soil soft and causes soil carrying capacity to be low. Low water levels (caused by drainage, and other natural factors) can cause a decrease in water content which in turn causes the volume of peat to shrink and subsidence. Subsidence can also be caused by decomposition and erosion.

Soil moisture and temperature

Peat soil moisture and temperature varies greatly depending on the condition of water table level and soil water content throughout the year. In this study, soil moisture and temperature were measured only in the burnt area but measured when wet and dry. The average water content in the wet conditions was 86.4 ± 1.0 and in the dry conditions was 70.4 ± 0.599% (Figure 8.A). The average soil temperature in the ex-burnt area when dry was 29.1 ± 0.1 and when wet was 30.4 ± 0.4ºC (Figure 8.B). Water is a poor heat conductor, however, when the temperature of water is high, it may absorb heat and could warm its surrounding (Davidson and Janssens 2006).

CO_2 emissions in ex-burnt area

The mean CO_2 emissions in burnt peatland were significantly higher than those in non-burnt area (Figure 9). Carbon dioxide emissions in the burnt area showed a significant magnitude at a rate of 60.2 ± 4.3 tons ha^{-1} yr^{-1} while in non-burnt sites was 52.8 ± 5.4 tons ha^{-1} yr^{-1}). The magnitude of these emissions is much higher compared to forests nearby the location. For comparison, peat soil emitted 17.4 tons ha^{-1} yr^{-1} in less disturbed forests and 38.9 ± 1.8 tons ha^{-1} yr^{-1} in forests that have been affected by lowering water table due to the surrounding development activities (Astiani et al. 2018b).

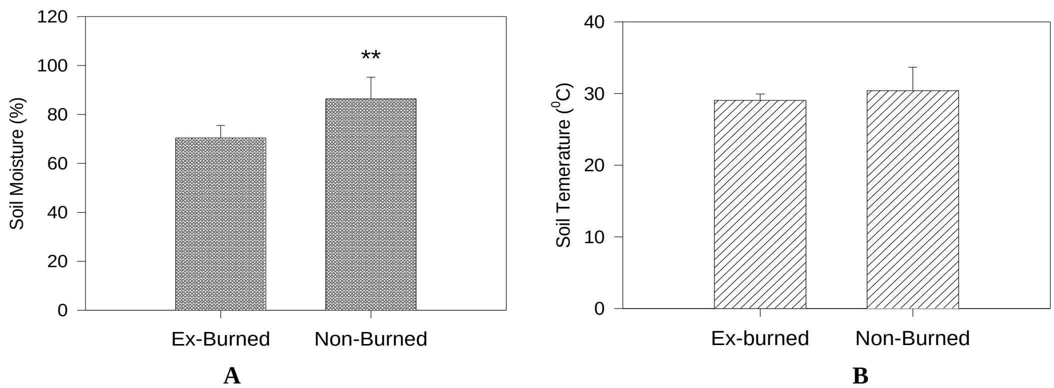


Figure 8. A. Soil moisture; B. Soil temperature, on ex-burnt and non-burnt sites

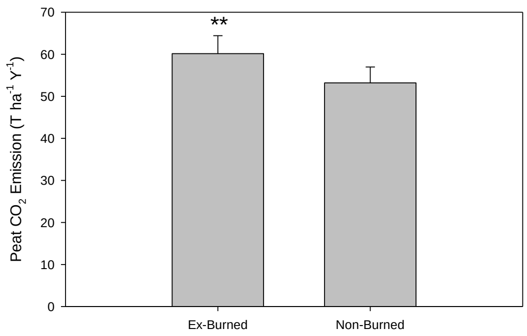


Figure 9. CO_2 emissions in ex-burnt and non-burnt peatland

However, CO_2 emissions changed dramatically throughout the year and fluctuated irrespective of environmental conditions (Figure 10.A). Multivariate Linear Regression shows that in the ex-burnt sites, water table level (WTL cm), water content (WC %), and surface soil temperature (T ^{0}C) significantly affected soil CO_2 emission on this open peatland. The resulted regression equation is as follows:

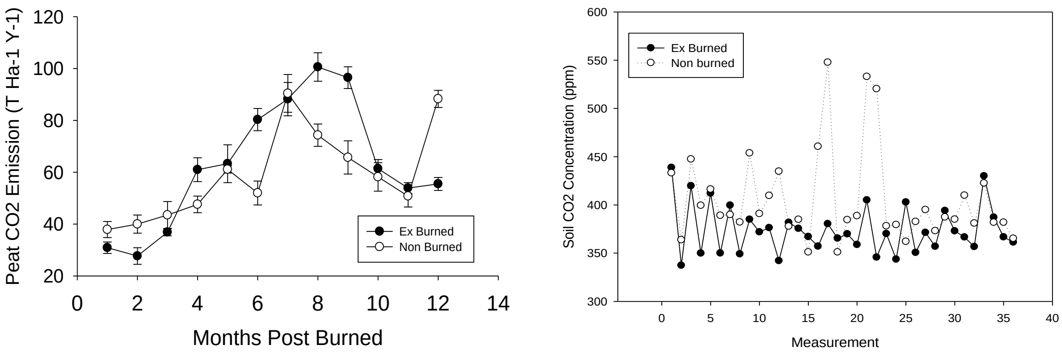
CO_2 Emissions = 0.918 + (0.110 * WTL)-(0.141 * Water Content) + (0,105 * Soil T);

Where: n = 1624 r = 0.768; r^2 = 0.590; Adj r^2 = 0.583; p<0.001).

This finding is supported by Melling et al. (2013) that several factors that control soil CO_2 emissions are soil moisture, surface soil temperature, and bulk density which influence the biochemical and microbial processes in respective ecosystems. Our results show that peatland CO_2 emission increased linearly 3.3 times in the 8-9 months after the fire and then declined again dramatically after nine months (Figure 10.A). The monthly mean of CO_2 emission (heterotroph) on ex-burned site was higher than that in non-burnt site. Conversely, the CO_2 concentration of peat surface in non-burnt peatland was significantly higher than that in ex-burnt (405.5 ± 7.9 vs 375.2 ± 4.2 ppm) (P <0.001) (Figure 10.B). This higher concentration of CO_2 on peat surface is likely caused by root respiration.

The result of this study demonstrated that carbon dioxide emissions were detected in well-exposed and degraded peatland, but emissions in burnt peatland were higher than those in non-burnt sites, strengthening the findings of previous studies (Limpens et al. 2008; Page et al. 2004). Nonetheless, we found that fire and biomass loss affected the physical and chemical properties of peat soils on the surface. Some of the processes that take place include the peat that was formed earlier and located in the lower layer appeared on the surface since the upper layer which was formed later had been burnt, providing opportunity for substrate material that should only be found in the deeper layers of the peat.

In addition, some peat characters were shifted during combustion and some nutrients that dissolve easily in peat were washed away. This can occur if the litterfall of the remaining vegetation cover on burnt peatland does not increase rapidly compared to that lost due to leaching. The addition of ash onto peat surface during fires provides enrichment of cations (Ca, Mg, Mn, Fe, Na, and Zn) in burnt areas (Hirano et al. 2014). Similar results were conveyed by Dikici and Yilmaz (2006) and they also stated that organic carbon and total nitrogen in the remaining peat decreased and peat pH increased. In contrast to what Hirano et al. (2014) found that mineral nutrition and peat bulk density increased, the results of this study showed that after nine months after burning, organic carbon and total nitrogen decreased but not for available phosphorus. This is understandable as the effects of combustion on the subsurface environment may vary, depending on the frequency of fire and the severity of the fire (Arief et al. 2019).



A B

Figure 10. A. CO_2 emissions in ex-burnt and non-burnt sites during 12 months; B. CO_2 concentrations on peat surface in ex-burnt and non-burnt sites

In conclusion, this study indicates that peat fires significantly changed the physical and chemical properties of peat soil over a long period of time. Peat fires impacted peat fertility, including lowering total nitrogen and carbon content, and the cation exchange capacity, while in contrast increasing soil acidity, available phosphorus and C/N ratio. Peat fires also impacted physical characteristics of the soil such as increasing soil mass density, reducing soil water content, soil temperature, especially in wet conditions. Emissions from burning peatlands were considered higher than non-burnt sites, both in the wet rainy season and in dry season.

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