Evaluation of change in the peat soil properties affected by different fire severities

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Abstract

Tropical peatland ecosystems of Indonesia provide direct economic benefits to the local communities and act to maintain the local weather patterns. The impact of burning tropical peat swamp forests of land clearing for palm oil plantations can have significant consequences on the change in the characteristics of peat soil. The aim of this study was to determine the physical, chemical, and biological properties of the peat soils by the field and laboratory testing and analysis for understanding a change in the nature and characteristics of the peatlands at four locations in the Pelalawan regency of Riau province. The results showed that the effect of burning peat swamp forests can lead to a change in the physical, chemical, and biological properties of the peat soils. Soil permeability and soil microbial population can significantly decrease with increasing of the fire severity. The effect of different fire severities on the characteristics of peat soil are verified to contribute to advanced management of the tropical peatland in the future.

1. Introduction

Even though the Riau province of Indonesia has an extensive forest resource of peatlands, the management of such potential natural resource as the lifeblood of tropical region has not been optimally carried out to satisfy the human needs. Peatland has a particular value in term of species and needs to be managed with the principles of multiple uses to receive a fair share of the benefits for many people. Digital mapping of the tropical peatlands of Bengkalis Island has been proposed using the electrical resistivity tomography to determine peat layer thickness (Illés et al. 2019). Sadly, many peatlands are threatened by the human activities for the development of the plantation areas. The Pelalawan regency of Riau province has been considered as the prone area of forest and land fire and was the area affected most by fire for the year 2015 (Field et al. 2016). Peat swamp forest fires at the Kerinci Barat village of Pangkalan Kerinci district, the Langgam village of Langgam district, and the Pangkalan Gondai village of Langgam district located in the Pelalawan regency are the causes of environmental destruction. The effect of peatland fires on people, property, and the environment has been considered to affect almost all aspects of social life and economic development in the Riau province and its surrounding regions (Saharjo and Yungan 2018). Approximately 1.83 million hectares of the peatlands to be equal to approximately 57% of the total peatlands in Indonesia have been converted to non-forest purposes during three decades from 1982 to 2007 (Saputra 2019).

Peatlands are the features of areas commonly located in the tropical countries with a very low topographic relief. Peat soils in the Pelalawan regency of Riau province and other regions of Indonesia are suitable for growth of many special crops that require an acid reaction but have a vulnerability to fire. It can have a great difficulty in extinguishing flames when the large areas of such peat swamp forests have been burned to increase the conversion of peatlands into other land uses and therefore needs to involve the participation of stakeholders in the management of swamp forest, peatland, and water in the whole country (Fulazzaky 2017). Even though the peat swamp forest fires may affect people and the environment in many ways, this study has focused on the assessment of the impacts of low, moderate, and high severity of the peat swamp forest fires on the physical, chemical, and biological properties of the peat soils. Fire effects can alter the soil nature and pace of the environmental change (Elmes et al. 2019), potentially allowing certain organisms to adapt quickly with a new terrestrial environment. The area of peatland affected by tidal of fluctuated water level causing an alternating dry and wet peat can affect the salinity and dissolved organic carbon of the peat soil (Qu et al. 2019). The quality of water from a river flowing through the area of peatland to a sink of most water chemical elements may influence the characteristics of peat soil (Lundin et al. 2017). Certain native tree species are still suitable for the reforestation of degraded tropical peatland after a fire (Lampela et al. 2017). A change in the physical properties of peat soil can be verified through the measurements of water content (WC), water binding capacity (WBC), total porosity (TP), bulk density (BD), particle density (PD), and soil permeability (SP). Oven drying of peat soil at different temperatures showing WC of the low temperature peat soil is higher than that of the high temperature ranged from 100°C to 110°C (O'Kelly and Sivakumar 2014). The values of WBC, TP, BD, and PD for a peat soil depend on the relation between organic and inorganic constituents (Walczak et al. 2002). The yields of total organic carbon per year in the Riau province have been estimated at a small catchment area of 4.8 km^2 for artificial flowing watercourse within the Meranti Ditch basin ranged from 41.6 to 55.5 g C/m^2 and at a relatively large catchment area of 458 km^2 for natural flowing watercourse within the Turip River basin ranged from 26.2 to 34.9 g C/m^2 (Yupi et al. 2016). An addition of the water-reducing admixtures was able to reduce SP of stabilized soil in the area of natural peatland (Wong et al. 2008). A change in the chemical properties of peat soil can be verified through the measurements of pH, redox potential (Eh), and electrical conductivity (EC) while a change in the biological properties of peat soil can be verified by measuring the soil microbial population (SMP). Liming to a recommended pH value of the peat soil is important to maintain the quality of soil and reduces the risks of degradation and desertification, allowing to increase the potential productivity of soil, to improve the soil structure, and to gain the benefit peatland biodiversity (Goulding 2016). Eh of peat soil beneath the surface of the Earth throughout the 30–100 cm profile varies with season and depth while the average Eh value over whole profile for a peat soil during wet season is lower than that during dry season (Niedermeier and Robinson 2007; Urquhart and Gore 1973). A clay soil at the given values of WC, BD, and peat content exhibits a greater EC value than clay loam or sandy loam soil (Ekwue and Bartholomew 2011). Pore dilation of peat soil may occur due to the presence of NaCl in the soil pore space can react with organic functional groups (Comas and Slater 2004). Biological properties of peat soil related to enzymatic and biological potential for the mineralization of organic compounds are dependent on pH, WC, and organic matter content (Bobuľská et al. 2015).

The formation of the ash particles through the minerals transformation during the peatland burnout can reduce the value of WC due the presence of ash deposited on the peat surface tends to fill the pore spaces of peat soil to lower the porosity of peatland and disturbs the storage process of groundwater (Walczak et al. 2002). Chemical reactivity of ash produced during the burning of peatland denotes that the materials having the functional groups tend to form the adhesive bonds by dusty microparticles through sharing of electrons to prevent the penetration of soil particles into its voids (Sutton and Sposito 2005). The presence of the ash particles in peat soil can reduce the macropore space to impede the infiltration of water (Sepehrnia et al. 2017). The production of hydrophobic biochar after a fire has an applied force of positive water entry pressure during the rain infiltration into a semi-infinite soil column and enters the intrapores of peat soil (Liu et al. 2017; Talbot and Ogden 2008). The laboratory experiments showed that the physical property of PD for the intact soil cores collected in the field can increase with increasing of the soil temperature due to the percentage of soil organic matter reduces in proportion to fire severity (Wieting et al. 2017). A complex porous medium of peat soil with high content of organic matter can maintain the permeability of peat soil (Rezanezhad et al. 2016). In spite of the pH value of peat soil is increasing slightly with increasing of the soil temperature, the surface and subsurface soil layers can significantly reduce the carbon content during wildfire (Fernández et al. 1997). A high severity of the forest fires can significantly increase the pH of the Haplic Luvisol soils in Central Europe and alters the adsorption of anions and cations in the soils (Bridges et al. 2019). The results of experimental and modeling study showed that thermal conductivity of fire-heated soil is slightly lower than that of unburned soil (Smits et al. 2016). An investigation of the spatial distribution of soil microbes along the latitude gradient across New South Wales of Australia showed that the environmental factor of soil temperature has a lesser impact on the SMP value of soil (Xue et al. 2018). Even though many studies in the areas of peat soil have been carried out to assess the negative effects of peatland fire on human and the environment, the effect of different fire severities, which are classified by the burned peatland area covered during a fire, on the changes in the physical, chemical, and biological properties of the peat soil needs to be verified. The limitations of this study related to different levels of fire severity that influenced the characteristics of tropical peat soil may provide an insight on the importance of environmental protection strategies for sustainable development.

The objectives of this study are: (1) to define and classify the different severities of swamp forest fire that had occurred in the Pelalawan regency of Riau province at four locations, (2) to identify the physical, chemical, and biological properties of WC, WBC, TP, BD, PD, SP, pH, Eh, EC, SMP as the indicators of change in the nature and characteristics of the peat soils, and (3) to analyze the nature and characteristics of the peat soils change after a fire with different severities at four peatland locations of Kerinci Timur, Kerinci Barat, Langgam, and Pangkalan Gondai villages in the Pelalawan regency.

2. Materials And Methods

2.1. Sampling location of the peat soil

Four locations of peatland in the Pelalawan regency of Riau province were selected to investigate the impact of different fire severities on the physical, chemical, and biological properties of the peat soils (see Fig. 1). Kerinci Timur village in the Pangkalan Kerinci district was selected to represent an unburned peatland. The selection of Kerinci Barat village in the Pangkalan Kerinci district was to represent a burned peatland with low fire severity. Langgam village in the Langgam district was considered to represent a burned peatland with moderate fire severity. The consideration of Pangkalan Gondai village in the Langgam district was to represent a burned peatland with high fire severity. The Pelalawan regency of

Riau province with coordinates 0º16’00”N and 101º10’01”E was considered to be one of the most important disturbance regions in Indonesia since it has experienced a great peat swamp forest fire disaster with different fire severities during one year affecting the nature and properties of the peat soils. The selection of these four locations was aimed to represent the ranges of the physical, chemical, and biological parameters affected by different fire severities. These locations were considered appropriate for assessing the vulnerability of peatlands responded to different levels of fire disturbances related to a change in the soil properties of originally considered similar nature. A change in the physical, chemical, and biological properties of the peat soils affected by soil temperature could be dependent on the severity of peat swamp forest fire. A quantitative definition of fire severity classification includes the size of burned swamp forest area, portion of burned peat swamp forest, soil sampling point surrounded by the heterogeneous trees species, and depth of peat soil affected by fire. The sampling locations of peat soil were selected four locations of peatland at different villages in the Pelalawan regency that had ever fire in 2015. This aims to ensure that the natural variations associated with the physical, chemical, and biological properties of the peat soils are almost the same in terms of their mean values. The maturity level of peat at depth of 4–7 m is actually a peatland category between milk and cheesecloth (Hooijer et al. 2012; Sulaeman et al. 2018). Although several sampling approaches have been proposed for collecting the representative soil samples, this study used the Purposive Sampling Method of non-probability sample (Zhu et al. 2008) to collect the peat soil samples from a depth of 50 cm is due to the impact of soil temperature caused by a peat swamp forest fire can reach a depth of 100 cm below the ground surface (Leng et al. 2019). The limitation of sampling depth at 50 cm can avoid a misinterpretation of data accounted effect of soil temperature on the level of change in peat soil properties at different depths. The soil samples at four locations of the Kerinci Timur, Kerinci Barat, Langgam and Pangkalan Gondai villages were taken out of the peat soils each month from May 16, 2018 to August 25, 2018. The measurements of physical, chemical, and biological properties of peat soil were performed for the soil samples collected from three contiguous peat soil sites of every sampling point at each location of the peatland for both the purposes of field and laboratory tests. The average value of each parameter was used to analyze the effects of peat swamp forest fire on the physical, chemical, and biological properties of the peat soils.

2.2. Classification of the peat swamp forest fire severity

The classification of peat swamp forest fire severity was based on the observation of peatland area burned a limited size of 10 hectares during dry season. Hierarchical object-based image analysis approach has been used to classify the active fire and burned areas (Atwood et al. 2016). The burned-over area of peatland was focused on the peat swamp forests dominated by heterogeneous trees species and bounded by the natural creeks in reducing the spread and intensity of the wildfire. The post fire soil characteristic change of peatland was determined at 50-cm depth for predicting a depth of heat penetration into the peat soil beneath a spreading fire. The burned peatland area of less than 20% was classified as low severity of peat swamp forest fire. The burned peatland area in the range of 20 to 40% was classified as moderate severity of peat swamp forest fire. The burned peatland area of greater than

40% was classified as high severity of peat swamp forest fire. The locations of peat soil chosen for sampling were in the burned peatland areas surrounded by different classifications according to their fire severities in gaining a better understanding of the impacts of fire on the physical, chemical, and biological properties of the peat soils in tropical peat swamp forest ecosystem.

2.3. Measurement of the physical properties of peat soil

A part of the experiments was conducted at the Soil Laboratory of the Faculty of Agriculture, Universitas Riau. Each physical property of the peat soil samples was measured in triplo per measurement for every location of the peatland. The moisture content of peat soil was measured using the gravimetric method (Reynolds 1970). Approximately 100 g of fresh peat soil sample was weighed using the analytical balance (KERN ABJ 220-4NM Electronic Digital Balance, Tovatech, Kern & Sohn GmbH, Ebingen, Germany), then dried in the drying oven (ThermoFisher Scientific, Massachusetts, United States) at 105^{o}C until all water loss, and then reweighed again. The WC value in peat soil (in %) is expressed as the mass of water lost on drying to the oven-dry mass of the peat soil.

The capacity of water binding in peat soil was measured by centrifuging the peat soil due to a large part of the impurities did not remain in the supernatant (Chen et al. 1984). Many methods of measuring the WCB value have been proposed to quantify the tendency of water associated with hydrophilic substances of peat soil (Trout 1988). In this work, 100 g of peat soil sample was placed in a perforated box and then centrifuged in a centrifuge (Aiyi Mini Mx17-A, Hunan, China) at the speed of 1000 rpm and then weighed again to determine the WBC of peat soil. The WBC of peat soil referred to the ability of soil to retain water within its matrix can be expressed as the mass of water absorbed per mass of centrifuged peat soil sample in percentage.

The measurement of TP value aimed to determine the percentage of void space in peat soil could be expressed as fraction of the volume of voids over the total volume. The method used to determine the TP value was based on the extraction of water and air from 100 cm^3 of peat soil by heating in drying oven at 105^{o}C and vacuum drying (Horton et al. 1988). The TP of peat soil referred to the fraction of the total peat soil volume taken up by the pore space can be expressed as the volume of pore space per volume of the peat soil in percentage.

The BD value of peat soil inversely related to its TP value could be greatly dependent on the minerals made up of peat soil and the degree of compaction. The methods of measuring the BD value of soil can be categorized into (1) direct methods: core, clod, and excavation sampling and (2) indirect methods: radiation and regression analysis (Al-Shammary et al. 2018). For the purpose of this work, 100 cm^3 of peat soil sample was taken from each sampling location by driving the metal core into the earth at a depth of 50 cm. Then each peat soil sample was oven dried and then weighed to calculate the BD value in mass of oven dry soil (in g) per volume of the peat soil (in cm^3).

The measurement of PD value for each peat soil sample was carried out using the volume replacement method (Ma et al. 2014). The peat soil sample was completely dried and then put into the graduated cylinder up to 100 cm^3. The graduated cylinder was filled up with water to replace the air-filled volume. The replaced volume was computed from the volume of water used to fill the graduated cylinder (Ma et al. 2014). The PD of peat soil can be expressed as the mass of particles (in g) per volume of the dried peat soil (in cm^3).

The permeability of peat soil was measured in term of the infiltration rate of water (in cm/h) to enter into the peat soil for a given period of time at four locations of Kerinci Timur village, Kerinci Barat village, Langgam village, and Pangkalan Gondai village. The measurements of infiltration rate at every location were carried out in triplo using the double-ring infiltrometer (Arriaga et al. 2010; Fulazzaky et al. 2014). A double-ring infiltrometer of 30-cm inner ring and 53-cm outer ring that has 6 cm of insertion depth and 10 cm of ponded water depth was used to measure the decreasing of water level for determining the SP value (Fulazzaky et al. 2014). The decreasing of water level in the inner ring was observed over time while approximately the same level of a puddle of water was maintained in the outer ring to reduce the amount of lateral flow from the inner ring.

2.4. Measurement of the chemical and biological properties of peat soil

The chemical properties of peat soil were analyzed based on the values of pH, Eh, and EC at the appropriate sampling location of peatland affected by different fire severities. Each chemical property of the peat soil samples was measured using the correct type of measuring equipment with each measurement repeated three times at the measuring point referenced in the field. The pH of peat soil was directly measured at each designated peatland using the pH meter (pH Portable Meter - HI99121). The electrical measurement of Eh shows a tendency of the peat soil environment to oxidize or reduce substrates (Fiedler et al. 2007). The measurement of Eh for peat soil was carried out using the soil redox potential meter (ORP Oakton Waterproof ORP Tester, Cole-Parmer, Eaton Socon, UK) at the appropriate location of peatland affected by different fire severities. The EC value of peat soil expressed in the unit of milliSiemens per meter (mS/m) is the ability of peatland to transmit an electrical current (Noborio et al. 1994). The measurement of EC value for each peat soil was carried out using an electronic instrument of the Time Domain Reflectometer (KE2100 Time Domain Reflectometer, Yokogawa, Japan). The biological property of peat soil was analyzed based on the measurement of SMP value in term of the colony-forming unit (CFU) value for the peat soil sample affected by different fire severities (Bevivino et al. 2014). The CFU value is a measure of the viable bacterial or fungal cells and only measures the viable cells to gain better understanding of the impact of burning on the biological properties of the peat soil. The measurement of SMP value was carried out in triplo for every measuring point. The value of SMP in term of the CFU per milliliter was calculated using the Miles-Misra plating technique (Guo et al. 2017).

3. Results

3.1. Physical properties of the peat soil

3.1.1. Water content

The water content of a soil may range from completely dry to a saturated condition and is the quantity of water it contains. In this work, the WC value was used as one of the physical parameters of soil to assess the physical properties of peat soil in the Riau province of Indonesia. The results (Table 1) of gravimetric analysis show that the highest WC value of 296.6% was found for a peat soil located in the natural peat swamp forest at the Kerinci Timur village. A decrease in the WC value of peat soil from 288.3% at the Kerinci Barat village to 280.2% at the Langgam village and then to 273.9% at the Pangkalan Gondai village could be due to the fire severity increases from the burned peatland area of less than 20% with low fire severity to the burned peatland area ranged from 20 to 40% with moderate fire severity and then to the larger than 40% of burned peatland area with high fire severity.

Table 1
Physical properties of peat soil at different locations

Location	FS	WC (%)	WBC (%)	TP (%)	BD (g/cm^3)	PD (g/cm^3)	SP (cm/h)
Kerinci Timur	No fire	296.6 ± 14.8	208.7 ± 10.4	85.82 ± 4.25	0.20 ± 0.01	1.36 ± 0.07	19.43 ± 0.97
Kerinci Barat	Low	288.3 ± 14.4	187.3 ± 9.5	85.80 ± 4.22	0.21 ± 0.01	1.38 ± 0.07	8.13 ± 0.41
Langgam	Moderate	280.2 ± 13.9	177.1 ± 8.8	84.24 ± 4.19	0.22 ± 0.01	1.39 ± 0.07	4.10 ± 0.21
Pangkalan Gondai	High	273.9 ± 13.6	164.8 ± 8.2	83.70 ± 4.08	0.23 ± 0.01	1.52 ± 0.08	2.40 ± 0.12

Noted that FS is the fire severity, WC is the water content (in %), WBC is the water binding capacity (in mV), TP is the total porosity (in %), BD is the bulk density (in g/cm^3), PD is the particle density (in g/cm^3) and SP is the soil permeability (in cm/h).

3.1.2. Water binding capacity

The results (Table 1) of centrifuge testing show that the highest WBC value of 208.7% was verified for the peatland of natural forest located at the Kerinci Timur village. A decrease in the WBC value of peat soil from 187.3% at the Kerinci Barat village to 177.1% at the Langgam village and to 164.8% at the Pangkalan Gondai village could be due to the level of burning in peatland forest increases from low severity to moderate and then to high severity of the peat swamp forest fire.

3.1.3. Total porosity

The results (Table 1) of measuring the pore space of peat soil show that the highest TP value of 85.82% was verified for the natural swamp forest of peat soil located at the Kerinci Timur village. The TP value of peat soil in the burned peatland slightly decreases from 85.80% at the Kerinci Barat village to 84.24% at the Langgam village and then to 83.70% at the Pangkalan Gondai village due to the peat swamp forest fire severity increases from the burned peatland area of less than 20% to burned peatland area in the range of 20 to 40% and then to burned peatland area of larger than 40%.

3.2.4. Bulk density

The BD value is used as an indicator to assess the soil compaction and soil health of the peatland. The results (Table 1) of BD measurement show that the lowest BD value of 0.20 g/cm^3 is at the peatland of natural swamp forest located at the Kerinci Timur village. An increase in the BD value of peat soil from 0.21 g/cm^3 at the Kerinci Barat village to 0.22 g/cm^3 at the Langgam village and then to 0.23 g/cm^3 at the Pangkalan Gondai village could be due to an increase in the burned peatland from less than 20% of the swamp forest area with low fire severity to a swamp forest area in the range of 20 to 40% with moderate fire severity and then to a swamp forest area of more than 40% with high fire severity.

3.2.5. Particle density

The PD value is used to describe state of the physical system of peat soil and this measures the mass of peat soil sample in a given volume of particles. The results (Table 1) of PD determination show that the lowest PD value of 1.36 g/cm^3 was verified for the natural peatland located at the Kerinci Timur village. An increase in the PD value of peat soil from 1.38 g/cm^3 at the Kerinci Barat village to 1.39 g/cm^3 at the Langgam village and then to 1.52 g/cm^3 at the Pangkalan Gondai village could be due to the fire severity of burned peatland increases from low to moderate and then to high severity relying on the less than 20% of burned forest area to burned forest area in the range of 20 to 40% and then to burned forest area of larger than 40%, respectively.

3.1.6. Soil permeability

The SP value is used to define the property of soil to transmit water and air passing through the pore spaces by the pressure gradient force and is one of the soil physical properties for the assessment of peatland quality affected by fire. The results (Table 1) of SP measurement show that the very high SP value of 19.43 cm/h is at Kerinci Timur village for the unburned peatlands of natural swamp forest. A decrease in the SP value of peat soil from 8.13 cm/h at the Kerinci Barat village to 4.10 cm/h at the Langgam village and then to 2.40 cm/h at the Pangkalan Gondai village is due to the increasing of burned peatland from a swamp forest area of less than 20% with low fire severity to a swamp forest area in the range of 20 to 40% with moderate fire severity and then to a swamp forest area of larger than 40% with high fire severity.

3.2. Chemical properties of the peat soil

3.2.1. pH

The results (Table 2) show that the lowest pH value of 4.11 for peat soil is at the Kerinci Timur village for the unburned peatland of natural swamp forest. An increase in the pH value of peat soil from 4.23 at the Kerinci Barat village to 4.34 at the Langgam village and then to 4.37 at the Pangkalan Gondai village could be due to the peat swamp forest has burnt once to get verified from a burned peatland of less than

20% with low fire severity to that in the range of 20 to 40% with moderate fire severity and then to that of larger than 40% with high fire severity.

Table 2
Chemical and biological properties of peat soil at different locations

Location	FS	pH	Eh (mV)	EC (mS/m)	SMP (CFU/mL)
Kerinci Timur	No fire	4.11 ± 0.21	195.6 ± 9.78	86.9 ± 4.3	$12.64x10^8 \pm 0.63x10^8$
Kerinci Barat	Low	4.23 ± 0.22	175.6 ± 8.78	106.1 ± 5.2	$8.53x10^8 \pm 0.43x10^8$
Langgam	Moderate	4.34 ± 0.22	167.0 ± 8.34	109.6 ± 5.5	$3.63x10^8 \pm 0.18x10^8$
Pangkalan Gondai	High	4.37 ± 0.23	165.0 ± 8.22	118.6 ± 7.1	$1.86x10^8 \pm 0.09x10^8$

Noted that FS is the fire severity, Eh is the redox potential (in mV), EC is the electrical conductivity (in mS/m), and SMP is the soil microbial population (in CFU/mL).

3.2.2. Redox potential

Table 2 shows that the highest Eh value of 195.6 mV is at the Kerinci Timur village for the unburned peatland of natural swamp forest. A decrease in the Eh value of peat soil from 175.6 mV at the Kerinci Barat village to 167.0 mV at the Langgam village and then to 165.0 mV at the Pangkalan Gondai village could be due to an increase of the peatland burnt from less than 20% of the swamp forest area with low fire severity to swamp forest area in the range of 20 to 40% with moderate fire severity and then to larger than 40% of the swamp forest area with high fire severity.

3.2.3. Electrical conductivity

The EC value expressed in the unit of milliSiemens per meter (mS/m) is the ability of peat soil to transmit an electrical current. Empirical evidence (Table 2) shows that the lowest EC value of 86.9 mS/m is at the Kerinci Timur village for the unburned peatland of natural swamp forest. An increase in the EC value of peat soil from 106.1 mS/m at the Kerinci Barat village to 109.6 mS/m at the Langgam village and then to 118.6 mS/m at the Pangkalan Gondai village could be due to an increase in the fire severity of burned swamp forest from less than 20% of the peatland area to peatland area in the range of 20 to 40% and then to larger than 40% of the peatland area. This finding may contradict a previous result of the experimental and modeling study that thermal conductivity of fire-heated soil slightly decreases with increasing of fire severity (Smits et al. 2016).

3.3. Biological properties of the peat soil

The results (Table 2) of CFU measurement used to estimate the number of viable bacteria or fungal cells in the peat soil sample show that the highest SMP value of $12.64x10^8$ CFU/mL is at the Kerinci Timur village for soil collected from the unburned area of peatland forest. A decrease in the SMP value of peat soil from $8.53x10^8$ CFU/mL at the Kerinci Barat village to $3.63x10^8$ CFU/mL at the Langgam village and then to 1.86x10^8 CFU/mL at the Pangkalan Gondai village could be due to an increase of the burned peatland from less than 20% of swamp forest area with low fire severity to swamp forest area in the range of 20 to 40% with moderate fire severity and then to larger than 40% of swamp forest area with high fire severity.

4. Discussion

The foundation of peat soil sampling plan of clearly defined goals was to assess the changing nature of peat soil by a fire. The urgency of tropical peatlands originally covered by peat swamp forests was selected at the locations relatively close to each other to possibly provide a similarity in the nature of peat soil characteristics. Initially, the physical, chemical, and biological properties of the peat soils at four locations of the Kerinci Timur, Kerinci Barat, Langgam and Pangkalan Gondai villages could be very similar to each other. High severity of swamp forest fire consumes more soil organic matter leading to a detrimental effect on the physical properties of peat soil. Because of the important function of soil organic matter is to hold sand, silt, and clay particles into an aggregate, the loss of organic matter in peat soil caused by a fire can result in the loss of soil structure. This can be verified from a decrease in the WC value of peat soil from 296.6% for the unburned peatland at Kerinci Timur village to 273.9% for the burned peatland with high fire severity at the Pangkalan Gondai village (see Table 1). An increase of the burned peatland area with increasing of the fire severity speeds up the process of evaporation and reduces the moisture content of peat soil. This result appears consistent with the finding of previous study that the presence of wood-burned ash on the peatland surface filling the voids of peat soil matrix can decrease the WC value after a fire (Walczak et al. 2002). Fire severity could influence firefighting of peatland forest when using water as a management tool for the recovery of peatland (Noble et al. 2018). The incorporation and retention of the water in peat soil profile is highly important to hydrological cycle in the tropical peatland with high fire frequency (Hobley et al. 2017). When burning the peat swamp forest reached at certain temperature this can lead to an increased carbon loss, while carbon in the peatland combined with oxygen from the air forms the CO_2 gas to escape into the air (Armstrong et al. 2010; Atwood et al. 2016; Uda et al. 2017). This demands the plantation of more trees in the areas of the burned peat swamp forests for returning the enrichment of soil and enhancement of carbon sequestration (Mehraj et al. 2022).

The level of WBC value in the area of peatland can be used to describe the tendency of water associated with hydrophilic colloids of peat such as the humic acids and hemicelluloses. The WBC value in tropical peat soil is naturally higher than that in dense soil because of the peat soil is associated with a large number of macrospores and high porosity (Yule et al. 2016). An increase in the severity of swamp forest fire from a burned peatland area of less than 20% to an area of larger than 40% forest burnt can lead to increase the loss of humic acids and hemicelluloses, which empirically refers to a decrease in the WBC value of peat soil by 12% from 187.3 to 164.8%, and thus reduces the ability of peat soil to entrap a large amount of water (see Table 1). This result supports the previous finding of studying chemical reactivity of ash produced during a fire due to the adhesive bonds by dusty microparticles preventing the penetration of soil particles into the pore spaces of peat soil can decrease the WBC value (Sutton and Sposito 2005). Fire in the peatland can continue smouldering for weeks and months affecting a change in the soil temperature, soil structure, and the ability of peat soil to absorb water and thus results in the loss of biodiversity (Certini 2005). An increase in the peatland forest fire severity can increase the bulk density and reduces the porosity and infiltration rate of the peat soil, which in turn reduces the WBC value of peat soil. Surface runoff increased with increasing of the peatland fire severity can increase the erosion of upper layers of the peat soil and finally leads to an increased flood risk and damage in the surrounding areas (Fulazzaky et al. 2013; Klimaszyk et al. 2015). The tropical peat swamp forests as the unique ecosystems in the Riau province and other regions of Indonesia are under enormous threat from legal and illegal logging, burning during the peatlands preparation, and land conversion for the expansion of the oil palm plantations (Uda et al. 2017). The existence of tropical peatland damage raises a number of challenges for the Indonesian government. The demand of tropical peatland for agricultural practices in the oil palm plantations expected to continue and increase further in the future can result in greater pressure on the areas of tropical forests (Yan et al. 2020). The reforestation of heavily degraded tropical peatlands by fire has been recommended for the use of native tree species to reestablish a stable ecosystem (Lampela et al. 2018).

Tropical peatland consisting of solid, liquid, and gas phases is characterized as the polydisperse system. Pore space of peatland contains the liquid and gas phases of the soil whereas the solid phase contains the minerals with varying sizes and organic compounds. An increase in the severity of swamp forest fire on peat soil can result in an increase of wood ash consisting of inorganic minerals and organic compounds. Wood ash entering the peat soil during an intense rainfall can reduce the gap between solid particles and increases the loss of soil porosity, which can be verified from a decreased TP value of peat soil by 2.45% from 85.8% for the burned peatland area of less than 20% with low fire severity to 83.7% for larger than 40% of the burned peatland area with high fire severity (see Table 1). This result agrees with the previous investigation of soil porosity that ash particles entering the ground can fill the macropore spaces of peat soil leading to decrease the TP value (Sepehrnia et al. 2017). The loss of soil porosity reduced infiltration capacity of peat blanket can result in the less water entering a peat soil and leads to an increased overland flow causing accelerated erosion (Owens 2020). A larger area of the burned peatland promotes the larger risk of altering pore structure and configuration in the peat soil due to a thermal stress (Harenda et al. 2018). More ash particles of burned peatland occupied the same volume of peat soil can result in the less porosity and reduces the number of soil pores so the peat soil gets denser (Bodner et al. 2014; Huang and Rein 2015). Ash particles of burned peat swamp forest can typically bond together to create a high density of the peat soil that can be hard for plant roots to penetrate (Scholl et al. 2014). Fire can severely damage the soil structure to reduce pore space that altering the physical, chemical, and biological characteristics of the peat soil (Santín and Doerr 2016). Fire of peatland can make the soil more vulnerable to the losses of moisture, understory, canopy, organic matter, and WC value but increases the temperature and rate of the evaporation from burning peat swamp forest (Hirano et al. 2015). Experimental evidence (see Table 1) shows that the increasing of fire severity can affect the soil physical properties of decreased WC, WBC, and TP values, which can result in the loss of soil structure and the increase of soil density leading to an increased flood risk and damage in the surrounding areas of burned peat swamp forest.

The increasing of swamp forest fire severity corresponded to an increased poor aboveground production following a fire contributes to an increase in the compaction of peat soil. This deals with an increased BD value of peat soil by 9.5% from 0.21 g/cm^3 for the burned peatland area of less than 20% with low fire severity at the Kerinci Barat to 0.23 g/cm^3 for larger than 40% of the burned peatland area with high fire severity at the Pangkalan Gondai (see Table 1). An investigation of the interaction of soil compaction with fire does support the previous findings of hydrophobic biochar entered the intrapores of peat soil during the rainfall leading to an increase in the BD value after a fire (Liu et al. 2017; Talbot and Ogden 2008). Peat swamp forest fires in the Riau province of Indonesia and other tropical regions can burn hundred hectares of forests during one dry season and produce hundred tons of biochar deposited on the ground (Homagain et al. 2015). Forest fire regimes of many tropical regions like in the Palalawan regency are dependent on the human activities and determine a consequence of opening the agricultural lands. The process of ignition near a point of the origin of fire can cause a pyrolysis in the solid fuels to produce ash entering the peatland through rainwater infiltration. As a consequence, the peat soil becomes dense leading to an increased BD value of the peatland. This may alter the soil pore structure and the chemical properties of peat soil due to the compaction of soil affects the peat matrix and hydraulic gradients of the peatland (Rezanezhad et al. 2016).

The measurement of PD value focuses on just the soil particles and does not describe the total volume that includes the soil particles and pore spaces in the peat soil. The PD value that lies between 2.5 and 2.7 g/cm^3 for the most mineral soils is dependent on the density of various constituent solids (Cong et al. 2015). Severe fire of swamp forests on peatland can cause an increased inorganic fraction of the peat soil due to the loss of organic matter results in a change of the soil properties contributing to an increase in the mass of peat soil. Peatland burning increased particle density as a consequence of the fire-associated soil heat pulse can be verified with increasing of the PD value of peat soil from 1.36 g/cm^3 at the Kerinci Timur village for the unburned peatland to 1.52 g/cm^3 at the Pangkalan Gondai village for the burned peatland area of larger than 40% with high fire severity (see Table 1). This result is consistent with the previous result of testing the intact soil cores in the laboratory that the PD value of soil increases with increasing of the fire severity (Wieting et al. 2017). A highest PD value of 1.52 g/cm^3 observed for peat soil located at the Pangkalan Gondai village after burning of the peatland with high fire severity is still lower than an average PD value of 2.65 g/cm^3 often assumed for the common soil minerals (Nwosu et al. 2018). Peatland fires for certain locations in Indonesia such as the Palalawan regency of Riau province are promoted by the deforestation and forest degradation and result in a unique fertilizer that provides a base line program for plant, root, and microbial populations by the oil palm plantation companies (Comeau et al. 2016). The effect of fire on the peatland-soil-driven controls can increase the density of particles filled the pore spaces and reduces the permeability of peat soil.

Severe fire of swamp forests on peatland limits the transport of water caused by the soil compaction because of the evaporation of water during a fire can cause a major modification in the peat soil structure. As a consequence, the infiltration rate of peat soil decreases with increasing of the fire severity as shown by a decreased SP value of peat soil by 70.5% from 8.13 cm/h for the burned peatland area of less than 20% with low fire severity at the Kerinci Barat village to 2.40 cm/h for the burned peatland area of larger than 40% with high fire severity at the Pangkalan Gondai village (see Table 1). This study supports earlier knowledge of investigating the physical and hydraulic properties of the peat soil that severe fire causing the loss of soil organic matter can alter the soil structure leading to a decreased permeability of the peat soil (Rezanezhad et al. 2016). The decreasing of SP for a peat soil can reduce the seepage rate of groundwater discharge from the peatland forestry area. Tropical peat swamp forest as a unique ecosystem in the regions plays an important functional role in the regulation of ecological and hydrological patterns to maintain the amount of water reaching a river along the year. Temporal and spatial variations of water distribution in an area to sustain the river water need a strategic management by using certain scenarios and modeling (Fulazzaky et al. 2017; Li et al. 2017). Equatorial rainforest induced runoff floods are the most common type of flooding in the Riau province and other regions of Indonesia and generally occur in the rainy season. Flooding hazard in the area of peatland burned can increase due to a decreased SP level by fire (Wieting et al. 2017) and a decreased sediment trapping efficiency by grass loss (Fulazzaky et al. 2013). A fire in the area of peatland can release the large amount of carbon into the atmosphere and influences the role of peat swamp forests in regulating the runoff for controlling soil erosion after heavy rain events (Leng et al. 2019; Zhao et al. 2018). A method of tallying the surviving large trees in the burnt area has been proposed for the estimation of fuel mass and greenhouse gases emission during a forest fire in the tropical peatlands (Toriyama et al. 2014). Conversion of peat swamp forests to agricultural lands for the industrial oil palm plantations by burning forests has always been a controversial subject and can influence the level of soil organic matter contained in the peatland (Veloo et al. 2015). Sustained effort is required to maintain a good level of organic matter in peat soil by the rotations with high-residue crops and deep- or dense-rooting crops (Lazicki et al. 2016). The neutralized phosphogypsum has been used to improve the soil fertility and quality of the plant products (Efremova et al. 2020). Strength and permeability of stabilized peat soil are influenced by many factors like the soil texture, soil structure, soil organic matter, pore size, aggregate-size distribution, and pore-size distribution (Oliveira et al. 2017; Scholl et al. 2014). A change in the physical property of peat soil with increased peat swamp forest fire severity can cause the increased values of BD and PD and a decreased SP value, as shown in Table 1. An increased mass and compaction of the peat soil leading to a decreased infiltration rate of the peatland can reduce the capacity of water storage consequently faced a burden of the climate change threat locally.

The increasing of swamp forest fire can cause decreased concentration of H^+ ions in the groundwater due to the export of ash alkalinity into the peat soil during rainfall increases with increasing of the wood-burned ash availability after a fire. The increasing of alkalinity can be described by an increased pH value of peat soil from pH 4.23 for the burned peatland area of less than 20% with low fire severity at the Kerinci Barat village to pH 4.37 for the burned peatland area of larger than 40% with high fire severity at the Pangkalan Gondai village (see Table 2). This result is consistent with the previous finding that a fire in the peatland can reduce the amount of unhumified organic matter and alkali-soluble compounds of humic acids leading to an increase in the pH value of peat soil (Bridges et al. 2019; Fernández et al. 1997). The impact of ground fire on the peatland of Pelalawan regency can increase the pH value of peat soil from pH 4.11 at the Kerinci Timur village for soil of unburned peatland to pH 4.37 at the Pangkalan Gondai village for soil of burned peatland with high severity of the peat swamp forest fire, leading to an increased availability of the plant nutrients (Morgan and Connolly 2013; White and Brown 2010). It is suggested that the purpose of land preparation by burning the tropical peat swamp forests in the Riau province and other regions of Indonesia before planting the oil palms is to provide the necessary soil conditions and is the ways to having the agricultural lands to be more productive. A big concern of the Indonesian government is that many largest agribusiness corporations have intentionally burned the tropical peatland forests for the expansion of their oil palm plantations. Challenges to improve the water resources and environmental management by the use of ash burned forest and sludge as fertilizer for the agricultural lands need to be considered in the future directions for supporting effective problem solving (Fulazzaky 2014; Fulazzaky and Gany 2009). The formulation of using a multiple criteria matrix has been suggested for the management modeling of tropical wetland as an appropriate approach of the wetland management strategic plan (López-Calatayud et al. 2021).

Limited supply of oxygen in the soil pore spaces of peatland shortly depleted by the microorganisms and soil reductants after severe swamp forest fire can lead to a decreased Eh value following by the soil chemical changes. The Eh value of peat soil decreases from 195.6 mV for the unburned peatland at the Kerinci Timur village to 165.0 mV for the burned peatland area of larger than 40% with high fire severity at the Pangkalan Gondai village (see Table 2). This creates the prerequisite of beginning the reactivation of oxidation process in peat soil after the fire with high severity. The result of this study supported earlier experimental result shows that fire severity is accompanied by a considerable change in the soil adsorption of anions and cations caused by altering Eh of forest soil in Central Europe that having a significant effect on the local agricultural production (Bridges et al. 2019). Fire with a weak severity may not have a considerable effect on the number and composition of the adsorbed anions and cations (Tavakkoli et al. 2015). Fires greatly alter the chemical characteristics of peat soil in three ways of minerals released during combustion process to produce ash, microclimate change during and after a fire in the area of peatland, and conversion complex organic compounds into simplest organic and inorganic compounds through various decomposition procedures (Ciccioli et al. 2014; Kleinhans et al. 2018; Tepley et al. 2018). The use of fire as cheaper land preparation method has been widely practiced as tool to increase soil nutrients but its contribution to fertilize the soils is limited and will not last long (Santín and Doerr 2016; Simorangkir 2007). Land degradation remained an important issue for the restoration of burned peatland is due to its adverse impact on the nutrient impoverishment, agronomic productivity, and the environment may threaten food security and the quality of life for many people (Caron et al. 2018).

The increasing of swamp forest fire on peatland leading to an increased compaction of peat soil could be due to the transport of wood-burned ash into the soil during rainfall event increases with increasing of the amount of ash above the peat soil surface. An increase in the compaction of peat soil can lead to the increased values of EC and pH for an affected peatland. Empirical evidence shows that the EC value of peat soil increased from 106.1 mS/m at the Kerinci Barat village to 118.6 mS/m at the Pangkalan Gondai village (see Table 2) related to the value of SP decreased from 8.13 to 2.40 cm/h but the value of PD increased from 1.38 to 1.52 g/cm^3 (see Table 1) could be due to a burned peatland increased from less than 20% with low fire severity to larger than 40% of the swamp forest area with high fire severity. Fires on the peatland of Pelalawan regency typically affected the microclimates of Riau province occupied central part of eastern region of Sumatra Island can alter the physical, chemical, and biological properties of the peat soil and have long been used as tool to increase the productivity of the agricultural soils and to control the growth of the oil palm plants (Paterson and Lima 2018). Fires can substantially change certain types of vegetation in the tropical peatland ecosystems, enhance the soil erosion in severely burned areas, and even cause the desertification of previously productive areas (Santín and Doerr 2016; Paterson and Lima 2018). Coverage of woody canopy by unassisted regeneration in the degraded tropical peatlands may occur slowly but patchy with low species diversity (Blackham et al. 2014).

The highest SMP value of 12.64x10^8 CFU/mL verified for the peat soil of unburned swamp forest could be due to there are no changes to the biological properties of peatland, organic matter amount in the peat soil, and water available for the crops over time (Lampela et al. 2016; Sazawa et al. 2018). Fire in the peatland causing a drastic reduction in the peat soil microbial biomass can be investigated from a significant decrease in the SMP value of peat soil from 8.53x10^8 CFU/mL at the Kerinci Barat village to 1.86x10^8 CFU/mL at the Pangkalan Gondai village with increasing of the fire severity from swamp forest area of less than 20% to an area of larger than 40% of the burned forest (see Table 2). Fire produced heat killing any microbe except for virus can lead to the changes of the physical, chemical, and biological properties of the peat soil. This result is the confirmation of previous finding that the impact of fire severity on the soil biological properties can locally reduce the number and variation of the microbial communities affecting the spatial distribution of microbes (Xue et al. 2018). The most obvious differences between the unburned and burned areas of the peat swamp forest are: (1) the peat soil becoming denser at every liter of the soil weigh more due to the compressed pores after peat burning (Santín and Doerr 2016) and (2) the appearance of white coating for surface color of peatland indicated more easily microorganisms to grow up to certain point on the surface of burned peatland (Preston et al. 2012). The increasing of fire severity in peatland can alter the peat soil chemical properties by increasing approximately 3.3% of the pH value and approximately 11.8% of the EC value and by decreasing approximately 6.0% of the Eh value. But this can significantly change the biological properties by decreasing approximately 78.2% of the SMP value with increasing of the burned swamp forest from less than 20% to larger than 40% of the peatland area. It seems that the influence of small change in the chemical properties of peat soil can have a significant effect on the altering of the biological properties thus threatening the sustainability of the unique tropical ecosystems. The important implication of the results of this study is that the consideration of degraded peat soil ecosystems affected by different fire severities in formulating the effective government policies and procedures is critical in the conservation and restoration of the tropical peatlands. This aims to ensure the reliability and accuracy of the land use in regard to the expansion of oil palm plantations aimed to support economic growth.

5. Conclusions

This study investigated changes in the physical, chemical, and biological properties of the peat soil at the Pelalawan regency of Riau province. The values of WC, WBC, and TP decrease but the values of BD and PD increase with increasing of the fire severity of the peat swamp forests. A decrease in the SP value from 19.43 cm/h for the peatland of natural swamp forest to 2.40 cm/h for the burned peatland with high fire severity is very remarkable due to ash coming from the burning of peatland forests produces small amount of cementitious compounds to fill the pore spaces of peat soil during rainfall events. Both the pH and EC values of peat soil increase but the Eh value decreases with increasing of the severity of peat forest fire. A decrease in the SMP value from 12.64×10^8 CFU/mL for the natural peatland without burning out to 1.86×10^8 CFU/mL for the burned peatland with high severity of peat swamp forest fire is very important due to the moist heat of high fire severity is efficient at killing soil microorganisms in the area of peatland. A change in the nature and characteristics of the peat soil caused by the burning of tropical peat swamp forest has been verified to contribute to future directions for the management of typical natural resources in the tropical regions.

Declarations

Ethic approval and consent to participate

This manuscript does not contain any studies with human participants or animals performed by any of the authors.

Consent to Participate

Informed consent was obtained from all individual participants included in this study.

Consent to Publish

All authors affirm that (a) neither this manuscript nor portions of it have been previously published elsewhere, (b) the manuscript is not under consideration for publication in another journal, and will not be submitted elsewhere until the Environmental Quality Management editorial process is completed, and (c) all authors consent to the publication of the manuscript in Environmental Quality Management, should the article be accepted by the Editor-in-chief upon completion of the refereeing process.

Availability of data and materials

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Competing interest

All authors declare that they have no conflict of interest

Authors’ contribution

All authors contributed extensively to the work presented in this paper. II, HH, and MAF conceived and designed the study and are the principal investigators. HH, SS, MR and YIS supervised the research project. II, MAF, HH, SS, MR and YIS compiled and analyzed the data and wrote the manuscript. II, MAF, HH, SS, MR and YIS analyzed the data and contributed to discussion and made interpretation of mechanistic study data. MAF edited and finalized the manuscript. All authors critically reviewed and revised the manuscript, and they have read and approved the final version.

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Figures

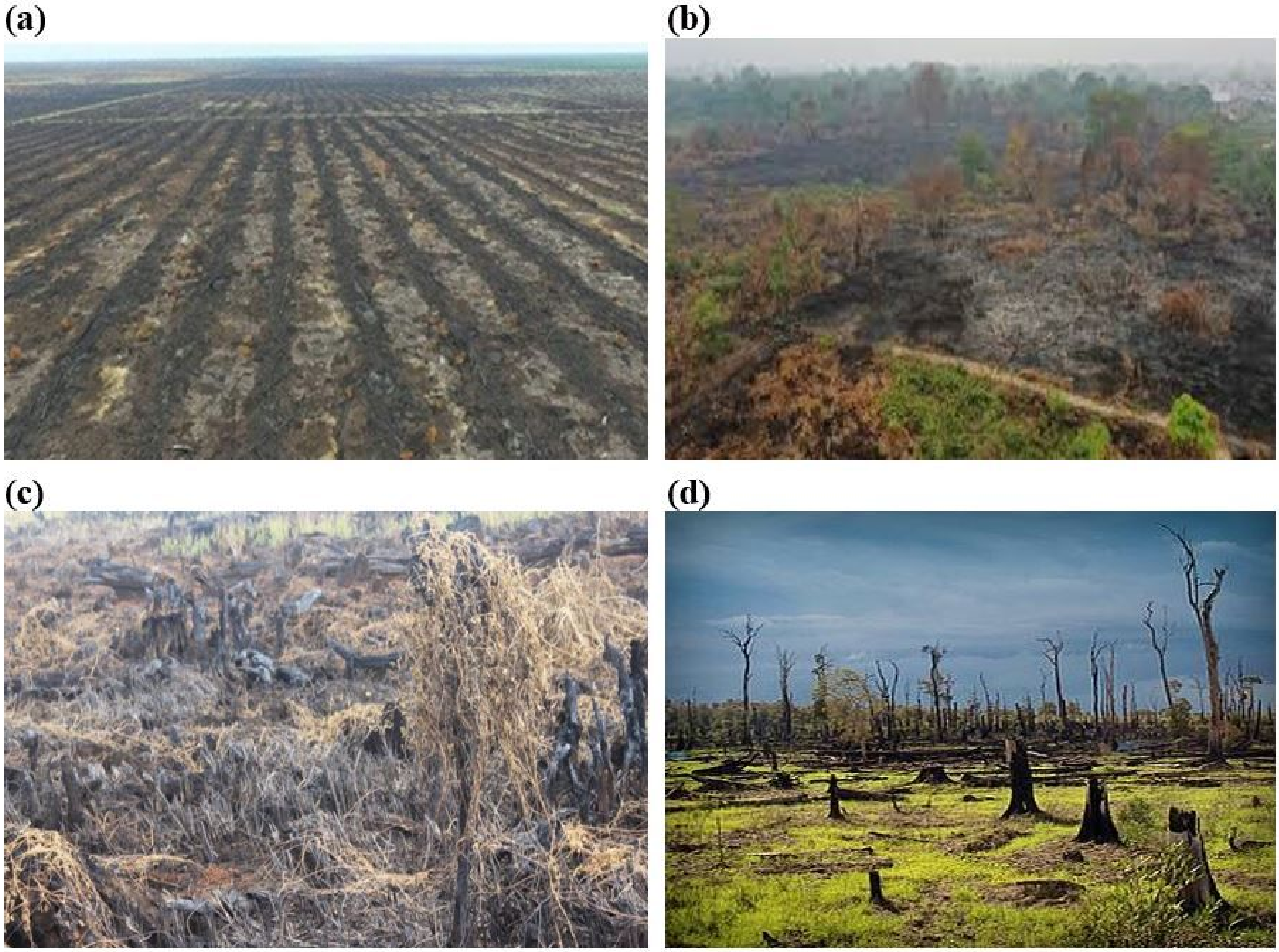

Figure 1

Picture of the burned peatlands with (a) no fire at the Kerinci Timur village, (b) low fire severity at the Kerinci Barat village, (c) moderate fire severity at the Langgam village, and (d) high fire severity at the Pangkalan Gondai village.

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