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

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Abstract The tropical peatland ecosystems of Indonesia provide direct economic benefits to local communities and act to maintain 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 peat soils by field and laboratory testing and analysis to understand changes in the nature and characteristics of 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 the soil microbial population can significantly decrease with increasing fire severity. The effect of different fire severities on the characteristics of peat soil is verified to contribute to advanced management of the tropical peatland in the future.

Keywords Fire severity · Peat swamp forest · Pelalawan Regency · Soil biological property · Soil chemical property · Soil physical property

Introduction

Even though the Riau Province of Indonesia has an extensive forest resource of peatlands, the management of potential natural resources such as the lifeblood of tropical regions has not been optimally carried out to satisfy human needs. Peatland has a particular value in terms 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 electrical resistivity tomography to determine peat layer thickness (Illés et al., 2019). Sadly, many peatlands are threatened by human activities for the development of plantation areas. The Pelalawan Regency of Riau Province has been considered the area prone to forest and land...
fires and was the area affected most by fires in 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 Riau Province and its surrounding regions (Saharjo & Yungan, 2018). Approximately 1.83 million hectares of peatlands, which is equal to approximately 57% of the total peatlands in Indonesia, were converted to non-forest purposes during three decades from 1982 to 2007 (Saputra, 2019).

Peatlands are the features of areas commonly located in tropical countries with very low topographic relief. Peat soils in the Pelalawan Regency of Riau Province and other regions of Indonesia are suitable for the growth of many special crops that require an acid reaction but are vulnerable 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 peat swamp forest fires may affect people and the environment in many ways, this study focused on the assessment of the impacts of low, moderate, and high severity of peat swamp forest fires on the physical, chemical, and biological properties of peat soils. Fire effects can alter the soil nature and pace of environmental change (Elmes et al., 2019), potentially allowing certain organisms to adapt quickly to a new terrestrial environment. The area of peatland affected by tidal fluctuations in the water level causing 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 showed that the WC of the low temperature peat soil was higher than that of the high-temperature peat soil, ranging from 100 to 110 °C (O’Kelly & 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 km² for artificial flowing watercourses within the Meranti Ditch basin ranging from 41.6 to 55.5 g C/m² and at a relatively large catchment area of 458 km² for natural flowing watercourses within the Turip River basin ranging from 26.2 to 34.9 g C/m² (Yupi et al., 2016). An addition of the water-reducing admixtures was able to reduce the 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). Limiting to a recommended pH value of the peat soil is important to maintain the quality of soil and reduce the risks of degradation and desertification, allowing an increase in the potential productivity of soil, to improve the soil structure and to gain the benefit of peatland biodiversity (Goulding, 2016). The 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 the whole profile for peat soil during the wet season is lower than that during the dry season (Niedermeier & Robinson, 2007; Urquhart & 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 & Bartholomew, 2011). Pore dilation of peat soil may occur because the presence of NaCl in the soil pore space can react with organic functional groups (Comas & Slater, 2004). The 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 ash particles through mineral transformation during peatland burnout can reduce the value of WC because 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). The chemical reactivity of ash produced during the burning of peatland denotes that materials with functional groups tend to form adhesive bonds by dusty microparticles through the sharing of electrons to prevent the penetration of soil particles into voids (Sutton & Sposito, 2005). The presence of 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 rain infiltration into a semi-infinite soil column and enters the intrapores of peat soil (Liu et al., 2017; Talbot & 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 soil temperature because the percentage of soil organic matter (SOM) decreases in proportion to fire severity (Wieting et al., 2017). A complex porous medium of peat soil with a high content of organic matter can maintain the permeability of peat soil (Rezanezhad et al., 2016). Although the pH value of peat soil increases slightly with increasing soil temperature, the surface and subsurface soil layers can significantly reduce the carbon content during wildfire (Fernández et al., 1997). A high severity of forest fires can significantly increase the pH of Haplic Luvisol soils in Central Europe and alter the adsorption of anions and cations in the soils (Bridges et al., 2019). The results of experimental and modeling studies showed that the 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). Although many studies in the areas of peat soil have been carried out to assess the negative effects of peatland fire on humans 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 the assessment of different levels of fire severity that influenced the characteristics of tropical peat soil may provide insight into 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, and SMP as 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.

Materials and methods

Sampling location of the peat soil

Indonesia has more than 500 tropical peatland ecosystems that stretch from Aceh Province at the northern end of Sumatra to South Papua Province located in the southern portion of Papua, which follows the borders of Papua New Guinea (Budiman et al., 2020; Uda et al., 2017). The total tropical peatlands in three large islands of Sumatra, Kalimantan, and Papua were estimated to be approximately 14.8 million hectares (Mha), which are still covered by forested areas of 7.70 Mha (52%) and by bushes of 3.23 Mha (21.7%) and have been used for agricultures and settlements of 3.87 Mha (26.3%) (Anda et al., 2021; Hein et al., 2022). 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 Figs. 1–4). Kerinci Timur village in the Pangkalan Kerinci district was selected to represent an unburned peatland, as shown in Fig. 1. The collection of peat soil sample conducted every month starting from May to August 2018 was repeated for 4 times at a contiguous sampling site of the unburned peatland. The selection of Kerinci Barat village in the Pangkalan Kerinci district was to represent a burned peatland with low fire severity, as shown in Fig. 2. The collection of peat soil sample
conducted at a contiguous sampling site of the burned peatland with low fire severity was repeated monthly from May to August 2018 for 4 times. Langgam village in the Langgam district was considered to represent a burned peatland with moderate fire severity, as shown in Fig. 3. The collection of peat soil sample at a contiguous sampling site of the burned peatland with moderate fire severity was conducted monthly 4 times from May to August 2018. The consideration of Pangkalan Gondai village in the Langgam district was to represent a burned peatland with high fire severity, as shown in Fig. 4. The collection of peat soil sample repeated monthly 4 times from May to August 2018 was conducted at a contiguous sampling site of the burned peatland with high fire severity. The Pelalawan Regency of Riau Province with coordinates 0°16’00″N and 101°10’01″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 1 year, affecting the nature and properties of the peat soils. Four locations of the Kerinci Timur, Kerinci Barat, Langgam and Pangkalan Gondai villages in two districts of the Pelalawan Regency adequately represent the importance of Indonesian peatland ecosystems due to the population density of Sumatra is higher compared to Kalimantan and Papua and the impact of Sumatran peatland fires has caused a thick haze reaching the neighboring countries of Malaysia and Singapore (Hein et al., 2022; Sheldon & Sankaran, 2017). The selection of these four locations 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 responding to different levels of fire disturbances related to a change in the soil properties of an 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 tree 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 depths 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 representative soil samples, this study used the purposive sampling method of nonprobability samples (Zhu et al., 2008) to collect peat soil samples from a depth of 50 cm because 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 accounting for the effect of soil temperature on the level of change in 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. The limitations of this study are only centered on the peatland ecosystem of Palawan Regency in Riau Province to represent more than 500 tropical peatland ecosystems in Indonesia and evaluated a change in the physical, chemical, and biological properties of peat soils using data gathered four times during four months at four sampling sites with the limited parameters.

Classification of peat swamp forest fire severity

The classification of peat swamp forest fire severity was based on the observation that peatland area burned a limited size of 10 hectares during the dry season. A hierarchical object-based image analysis approach has been used to classify active fire and burned areas (Atwood et al., 2016; Simioni et al., 2022). The burned-over area of peatland was focused on peat swamp forests dominated by heterogeneous tree species and bounded by natural creeks to reduce the spread and intensity of wildfire. The post-fire soil
characteristic change in peatland was determined at 50-cm depth to predict the depth of heat penetration into the peat soil beneath a spreading fire. A burned peatland area of less than 20% was classified as having a low severity of peat swamp forest fire. The burned peatland area in the range of 20 to 40% was classified as having moderate severity of peat swamp forest fire. A burned peatland area of greater than 40% was classified as having a 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 to gain a better understanding of the impacts of fire on the physical, chemical, and biological properties of the peat soils in tropical peat swamp forest ecosystems.

Measurement of the physical properties of peat soil

Some of the experiments were conducted at the Soil Laboratory of the Faculty of Agriculture, Universitas Riau. Each physical property of the peat soil samples was measured in triplicate 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 an analytical balance (KERN ABJ 220-4NM Electronic Digital Balance, Tovatech, Kern & Sohn GmbH, Ebingen, Germany), dried in a drying oven (ThermoFisher Scientific, Massachusetts, USA) at 105 °C until all water was loss and then reweighed again. The WC value in peat soil (in %) is expressed as the mass of water lost upon drying to the oven-dried mass of the peat soil.

The capacity of water binding in peat soil was measured by centrifuging the peat soil because 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 1000 rpm and then weighed again to determine the WBC value of peat soil. The WBC of peat soil refers to the ability of soil to retain water within its matrix and can be expressed as the mass of water absorbed per mass of centrifuged peat soil sample as a percentage.

The measurement of the TP value aimed to determine the percentage of void space in peat soil, which could be expressed as the 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 cm³ of peat soil by heating in a drying oven at 105 °C and vacuum drying (Horton et al., 1988). The TP of peat soil refers to the fraction of the total peat soil volume taken up by the pore space and can be expressed as the volume of pore space per volume of the peat soil as a 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 cm³ 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 weighed to calculate the BD value in mass of oven dry soil (in g) per volume of the peat soil (in cm³).

The measurement of the 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 a graduated cylinder up to 100 cm³. The graduated cylinder was filled 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 cm³).

The permeability of peat soil was measured in terms of the infiltration rate of water (in cm/h) to enter into the peat soil for a given period of time at four locations: Kerinci Timur village, Kerinci Barat village, Langgam village, and Pangkalan Gondai village. The measurements of the infiltration rate at every location were carried out in triplo using a 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 decrease in of water level for determining the SP value (Fulazzaky et al., 2014).
The decreasing 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.

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 a 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 a 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 units of millisiemens per meter (mS/m) is the ability of peatland to transmit an electrical current (Noborio et al., 1994). The measurement of the 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 the SMP value in terms 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 viable bacterial or fungal cells and only measures viable cells to gain a better understanding of the impact of burning on the biological properties of peat soil. The measurement of the SMP value was carried out in triplicate for every measuring point. The value of SMP in terms of the CFU per milliliter was calculated using the Miles-Misra plating technique (Guo et al., 2017).

Results

Physical properties of the peat soil

Water content

The water content of a soil may range from completely dry to saturated conditions 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 Kerinci Timur village. A decrease in the WC value of peat soil from 288.3% at Kerinci Barat village to 280.2% at Langgam village and then to 273.9% at 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 ranging from 20 to 40% with moderate fire severity and then to the larger than 40% burned peatland area with high fire severity.

Water binding capacity

The results (Table 1) of centrifuge testing show that the highest WBC value of 208.7% was verified for the

| Table 1 | Physical properties of peat soil at different locations |
|---------|--------------------------------------------------------|
| Location | FS     | WC (%) | WBC (%) | TP (%) | BD (g/cm³) | PD (g/cm³) | 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 |

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/cm³), PD is the particle density (in g/cm³), and SP is the soil permeability (in cm/h)
peatland of a natural forest located in Kerinci Timur village. A decrease in the WBC value of peat soil from 187.3% at Kerinci Barat village to 177.1% at Langgam village and to 164.8% at Pangkalan Gondai village could be due to the level of burning in peatland forest increasing from low severity to moderate and then to high severity of the peat swamp forest fire.

**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 in Kerinci Timur village. The TP value of peat soil in the burned peatland slightly decreases from 85.80% at Kerinci Barat village to 84.24% at Langgam village and then to 83.70% at 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%.

**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 measurements show that the lowest BD value of 0.20 g/cm³ is at the peatland of the natural swamp forest located in Kerinci Timur village. An increase in the BD value of peat soil from 0.21 g/cm³ at Kerinci Barat village to 0.22 g/cm³ at Langgam village and then to 0.23 g/cm³ at 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.

**Particle density**

The PD value is used to describe the state of the physical system of peat soil, which measures the mass of peat soil samples in a given volume of particles. The results (Table 1) of the PD determination show that the lowest PD value of 1.36 g/cm³ was verified for the natural peatland located in Kerinci Timur village. An increase in the PD value of peat soil from 1.38 g/cm³ at Kerinci Barat village to 1.39 g/cm³ at Langgam village and then to 1.52 g/cm³ at Pangkalan Gondai village could be due to the fire severity of burned peatland increasing 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.

**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 Kerinci Barat village to 4.10 cm/h at Langgam village and then to 2.40 cm/h at Pangkalan Gondai village is due to the increase in 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.

### Table 2 Chemical properties of peat soil at different locations

| Location            | FS   | pH    | Eh (mV)   | EC (mS/m) |
|---------------------|------|-------|-----------|-----------|
| Kerinci Timur       | No fire | 4.11 ± 0.21 | 195.6 ± 9.78 | 86.9 ± 4.3 |
| Kerinci Barat       | Low   | 4.23 ± 0.22 | 175.6 ± 8.78 | 106.1 ± 5.2 |
| Langgam             | Moderate | 4.34 ± 0.22 | 167.0 ± 8.34 | 109.6 ± 5.5 |
| Pangkalan Gondai    | High  | 4.37 ± 0.23 | 165.0 ± 8.22 | 118.6 ± 7.1 |

FS is the fire severity, Eh is the redox potential (in mV), and EC is the electrical conductivity (in mS/m)
Chemical properties of the peat soil

\textbf{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 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.

\textbf{Redox potential}

Table 2 shows that the highest Eh value of 195.6 mV is at Kerinci Timur village for the unburned peatland of the natural swamp forest. A decrease in the Eh value of peat soil from 175.6 mV at Kerinci Barat village to 167.0 mV at Langgam village and then to 165.0 mV at Pangkalan Gondai village could be due to an increase in 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.

\textbf{Electrical conductivity}

The EC value expressed in the units 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 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 Kerinci Barat village to 109.6 mS/m at Langgam village and then to 118.6 mS/m at 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 an experimental and modeling study showing that the thermal conductivity of fire-heated soil slightly decreases with increasing fire severity (Smits et al., 2016).

\textbf{Biological properties of the peat soil}

The results (Table 3) 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 12.64 × 10^8 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 8.53 × 10^8 CFU/mL at Kerinci Barat village to 3.63 × 10^8 CFU/mL at Langgam village and then to 1.86 × 10^8 CFU/mL at Pangkalan Gondai village could be due to an increase in 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.

\textbf{Discussion}

The foundation of the 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 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. A high severity of swamp forest fire consumes more SOM leading to a detrimental effect on the physical properties of peat soil. Because the important function of SOM is to hold sand, silt, and clay.

\begin{table}[h]
\centering
\caption{Biological property of peat soil at different locations}
\begin{tabular}{lll}
\hline
Location & FS & SMP (CFU/mL) \\
\hline
Kerinci Timur & No fire & 12.64 × 10^8 ± 0.63 × 10^8 \\
Kerinci Barat & Low & 8.53 × 10^8 ± 0.43 × 10^8 \\
Langgam & Moderate & 3.63 × 10^8 ± 0.18 × 10^8 \\
Pangkalan Gondai & High & 1.86 × 10^8 ± 0.09 × 10^8 \\
\hline
\end{tabular}
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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 Pangkalan Gondai village (see Table 1). An increase in the burned peatland area with increasing fire severity speeds up the process of evaporation and reduces the moisture content of peat soil. This result appears consistent with the finding of a 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).
presence of WC in peat soil has an important role for groundwater recharge, soil chemistry, and agriculture and determines the moisture and amount of nutrients influencing crop growth and the status of soil aeration (Bohlke, 2002). Fire severity could influence firefighting of peatland forests when using water as a management tool for the recovery of peatland (Noble et al., 2018). The incorporation and retention of water in peat soil profiles is highly important to the hydrological cycle in the tropical peatlands with high fire frequencies (Hobley et al., 2017). When burning, the peat swamp forest reaches a certain temperature, which can lead to an increased carbon loss, while carbon in the peatland combined with oxygen from the air forms
CO₂ gas to escape into the air (Armstrong et al., 2010; Atwood et al., 2016; Uda et al., 2017). This demands the planting of more trees in the areas of the burned peat swamp forests for returning the enrichment of soil and enhancement of carbon sequestration (Berger et al., 2019; Mehraj et al., 2022).

The level of the WBC value in the peatland area can be used to describe the tendency of water associated with hydrophilic colloids of peat, such as humic acids and hemicelluloses. The WBC value in tropical peat soil is naturally higher than that in dense soil because peat soil is associated with a large number of macropores 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 an increase in 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 the 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, which can decrease the WBC value (Sutton & Sposito, 2005). Fire in the peatland can continue smoldering for weeks and months affecting a change in the soil temperature, soil structure, and the ability of peat soil to absorb water and thus resulting in the loss of biodiversity (Certini, 2005). An increase in the peatland forest fire severity can increase the bulk density and reduce the porosity and infiltration rate of the peat soil, which in turn reduces the WBC value of peat soil. The benefit of maintaining an appropriate soil WBC value is able to optimize crop production and to explain the yield of crop varied across contrasting climates (He & Wang, 2019; Schoonover & Crim, 2015). Surface runoff increases with increasing peatland fire severity, which can increase the erosion of upper layers of peat soil and finally lead to an increased flood risk and damage in the surrounding areas (Fulazzaky et al., 2013; Klimaszyk et al., 2015). Tropical peat swamp forests, as unique ecosystems in Riau Province and other regions of Indonesia, are under enormous threat from legal and illegal logging, burning during peatland preparation, and land conversion for the expansion of oil palm plantations (Uda et al., 2017). The existence of tropical peatland damage raises a number of challenges for the Indonesian government. The demand for tropical peatland for agricultural practices in oil palm plantations is expected to continue and increase further in the future, which 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 a polydisperse system. The pore space of peatland contains the liquid and gas phases of the soil whereas the solid phase contains minerals with varying sizes and organic compounds. An increase in the severity of swamp forest fire on peat soil can result in an increase in wood ash consisting of inorganic minerals and organic compounds. Wood ash entering the peat soil during intense rainfall can reduce the gap between solid particles and increase 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 a previous investigation of soil porosity, which showed that ash particles entering the ground can fill the macropore spaces of peat soil, leading to a decrease in the TP value (Sepehrnia et al., 2017). The importance of an adequate TP value is to facilitate the availability and movement of either air or water within the soil environment and to conduct air, water, and nutrients into the soil for plant growth even though a change in the TP value is influenced by the content of organic matter in a peat soil (Robinson et al., 2022; Schoonover & Crim, 2015). The loss of soil porosity and reduced infiltration capacity of the peat blanket can result in less water entering a peat soil and lead 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 thermal stress (Harenda et al., 2018). More ash particles of burned peatland occupying the same volume of peat soil can result in less porosity and reduce the number of soil pores, so the peat soil becomes denser (Bodner et al., 2014; Huang & Rein, 2015). Ash particles of burned peatland swamp forests can typically bond together to create
a high density of 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 alters the physical, chemical, and biological characteristics of the peat soil (Santín & 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 evaporation from burning peat swamp forest (Hirano et al., 2015). Experimental evidence (see Table 1) shows that increasing 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 an increase in soil density, leading to an increased flood risk and damage in the surrounding areas of burned peat swamp forest.

The increase in swamp forest fire severity corresponded to an increase in poor aboveground production following a fire contributing 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/cm³ for the burned peatland area of less than 20% with low fire severity at the Kerinci Barat to 0.23 g/cm³ 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 that hydrophobic biochar entered the intrapores of peat soil during rainfall, leading to an increase in the BD value after a fire (Liu et al., 2017; Talbot & Ogden, 2008). The BD value of peat soil as an indicator of soil compaction and soil health reflecting the ability of soil to function for structural support, solute movement, water movement, and soil aeration can be changed by crop and land management practices (Lipiec & Hatano, 2003; Schoonover & Crim, 2015).

Peat swamp forest fires in the Riau Province of Indonesia and other tropical regions can burn hundreds of hectares of forests during one dry season and produce hundreds of tons of biochar deposited on the ground (Homagain et al., 2015). The forest fire regimes of many tropical regions, such as in the Palawan Regency, are dependent on human activities and determine the consequences of opening agricultural lands. The process of ignition near a point of the origin of fire can cause 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 because the compaction of soil affects the peat matrix and hydraulic gradients of the peatland (Rezanezhad et al., 2016).

The measurement of the 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/cm³ for 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 resulting in a change in the soil properties and 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, which can be verified by increasing the PD value of peat soil from 1.36 g/cm³ at Kerinci Timur village for the unburned peatland to 1.52 g/cm³ at 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 intact soil cores in the laboratory that the PD value of soil increases with increasing fire severity (Wieting et al., 2017). The highest PD value of 1.52 g/cm³ observed for peat soil located in Pangkalan Gondai village after burning of the peatland with high fire severity is still lower than the average PD value of 2.65 g/cm³ often assumed for common soil minerals (Nwosu et al., 2018). A high content of organic matter indicated with a low PD value provides information concerning the potential release of carbon from the peat soil into the atmosphere as the organic matter decomposes over time (Klingenfuß et al., 2014; Leifeld & Menichetti, 2018).

Peatland fires for certain locations in Indonesia, such as the Palawan Regency of Riau Province, are promoted by deforestation and forest degradation and result in a unique fertilizer that provides a baseline program for plant, root, and microbial populations by oil palm plantation companies (Comeau et al., 2016). The effect of fire on peatland-soil-driven controls can increase the density of particles filling the pore spaces and reduce the permeability of peat soil.

Severe fire of swamp forests on peatland limits the transport of water caused by soil compaction because 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 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 Kerinci Barat village to 2.40 cm/h for the burned peatland area of larger than 40% with high fire severity at Pangkalan Gondai village (see Table 1). This study supports earlier knowledge of investigating the physical and hydraulic properties of peat soil that severe fire causing the loss of SOM can alter the soil structure, leading to a decreased permeability of the peat soil (Rezanezhad et al., 2016). The decrease in SP value for a peat soil can reduce the seepage rate of groundwater discharge from the peatland forestry area. A low value of SP reduced active porosity of peat soil beneath the burned peatland surface leading to inhibit the movement of solute, water, and air could be one of the important considerations for fish culture (Rezanezhad et al., 2016).

Tropical peat swamp forests, as unique ecosystems in the regions, play an important functional role in the regulation of ecological and hydrological patterns to maintain the amount of water reaching a river throughout the year. Temporal and spatial variations in water distribution in an area need strategic management by using certain scenarios and modeling to sustain river water (Fulazzaky et al., 2017; Li et al., 2017). Equatorial rainforest-induced runoff floods are the most common type of flooding in 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 a large amount of carbon into the atmosphere and influence the role of peat swamp forests in regulating runoff to control 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 gas emissions during a forest fire in tropical peatlands (Toriyama et al., 2014). Conversion of peat swamp forests to agricultural lands for industrial oil palm plantations by burning forests has always been a controversial subject and can influence the level of SOM contained in the peatland (Veloo et al., 2015). Sustained effort is required to maintain a good level of organic matter in peat soil by rotations with high-residue crops and deep or dense-rooting crops (Lazicki et al., 2016). Neutralized phosphogypsum has been used to improve the soil fertility and quality of plant products (Efremova et al., 2020). The strength and permeability of stabilized peat soil are influenced by many factors such as the soil texture, soil structure, SOM, 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 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 posing a burden to the local climate change threat.

The increase in swamp forest fire can cause a decreased concentration of H\textsuperscript{+} ions in the groundwater due to the export of alkaline ash into the peat soil during rainfall increases with increasing wooded burned ash availability after a fire. The increase in 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 Kerinci Barat village to pH 4.37 for the burned peatland area of larger than 40% with high fire severity at 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 Kerinci Timur village for soil of unburned peatland to pH 4.37 at Pangkalan Gondai village for soil of burned peatland with a high severity of peat swamp forest fire, leading to an increased availability of plant nutrients (Morgan & Connolly, 2013; White & Brown, 2010). An increase in the pH value of peat soil pore water can accelerate the decomposition of SOM leading to an increased rate of CO\textsubscript{2} released from peat soil to the atmosphere (Deru et al., 2021; Pranskevičius & Paliulis, 2021). 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 way to have agricultural lands to be more productive. A major concern of the Indonesian government is that many of the largest agribusiness corporations have intentionally burned tropical peatland forests for the
expansion of their oil palm plantations. Challenges to improve water resources and environmental management by the use of ash burned forest and sludge as fertilizer for agricultural lands need to be considered in future directions to support effective problem solving (Fulazzaky, 2014; Fulazzaky & Gany, 2009). The formulation of using a multiple criteria matrix has been suggested for the management modeling of tropical wetlands as an appropriate approach to 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 followed by the soil chemical changes. The Eh value of peat soil decreases from 195.6 mV for the unburned peatland at Kerinci Timur village to 165.0 mV for the burned peatland area of larger than 40% with high fire severity at Pangkalan Gondai village (see Table 2). A decrease in the Eh value of peat soil pore water influenced by dissolved organic matter can decrease the rate of anaerobic respiration dominated by inorganic electron acceptor (Deng et al., 2021; Kane et al., 2019). This creates the prerequisite of beginning the reactivation of the oxidation process in peat soil after fire with high severity. The results of this study supported earlier experimental results showing that fire severity is accompanied by a considerable change in the soil adsorption of anions and cations caused by altering the Eh of forest soil in Central Europe, which has a significant effect on 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: release of minerals during the combustion process to produce ash, microclimate change during and after a fire in the area of peatland, and conversion of complex organic compounds into the 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 a cheaper land preparation method has been widely practiced as a tool to increase soil nutrients, but its contribution to fertilize soils is limited and will not last long (Santín & Doerr, 2016; Simorangkir, 2007). Land degradation remains an important issue for the restoration of burned peatland due to its adverse impact on nutrient impoverishment and agronomic productivity, and the environment may threaten food security and the quality of life for many people (Caron et al., 2018).

The increase in 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 events increasing with the amount of ash above the peat soil surface. An increase in the compaction of peat soil can lead to 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 Kerinci Barat village to 118.6 mS/m at Pangkalan Gondai village (see Table 2) related to the value of SP decreasing from 8.13 to 2.40 cm/h, but the value of PD increasing from 1.38 to 1.52 g/cm³ (see Table 1) could be due to a burned peatland increasing from less than 20% with low fire severity to larger than 40% of the swamp forest area with high fire severity. A decrease in the EC value of peat soil pore water at comparable water saturations can lead to an increased degree of decomposition with decreasing organic matter contents (Krüger et al., 2021). Fires on the peatland of Pelalawan Regency typically affect the microclimates of Riau Province, which occupies the central part of the eastern region of Sumatra Island, and can alter the physical, chemical, and biological properties of the peat soil and have long been used as tools to increase the productivity of agricultural soils and to control the growth of oil palm plants (Paterson & Lima, 2018). Fires can substantially change certain types of vegetation in tropical peatland ecosystems, enhance soil erosion in severely burned areas, and even cause the desertification of previously productive areas (Paterson & Lima, 2018; Santín & Doerr, 2016). Coverage of the woody canopy by unassisted regeneration in degraded tropical peatlands may occur slowly but patchy with low species diversity (Blackham et al., 2014).

The highest SMP value of $12.64 \times 10^8$ CFU/mL verified for the peat soil of unburned swamp forest could be due to there being 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 $8.53 \times 10^8$ CFU/mL at Kerinci Barat village to $1.86 \times 10^8$ CFU/mL at Pangkalan Gondai village with increasing fire severity from a swamp forest area of less than 20% to an area larger than 40% of the burned forest (see Table 2). Fire-produced heat killing any microbe except for viruses can lead to changes in the physical, chemical, and biological properties of peat soil. This result confirms previous findings that the impact of fire severity on soil biological properties can locally reduce the number and variation in the microbial communities affecting the spatial distribution of microbes (Xue et al., 2018). The presence of charred materials in the subsurface layer of soil can lead to the abundance of microbial communities at the burned peatland with a severe fire significantly decreased causing an inhibited mineralization of organic nutrients for plant growth and development compared to that at the unburned peatland (Sazawa 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 weighs more due to the compressed pores after peat burning (Santín & Doerr, 2016) and (2) the appearance of white coating for the surface color of peatland indicates more easily microorganisms to grow up to a certain point on the surface of burned peatland (Preston et al., 2012). The increasing fire severity in peatland can alter the peat soil chemical properties by increasing the pH value by approximately 3.3% and the EC value by approximately 11.8% and by decreasing the Eh value by approximately 6.0%. However, this can significantly change the biological properties by decreasing approximately 78.2% of the SMP value with increasing burned swamp forest from less than 20% to larger than 40% of the peatland area. It seems that the influence of small changes in the chemical properties of peat soil can have a significant effect on the alteration of biological properties, thus threatening the sustainability of unique tropical ecosystems. The important implication of the results of this study is that the consideration of the peatland degradations affected by different fire severities in formulating effective government policy and procedure is critical in the conservation and restoration of tropical peatland ecosystems. This aims to ensure the reliability and accuracy of land use in regard to the expansion of oil palm plantations aimed at supporting economic growth.

**Conclusions**

This study investigated changes in the physical, chemical, and biological properties of peat soil at the Pelalawan Regency of Riau Province. The values of WC, WBC, and TP decreased, but the values of BD and PD increased with increasing fire severity in 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 because ash coming from the burning of peatland forests produces a 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 severity of peat forest fire. A decrease in the SMP value from $12.64 \times 10^8$ CFU/mL for the natural peatland without burning out to $1.86 \times 10^8$ CFU/mL for the burned peatland with a high severity of peat swamp forest fire is very important because 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 tropical regions.

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**Availability of data and materials** Data sharing is not applicable to this article, as no datasets were generated or analyzed during the current study.

**Declarations**

**Ethics 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 for publication     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 Monitoring and Assessment editorial process is completed, and (c) all authors consent to the publication of the manuscript in Environmental Monitoring and Assessment should the article be accepted by the Editor-in-chief upon completion of the refereeing process.

Competing interest     The authors declare no competing interests.

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