Peat physical and hydraulic properties due to peatland fires

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Abstract. Fires on tropical peatlands in Indonesia are unexpected events that happened sporadically, especially during dry seasons. It is not easy to judge why a fire presents in a certain spot, and how it spreads. There are indications, and originally, a fire is ignited intentionally to clear bushes and wood remnants on the land surface for land clearing. Its most negative impacts are on human health due to dispersing smokes locally, and occasionally, reached neighboring countries. It is not unusual, the fire spread beyond the initial spot, and burned a vast area of commercial plantations, and protected forests in the vicinity. Fires caused significant economic losses. This investigation aimed at making clearer how peat properties changed before and sometime after the fires burned the areas. We observed how fires in peatlands occurred, and to what extent the physical properties of peats altered due to fires. Observations were carried out in 4 locations within Riau province, South Sumatra province, and South Kalimantan province that have vast areas of peatlands in the country, and peatland fires there are more frequent. The observations focused on peatland morphological appearances, and physical properties of non-burned and after fires in protected forests, plantations, and smallholder lands. The physical and hydraulic properties that were analyzed, among others, are bulk density, particle density, porosity, available water capacity, and water permeability. Positive changes were experienced successively by the air-entry head (21.3%) followed by permeability (19.6%), particle density (15.9%), bulk density (10.7%), available water (7.4%), fast-drain pore (3.9%) and n-parameter (0.1%). While, negative changes were experienced successively by slow-drain pore (-72.2%), residual water content (-22.5%), porosity (-7.3%), saturated water content (-6.3%) and m-parameter (-2.6%). The increase of air-entry head and the available water indicated more capable of retaining more water. Meanwhile, the increase of permeability and fast pore drain mean the burnt peats would be easier to drain under the same suction gradient. However, based on the F-test with a probability value of 5%, those all changes were not so significant or considerably small compared to the associated critical values.

1. Introduction

Fires on tropical peatlands in Indonesia are unexpected events that frequently happen in the same locations or extended to their vicinities, especially during dry seasons [1, 2, 3]. Negative impacts due to unhealthy smokes in the atmosphere were not only apparent locally but also, to some extent, sometimes reaching the neighboring countries [4]. With the advance of remote sensing technology that frequently
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monitors hotspots, it is easy to locate the origin of the fires and its spreading in space and time [5, 6]. Though, it is not easy to judge why a fire present in a particular spot and how it spreads [7, 8]. From an aerial view at a time of the fire, it was evident that the fire moved forward to the sites which have fuel materials. The generated smokes and fire sparks dispersed in the air and propagated to any sites as directed by the wind.

There were some strong indications; however, the fires initially started on designated spots or areas with the primary purpose to clear bushes or wood remnants on the soil surfaces before cultivations [9]. Knowing that this practice is easy and inexpensive with another expectation to get more ashes to neutralize or reduce soil acidity which is one of the main constraints in the peatland development for agriculture [10, 11]. Fewer accesses to agricultural input, equipment, and funding, it is likely that using fire still the first option to use by local farmers or incomers to clear the lands for agriculture. So, a precaution is crucial to prevent the flames from spreading uncontrolled [12].

Using fire to clear bushes on agricultural lands indeed is not a new practice. This practice had continued for years, such as in South Sumatra, which is known as Sonor [13, 14]. Sonor (swidden agriculture) is managed by experienced and trusted farmers so that the firing process can be controlled in such a way to meet well with specifically targeted areas and time. A manageable area and when to start and end Sonor are vital, which are recognized well by the local farmers. Trusted climate information and prediction are the essential knowledge that needs to be possessed by Sonor practitioners. At least, they should get trusted information on when the peak of the dry season and the onset of the wet season as the Sonor is appropriately carried out within this period. The practitioners of Sonor usually have been well equipped. Still, under abnormal conditions where dry season prolongs, and the rainfall does not come as expected before, they are commonly not prepared with these unanticipated circumstances. Fire may become wild and once intervene in the outskirts areas where they may be forests, plantation, and others that are difficult or impossible to be extinguished except for the sake of adequate rate and amount rainfall. Nowadays, not only local farmers but quantifiable incomers are searching for new lands to grow food plants or oil palm trees. They mainly encroached poorly supervised lands, whether in the forest-barrier, livelihood-uncultivated, or state-unmanaged lands [13].

Fires have more negative effects on many sectors of human life and the environment [15, 16]. Corrupt practices to open and clear the lands will degrade the further biophysical environment and downgrade the bearing capacity of the environment that will, in turn, threaten the sustainability of agriculture. Degradation of biophysical environments due to fires has degraded the function of peatlands as conservation of flora and fauna and as a natural water reservoir, which is very important to support plant growths in dry seasons. Any arguments that say burning bushes and wood remnants will provide more ashes to reduce peat acidity are unrealistic. The ashes will distinguish very soon whether to be dispersed by the wind in the dry season or flushed by water in the wet season. Many reports state peatlands after fires have otherwise less ash content and less water holding capacity, which are unbenefficial for plant growth [17, 18].

Acacia and oil palm plantations are the most susceptible when fires come to exist within their or the surrounding areas (Figure 1). Homogeneous trees in a vast area during a dry season provide easily burnt organic materials once a spark of fires splashed over the area. The Acacia plantation by the Indonesia law should allocate its land for the main tree, which is acacia about 70% and others for forest conservation, livelihood, and infrastructures. The forest conservation is mainly located within the barrier areas of the protected forest while the land for livelihood in the vicinity of the local communities.

The presence of plantation in one case as a purpose is to limit or stop the access of the local

![Figure 1. Fires over Acacia Plantation in Riau Province, March 2013](image-url)
people encroaching the protected forest; however, in some cases, it has depleted earnings of the local people that previously relied on the forest products and their sides. The lands for livelihood are to enhance the socio-economic of the local people. They can cultivate these lands with full support from the plantation and the government, as well. Besides the Acacia tree, the rubber tree is another plant that legally recommended planted within the forest areas.

This report presents observation results in 4 locations within Riau province, South Sumatra province, and South Kalimantan province that have vast areas of peatlands in the country, and peatland fires there are more frequent. Field observations focused on the morphological appearances of the peatlands before and after the fires within protected forests, plantations, and livelihood lands. This investigation aimed at making clearer how peat properties changed before and sometime after the fires burned the areas. The components of the physical properties of peats to be analyzed were bulk density, particle density, and porosity. The components of the hydraulic properties were permeability, available water, fast-pore drain, slow-pore drain, saturated water content, residual water content, air-entry suction head, and n-parameter and m-parameter of water of the water retention curve based on Genuchten model [19]. In this regard, we define peat as Organosol comprising organic-carbon content >18% with bulk density 0.03–0.3 g/cm³, and peatland is a landscape consisting of peats having peat thickness >50 cm [19, 20].

2. Methodology
We conducted field observations in 4 sites located in Riau Province (2 sites), South Sumatra Province (1 site), and South Kalimantan Province (1 site). These three provinces have vast areas of peatlands where fires are more frequent. There was no exact figure on how extensive the burn areas, but the government estimated over 1000 hectares in each site. Immediate field survey after the fire ceased was not possible due to unsecured conditions, and some time was not allowed if the burn site under law investigation. Field surveys were carried 6 to 12 months later after the fire ceased. The burn sites consequently have been covered with bushes, wild trees, or replanted with acacia or oil palm trees. A field survey was only possible in the dry season when the weather was clear. A field survey in the dry season would give a real insight into the environmental conditions which were susceptible to fires. It was rarely fire occurring in the vicinity at the time of surveys. Field surveys could only be carried out after having legal permission. Accurately, each observing site is as follows.

2.1. SRL Riau
SRL (Sumatera Riang Lestari) is a forest plantation located in Bengkalis Regency of Riau Province with acacia as the main cultivated tree with rubber tree planted in the livelihood lands located in Rupat Island, Bengkalis Regency of Riau Province. Fires occurred in some spots in June 2013. Field survey was conducted in March 2013 (9 months later after the fires) within the coordinate points of (N: 01:47:32:06, E: 101:28:57.2) – (N: 01:47:18.5, E: 101:29:56.3). Along with the ways to the site, fire spots existed sporadically in oil palm plantations, acacia plantations, protected forests, and unmanaged lands. Fire Danger Rating (FDR) was 86–100 categorized as an extreme risk to fire. The burn sites were in rubber plantations and acacia plantations. A total of 7 undisturbed samples representing fresh and burn peats were taken and analyzed in a soil laboratory.

2.2. RUJ Riau
RUJ (Ruas Utama Jaya) is an acacia plantation located in Rokan Hilir Regency of Riau province, covering more than 44,000 hectares. There were about 16,000 hectares of the planted area. The remaining area, however, was under land dispute with the local people who claimed parts of the area and used them for settlements, agriculture (corns), and oil palms. Illegal logging was rampant, including in the nearby protected forests. Logged timbers were collected and transported via nearby canals belong to the company. The opened lands/forests were cleared using fires to cultivate corns and oil palm trees. The company that should manage the lands had to bear responsibility and face persecution. The burn sites were investigated in December 2013 or 6 months after the fires and found in acacia plantations and protected forests within the coordinate points of (N: 01:52:46.2, E: 101:03:53.52) – (N: 01:50:48.66,
E: 101:03:54.84). A total of 12 undisturbed samples representing fresh and burn peats were taken and analyzed in a soil laboratory.

2.3. BMH Sumsel
BMH (Bumi Mekar Hijau) is an acacia plantation located in Ogan Komering Ilir regency of South Sumatra Province. A field survey was in April 2015 (7 months after the fires). The burn sites within the coordinate points of (S: 02:58:00, E: 105:29:53.6) – (S: 03:15:18.5, E: 105:29:58.1) have been covered with bushes and replanted with acacia trees. Two burn spots were in the peatlands with peat thickness above 3 m, and one spot was in the peatland with peat thickness lower than 0.5 m above marine clays layers. A total of 12 undisturbed samples representing fresh and burn peats were taken and analyzed in a soil laboratory.

2.4. PU Kalsel
PU (Palmina Utama) is an oil palm plantation located in Barito Kuala Regency of South Kalimantan Province. A field survey was carried out in August 2017 (18 months later after the fires). The burn area was within the coordinate points of (S: 03:04:08, E: 114:54:09) – (S: 03:05:05, E: 114:52:0) with shallow peat layers lower than 0.5 m. A total of 6 undisturbed samples representing fresh and burn peats were taken and analyzed in a soil laboratory.

2.5. Soil Sampling and Analysis
Before peat sampling, the soil surface was cleared from any materials covering it. A cross-section up to 30 cm depth was made to figure out the profile and to investigate how deep the peat layers were affected by fires using visual color identification. Since, in all cases, the affected layers were less than 10 cm, peat samplings were taken from two layers representing the depth of 0–5 cm and 5–10 cm with three replicates using ring samplers of 100 ml. Careful attention was given so that the sampled peats were free from unexpected materials such as big roots, dead woods, etc. The samples were packed and transported to a certified soil laboratory (ISO9001) stationed in Bogor city of West Java Province belongs to the Ministry of Agriculture, the Republic of Indonesia.

The samples were analyzed to get the physical properties consisting: 1) Actual Water Content (AWC); 2) Bulk Density (BD); 3) Particle Density (PD); 4) Porosity (POR); 5) Volumetric Water Content (VWC) at pF 1, pF 2, pF 2.54 and pF 4.2; and 5) Permeability (Ks). Calculations were then undertaken to determine: 6) Available Water (AW), which is VWC at pF 2.54 minus VWC at pF 4.2; 7) Fast Pore Drain (FPD), which is P minus VWC at pF 2; and 8) Slow Pore Drain (SPD), which is VWC at pF 2 minus VWC at pF 2.54. Furthermore, Genuchten Model (Eq. 1) was used to determine: 9) Saturated Water Content (SWC); 10) Residual Water Content (RWC); and 11) Air-entry Value (AEV). The model takes the form [21]:

\[
WC = RWC + (SWC - RWC)[1 + (AEV^{-1}h)^n]^{-m}
\]

Where \( h \) is water suction head (cm); \( n \) is fitted parameters, which was found using Solver available in MS-Excel; and, \( m=1-1/n \). Furthermore, statistics and graphs were used to see differences between fresh and burn peats, and F-test was used to see the significance of the differences.

3. Results and Discussions
3.1. SRL Riau
Department of Fire Control Health, Safety, and Environment of the company in June 2013 recoded the Fire Danger Rating (FDR) was 15 categorized as low. The daily rainfall was 4.6 mm, relative humidity was 73%, and the air temperature was 34°C. The fires occurred on the soil surface (surface fire), burn organic materials above the soil surface, and devastated acacia trees (crown fire) up to thousand hectares. The affected peat layers were not more than 5 cm below the soil surface. The surface fire ceased when the materials were utterly fed off. However, the smokes would remain until enough water from extinguisher or rainwater poured the burn sites. The crown fire, however, was difficult to stop by
extinguisher because of the abundant organic materials. The presences of water canals between two neighboring land compartments were not enough to prevent the movement of fires because the fire sparks could jump over the ditches. Along with smokes, generated fire sparks dispersed in the atmosphere, moved sporadically, and would initiate fires even to farther locations.

At the time of the survey, many fires were in the barrier zones, acacia plantations, oil palm plantations, farmlands, and protected forests (Figure 2). Sources of fire were initially from the barrier zones ignited on purpose to open and clear lands by irresponsible persons. Because of no access to the barrier zones and protected forest, it was difficult to stop the fires even by dropping buckets of water through helicopters. On the front side (Figure 2), acacia trees have been replanted between the dead trees. At this stage, the new trees grew normally in the burnt sites located in compartments E028 and E112. At the time of fires, groundwater levels (GWL) recorded on 1 Jun 2013 were 82 cm and 54 cm, respectively, which were still within the recommended range of 40–90 cm for acacia plantation in peatlands. Within those levels, the peats were relatively humid and not easy to get fires.

As mentioned earlier, the affected peat layers by the fires were not deeper than 10 cm. Figure 3 shows the components of physical properties, which are the averaged values from the two layers (0–5 cm and 5–10 cm). In the acacia plantation, particle density (PD) of the burn peats (yellow) was higher than that of the fresh peats (green) simply because of the loss of lighter materials due to fires. On the consequences, porosity (POR) was higher, while bulk density (BD) was lower. Fires knowns can reduce peat’s capacity to store the water, such as shown here by the consistent decreases of saturated water content (SWC), residual water content (RWC), and available water (AW). The increase of fast pore drain (FPD) in burn peats caused higher permeability (Ks) but not significantly affected the air-entry value (AEV) and slow pore drain (SPD). In rubber plantation, the burn peats were more compacted (high PD) and porous (high POR), In consequence, permeability was low with higher AEV.

3.2. RUJ Riau

Burn peatlands were in the barrier zones (livelihood lands) and inside the protected forests. At the time of the survey, some areas have been covered with bushes and wild trees. Illegal logging was very rampant and still happening. The unlawful loggers found were not local people but hired labors from outside. They were friendly to talk and knew what that job was illegal and would quit once they could find another better one. Railways made of Gelam tree (Melaleuca) were used to drag the timber to a temporary chainsaw house to process it into blocks and plates. These woods were collected around, and
transported through, nearby drainage canals to the outside. Occasionally, the canals were blocked by forest security, but most of the time was opened regularly for water transportation.

The opened areas were cleared by fires and planted, among others, with corns, oil palm, and rubber trees (Figure 4). The local people claimed parts of the plantation as their properties. These situations generated land disputes with the company. Planting the trees whatever good or harmful growths on these disputed lands were not mattered since the aim was to deliver messages that these lands belong to them. Settlements were still underway involving the local government, but it seemed it could not be resolved for some periods.

The fires in the disputed lands were meant to clear bushes, wild trees, and wood remnants but then dispersed to farther sites crossing over 15 km and reached acacia plantations. The burn areas were more massive as closer to the forests. Rubber and old acacia trees relatively could survive and produce new shoots and leaves, but most young acacia trees had to replant. The fires touched the peat surface and penetrated some deeps below it (<10 cm). Fresh and burn peats were easily identified by their color appearances. Fresh peats were light-brown (Figure 5, Figure 7), while burn peats were black like charcoal (Figure 6, Figure 8). Peats in the forest had lots of fine roots, decayed leaves, and other more abundant organic materials (Figure 5, Figure 6), while that in the plantation formed more homogenous crumbs (Figure 7, Figure 8).

Figure 5. Fresh peat in the protected forest
Figure 6. Burn peat in the protected forest
Figure 7. Fresh peat in the acacia plantation
Figure 8. Burn peat in the acacia plantation

Figure 9 shows the physical properties of fresh and burn peats, each in the protected forest and acacia plantation. Compared to the fresh peat, the burn peats both in the protected forest and acacia plantation
have higher values of the properties. In the protected forest, the fires might have consolidated fresh peats from fibrous forms (Figure 5) into more stable and structured particles (Figure 6). As consequences, POR, SWC, RWC, AW, and PD increased, and the capacity to hold water also increased. These conditions might be better for supporting plant growth. The ability of peat to keep water in the acacia plantation was less compared to that in the forest. Furthermore, the fires have made it lower as shown by the decreases of POR, SWC, RWC, and AW. However, the higher AEV of the burn peats would help retain the water when the GWL decreased.

3.3. MH Sumsel

Figure 10 shows burnt acacia plantations seven months after the fires. These areas are very susceptible to fire since it is very close to the farmlands cultivated by the local people that practice Sonor to clear the lands in every dry season. The fires in the form of crown fire devastated the acacia plantation over ten thousand hectares. Older trees could survive and regrew well, but replanting was undertaken in most areas. The fire sites situated in acacia plantations on peatlands in Sungai Beyuku District (DSB) and marine-clay lands in Simpang Tiga District (DST). The burnt sites in both districts have been naturally covered with bushes and some replanted by acacia trees.

Spots of thin white ashes were still left on the peat surface (Figure 11). The color of the peats beneath was light brown and contained a small number of fine roots indicating the peats were not substantially exposed to the fires. The fresh peats in the protected forest and the acacia plantation were of the same color containing more roots of many sizes of various vegetations. There were no considerable differences in the physical properties of the peats in the three sites. In average, bulk density was 0.17 g/cc, particle density 0.49 g/cc, porosity 66%, permeability 0.19 m/h, available water 5%, fast-drain pore 24%, slow-drain pore 6%, saturated water content 58%, residual water content 31%, and air-entry head 3 cm. Furthermore, ash content was 4.3%, organic matter was 95.7% and C-organic was 47.8%.
In the burnt sites on marine-clays in DST (Figure 12), the color of the surface soil was black, and there were no ashes left on the soil surface, which might have been swept away by rainwater and tides. There were no considerable differences in the physical properties of the peats in the three sites. In average, bulk density was 0.48 g/cc, particle density 1.45 g/cc, porosity 69%, permeability 0.07 m/h, available water 13%, fast-drain pore 17%, slow-drain pore 7%, saturated water content 57%, residual water content 32%, and air-entry head 46 cm. Furthermore, ash content was 78.9%, organic matter was 21.0% and C-organic was 10.9%.

3.4. PU Kalsel
The burnt site in the peatlands was inside the oil palm plantation (Figure 13), which has been covered entirely with bushes and wild trees. In some spots, there were replanted oil palm trees, but most of the trees with burnt leaves survived and regrew. The peat layers over the burnt site were very thin, underlying by marine clay, and in some spots, were not present. The marine clay also was the primary soil type in the protected forests.

The physical properties of the soils were not significantly different. In average, the bulk density was 0.34 g/cc, particle density 1.19 g/cc, porosity 71%, permeability 0.05 m/h, available water 23%, fast-drain pore 23%, slow-drain pore 6%, saturated water content 68%, residual water content 19%, and air-entry head 37 cm. Furthermore, ash content was 54%, organic matter was 46% and C-organic was 24%.

3.5. Comparisons of Fresh and Burnt Peats
Figure 14 shows radar charts displaying the fresh (green dots) and after burnt (red dots) peats for the investigated components of peat properties in all locations. The charts, as listed in Table 1, show from the most positive to the most negative changes of the properties.

After having burnt, in average, Air-entry Head changed most positively (21.3%) followed by Permeability (19.6%), Particle Density (15.9%), Bulk Density (10.7%), Available Water (7.4%), Fast Drain Pore (3.9%) and n-Parameter (0.1%). Whereas, Slow Drain Pore changed most negatively (-72.2%) followed by Residual Water Content (-22.5%), Porosity (-7.3%), Saturated Water Content (-6.3%), and m-Parameter (-2.6%). Higher Bulk Density after fires were also investigated elsewhere [10] between 0.087 g/cc to 0.896 g/cc with the average 0.253 g/cc and [22] between 0.07 g/cc to 1.73 g/cc. These values are closer or in a similar range with those of mature or decomposed sapric peats (>0.2 g/cc) [23].
Figure 14. Peat properties in the fresh and burnt peatlands
Those changes, as shown in Table 1, were statistically insignificant though the trends were apparent. Herewith, the increase of Air-entry head, which was also supported by the rise of Available Water, the burnt peats would be more water-retentive. With the increases in Particle Density and Bulk Density, the burnt peats would be denser. With the increases of Permeability and Fast Drain Pore as also indicated by the step decrease of Slow Drain Pore, the burnt peats would be more conducive to the water drain. If the changes were significant, it might be necessary to update the existing drainage scheme to be more adaptable to the new peat properties.

| No | Properties                        | Fresh Peat | Burn Peat | Changes | \( F_{value} \) | \( F_{0.05} \) | Sgnft |
|----|-----------------------------------|------------|-----------|---------|----------------|-------------|-------|
| 1  | Air-entry Head (cm)               | 0.01       | 61.49     | 20.92   | 90.37          | 25.37       | 21.3% |
| 2  | Permeability (cm/h)               | 0.27       | 25.71     | 7.73    | 28.63          | 9.25        | 19.6% |
| 3  | Particle Density (g/cc)           | 0.22       | 0.57      | 0.42    | 0.32           | 0.64        | 0.49  | 15.9% | 0.94 | 3.23 | No |
| 4  | Bulk Density (g/cc)               | 0.10       | 0.28      | 0.19    | 0.12           | 0.27        | 0.21  | 10.7% | 0.70 | 2.74 | No |
| 5  | Available Water (v/v)             | 0.00       | 0.18      | 0.10    | 0.04           | 0.19        | 0.11  | 7.4%  | 0.99 | 2.51 | No |
| 6  | Fast Drain Pore (v/v)             | 0.10       | 0.33      | 0.21    | 0.12           | 0.37        | 0.21  | 3.9%  | 0.42 | 2.51 | No |
| 7  | n-Parameter                       | 1.04       | 1.43      | 1.17    | 1.05           | 1.41        | 1.17  | 0.1%  | 0.21 | 2.51 | No |
| 8  | m-Parameter                       | 0.04       | 0.30      | 0.14    | 0.01           | 0.29        | 0.13  | -2.6% | 0.22 | 2.51 | No |
| 9  | Saturated Water Content (v/v)     | 0.39       | 0.80      | 0.55    | 0.26           | 0.74        | 0.51  | -6.3% | 0.38 | 2.51 | No |
| 10 | Porosity (v/v)                    | 0.39       | 0.80      | 0.61    | 0.30           | 0.76        | 0.56  | -7.3% | 0.65 | 2.51 | No |
| 11 | Residual Water Content (v/v)      | 0.03       | 0.48      | 0.24    | 0.02           | 0.35        | 0.18  | -22.5%| 0.12 | 2.51 | No |
| 12 | Slow Drain Pore (v/v)             | 0.12       | 0.37      | 0.21    | 0.02           | 0.08        | 0.06  | -72.2%| 0.19 | 2.51 | No |

4. Conclusions

Peatland fires that occurred in the investigated sites were generally in the form of surface and crown fires that burned aboveground biomass in acacia plantations, oil palm plantation, and the protected forests. The sources of fire mostly came from protected forests encroached for wood and agriculture, and from disputed lands. The fires burned the peats up to a fewer depth below the soil surface. Positive changes were experienced successively by air-entry head followed by permeability, particle density, bulk density, available water, fast-drain pore, and n-parameter. While negative changes were experienced successively by slow-drain pore, residual water content, porosity, saturated water content, and m-parameter. However, based on the F-test with a probability value of 5%, those all changes were not so significant or considerably small compared to the associated threshold values.

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