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Can Rain Suppress Smoldering Peat Fire?

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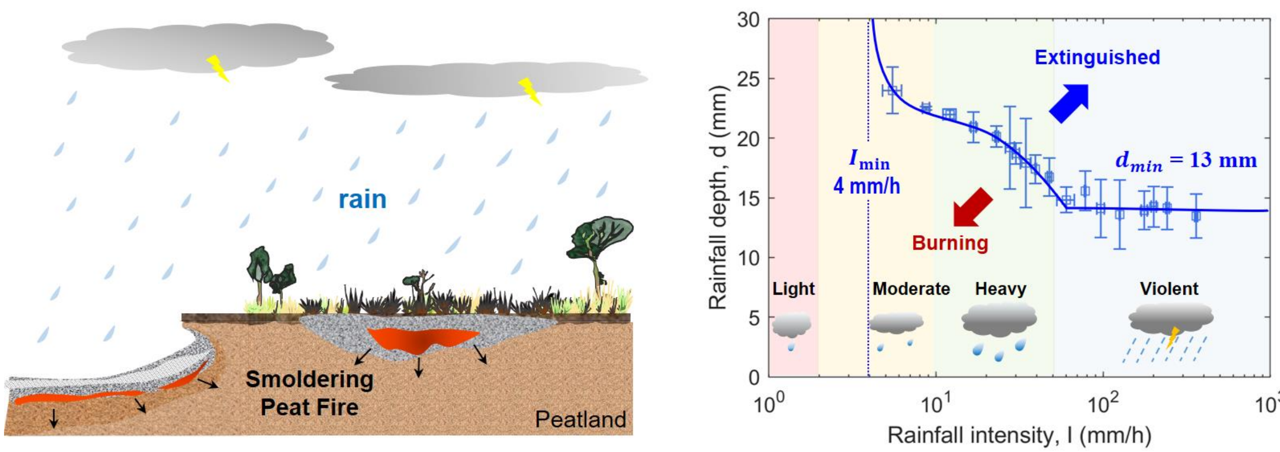
Abstract

Smoldering wildfire in peatlands contributes significantly to global carbon emissions and regional haze events. Smoldering fire in peatlands is one of the largest and most persistent fire phenomena on Earth. Here we assess the underlying mechanism of rain in suppressing the smoldering peat fire in the shallow soil layer up to 15 cm deep through laboratory experiments. We show that the minimum rainfall intensity to extinguish the peat fire is roughly 4 mm/h, so that the persistent light rain cannot suppress such smoldering wildfire. The required rain duration, Δt (min), for extinguishing smoldering peat fire decreases with the rainfall intensities, I (mm/h), as $\log_{10}\Delta t = -1.15\log_{10} I + 3.3$, and is much longer than that for extinguishing flaming wildfire. We also identify that the required rainfall depth for extinguishing peat fire gradually decreases with the rainfall intensity and approaches a minimum value of 13 mm under violent rain. As rainfall intensity increases, the carbon emission flux from peat fire decreases. Therefore, we conclude that the short-term violent rain is most effective for suppressing the persistent smoldering peat fire. This research helps evaluate the impact of weather on the development of peat fire and improve the prediction of carbon emissions from peat fire with the use of regional weather models.

Keywords: Wildland fire; underground fire; fire suppression; rainfall intensity; peatland; carbon emissions

Graphic Abstract



1. Introduction

Peatlands are important ecosystems in the boreal and tropical regions, which not only support the biological diversity for a wide range of wildlife habitats but also store 25% of the planet's terrestrial organic carbon, i.e., approximately the same mass of carbon that is in the atmosphere (Freeman et al., 2001; Page et al., 2011). Peat fire is the driving phenomenon of wildfire in peatlands, such as those that cause widespread destruction of ecosystems and episodes of haze in South Asia, North America, and north-east Europe (Page et al., 2002; Pellegrini et al., 2018; Turetsky et al., 2002, 2015). Peat fire is one of the largest and longest-lasting fire phenomena on Earth, and it can sustain for months and even for years despite extensive rain, weather changes, or fire-fighting attempts (Rein, 2013). Recently in September of 2019, large deposits of peat in Kalimantan and Sumatra were ignited and burned for several months, covering Indonesia and nearby countries with haze and causing the cancellation of enormous flights due to poor visibility (Normile, 2019). Moreover, the annual release of ancient carbon from peat fires is approximately equivalent to 15% of human-made carbon emissions (Ballhorn et al., 2009; Hu et al., 2018; Page et al., 2002; Prat-Guitart et al., 2016; Turetsky et al., 2015; Wakhid et al., 2017).

Peat fire is dominated by smoldering, a slow, low-temperature, and flameless form of combustion (Frandsen, 1997; Rein et al., 2008). Smoldering peat fire is different from regular flaming wildfire in its chemistry, transport processes, and time scales (Rein et al., 2009). Peat can hold a high water content to prevent the ignition, but natural or anthropogenic-induced droughts can increase the risk of peat fire (Sinclair et al., 2020; Turetsky et al., 2015). The ignition source for peat fire can be natural, such as lightning, flaming wildfire (Lin et al., 2019b), self-heating (Restuccia et al., 2017), and volcanic eruption, or anthropogenic, such as deforestation, poor land management, accidental ignition, and arson (Rein, 2013). Most recent peat fires were initiated on the surface by the flaming wildfires. The probability of ignition depends on the moisture content, mineral content, and other physicochemical properties (Benscoter et al., 2011; Frandsen, 1997; Huang et al., 2016; Lin et al., 2019b; Restuccia et al., 2017). Once ignited, smoldering fire can easily burn out an organic soil layer of more than 50 cm deep over an extensive area (Ballhorn et al., 2009; Huang and Rein, 2017; Rein, 2013; Wilkinson et al., 2018).

Fundamentally, three approaches can be used to extinguish the fire, that is, burnout, smothering, and cooling (Quintiere, 2006). For peat fire, burnout of peat soils is unacceptable since it will severely destroy the essential peatland resources and ecosystem, as well as release a significant amount of toxic and greenhouse gases into the atmosphere (Hu et al., 2019b, 2019a; Turetsky et al., 2015). Smothering is to extinguish the fire by removing or reducing oxygen. However, peat fire can be sustained in an extremely low oxygen concentration (Belcher et al., 2010; Huang and Rein, 2016), and there is neither a natural mechanism nor a manmade technique to prevent the diffusion of oxygen into the soil layer in the field scale. Therefore, quenching the peat fire by different cooling methods is the only practical approach, and water is the most widely used cooling agent in firefighting efforts. In reality, peat fire can also be quenched under several conditions, (i) the presence of an inorganic soil layer; (ii) the presence of a thick wet soil layer; (iii) the suppression of heavy continuous rains, and (iv) active firefighting (Migalenko et al., 2018; Rein, 2013). However, compared with extensive studies on the ignition and development of peat fire, very few studies are available on how to extinguish these smoldering wildfires.

Because of the persistence of peat fire, a short-term man-made water spray is not able to stop the fire spread (Ramadhan et al., 2017). Compared to flaming wildfire, smoldering wildland fire require at least 50% more water to extinguish the same amount of burning fuel (Rein, 2013). Some chemical foaming agents can easily penetrate into peat soil and shield the burning peat particles from the oxygen supply (Ratnasari et al., 2018), but the required quantity to suppress any real peat fire is enormous. In fact, limited trials in the literature have demonstrated the ineffectiveness of all man-made suppression methods in controlling or extinguishing any massive peat fire (Dianti et al., 2018; Mikalsen et al., 2018; Ramadhan et al., 2017). On the other hand, the authors have identified a research gap surrounding the natural suppression of peat fire by rain.

Rain is a crucial part of the Earth's water cycle (Jash et al., 2019; Seely and Louw, 1980), and it may decelerate the wildfire spread by wetting the fuels and even directly extinguish the flame (Sedona, 2018). For the recent wildfire in Amazonas, Brazil, the burning area decreased significantly when the regional rainfall increased (Vasconcelos et al., 2013). Although the suppression effect of rain on smoldering wildfire is still mostly unknown, it is hypothesized that the rain droplets can penetrate into the burning peat layer, and if the rainwater can overcome the combustion heat, eventually peat fire can be quenched. Nevertheless, if the peat fire was not entirely extinguished by rain, re-ignition could happen after an extended time, especially when the drought season arrives (Huang and Rein, 2019; Ramadhan et al., 2017). Thus, it is necessary to thoroughly explore the effectiveness of rain in suppressing peat fire and identify the critical rainfall intensity and depth.

Herein, well-controlled experiments were conducted to explore the possibility of the suppression of smoldering peat fire by rain. Rainfall intensities (I) of 'light (< 2 mm/h),' 'moderate (2-10 mm/h),' 'heavy (10-50 mm/h),' and 'violent (>50 mm/h)' were tested up to 400 mm/h. The required rainfall duration (Δt), rainfall depth (d), as well as, the mass loss per unit area of peat sample ($\Delta m''_p$) and carbon emissions of peat fire ($\Delta m''_C$) under different rainfall intensities were analyzed in detail. The minimum rainfall intensity (I_{min}) and rainfall depth (d_{min}) to extinguish the peat fire was also quantified.

2. Materials and Methods

2.1. Peat soil sample.

The organic-rich moss peat soil (Fig. 1) tested in the experiment came from the Netherlands, and it had an organic matter of about 96%. The bulk density of oven-dried peat was measured to be 145 kg/m^3 (±5%). The peat sample had an open-pore structure and an overall porosity of about 0.90. The element analysis for the peat organic matter showed 44.2/6.1/49.1/0.5/0.1% mass fraction for C/H/O/N/S, respectively (Lin et al., 2019b). Because peat soils could become hydrophobic under a high-temperature drying process (Bryant et al., 2005; Hatten and Zabowski, 2010; Perdana et al., 2018), all peat samples were dried in an oven at a constant temperature of 40 °C, which is close to the ambient temperature of tropical regions in the dry season. During the drying, the weight and moisture content of peat were measured every 1 h until its moisture content was close to 50 ± 5%, and its (wet) bulk density reached 218 ± 10 kg/m^3. The peat sample was similar to the natural drought condition found in previous work (Huang et al., 2016; Lin et al., 2019b; Watts, 2012). Afterward, samples were stored in the sealed boxes for homogenization. Before the experiment, the subsample of peat was collected and dried to ensure the value of sample moisture content.

2.2. Initiation of peat fire

The peat sample was placed in a mesh basket of a cylindrical shape with a diameter of 100 mm and a height of 150 mm (Fig. 1). During the filling-in process, the peat samples were shaken to ensure the bulk density of moist peat was close to 218 kg/m^3, and the sample mass was 256 ± 5 g.

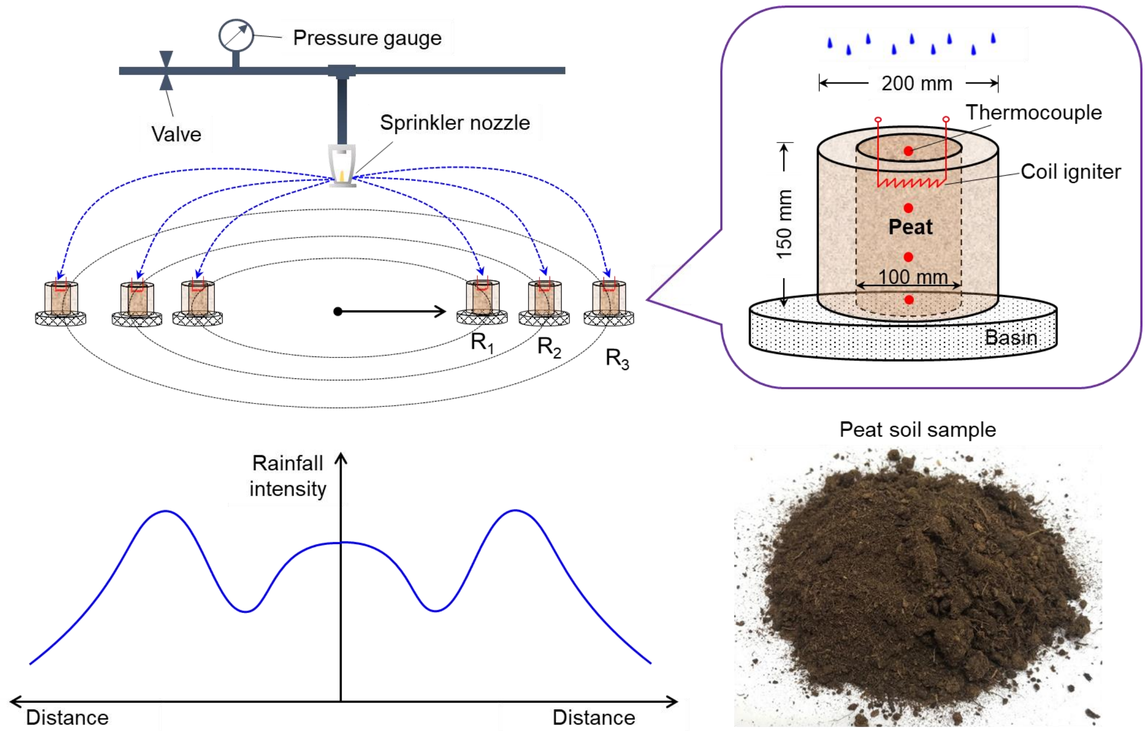


Figure 1. Experimental materials and setup. Photo of peat soil sample for smoldering fire suppression test and the illustration of rain suppression simulated by a sprinkler system and rainfall intensity distribution.

For ignition, an 8-cm long coil igniter ($Cr_{20}Ni_{80}$) was placed 5 cm below the top free sample surface to start the smoldering peat fire. The ignition power was fixed to 60 W for 60 min to initiate a robust peat fire (Ramadhan et al., 2017). The temperature profiles of peat at 0 cm (surface) and 5 cm, 10 cm and 15 cm below the top surface were carefully monitored using armored K-type thermocouples with 1-mm probe diameter. After ignition, the basket of peat sample was placed into a larger cylindrical mesh basket with a diameter of 200 mm and a height of 150 mm. In order to simulate the natural state and mimic a real boundary condition, the space between two baskets was filled with unheated peat soils (see more details in Fig. S1 of *Supplemental Materials*). Afterward, the entire setup was left to burn and self-stabilize for another 30 min before the start of rain suppression.

2.3. Simulated rain

The simulated rain-suppression experiments were conducted in a wet chamber with an area of 6 m × 10 m and a height of 3.5 m. The artificial rain was produced by a water sprinkler system that included a sprinkler nozzle, a pressure gauge, and a valve, as illustrated in Fig. 1. The vertical distance between the nozzle and the sample surface was fixed to 2.5 m. The median water droplet diameter depends on the water pressure, sprinkler orifice diameter, and the surface tension of the air-water interface (0.073 N/m). The value of the median water droplet diameter was calculated to be about 1.5 mm (see Eq. S1 in *Supplemental Materials*), which is within the range of typical raindrop sizes (Pruppacher and Klett, 1978). Therefore, the simulated raindrop size in this experiment is close to the natural rain. With the sprinkler spray, the intensity of simulated rainfall changed with the location. Thus, the distribution of rainfall intensity (Fig. 1) was measured by multiple cylindrical containers (with a diameter of 10 cm and a height of 15 cm) at the interval of 20 cm. Given a fixed rainfall duration ($\Delta t = 10$ min), the local rainfall intensity can be calculated by measuring rainfall depth (d) as $I = d/\Delta t$. Then, the desired rainfall intensity can be achieved by placing the burning sample at a specific location. The measured distribution of simulated rainfall intensity can be found in Fig. S2.

2.4. Experiment procedure

The rain-suppression experiments were conducted to determine the required rainfall duration (Δt), rainfall depth (d), as well as, the mass loss per unit area of peat sample ($\Delta m''_p$) and carbon emissions of peat fire ($\Delta m''_C$) under different rainfall intensities. After igniting the peat fire for 60 min and stabilizing the burning for another 30 min, the sprinkler system was activated for a prescribed duration (see more details in Fig. S1 and Videos S1 and S2).

Unlike the suppression of a flame, it was not possible to instantaneously determine by visual inspection whether the smoldering peat fire was extinguished or not (Ramadhan et al., 2017). Thus, after the artificial rainfall, the sample was left for another 24 h to determine if the peat fire survived or not. If the temperatures inside the sample re-rose above 250℃, i.e., the minimum smoldering temperature of peat (Lin et al., 2019b), and the peat sample eventually burned out, the fire-suppression was considered as a failure. Then, experiments were continued with fresh peat samples under a longer rainfall duration until the critical rainfall duration and depth were found.

For the extinguished peat fire, the sample residue was oven-dried at 100 ℃ for 48 h to obtain the end dry mass (m_e). The mass loss quantified the carbon emissions of peat fire under different suppression activities. To measure the mass loss during fire suppression, the initial sample mass (m_i) after the 90-min ignition and burning stage was first measured. After the initial burning stage, the sample was immersed into 8-L water for quick extinction, and then dried in the oven to obtain m_i. Thus, the burning mass flux of peat ($\Delta m''_p$ in kg/m^2) under different rainfall intensities is

$$\Delta m''_p = \frac{m_i - m_e}{A} \qquad (1a)$$

where $A = 8\times10^{-3}$ m^2 is the cross-section area of the cylindrical peat sample. For this peat soil, the mass fraction of carbon is around 44% (Lin et al., 2019b; Lin and Huang, 2020), so that the carbon emissions ($\Delta m''_C$ in kg/m^2) can then be estimated as

$$\Delta m''_C = 44\%\Delta m''_p \qquad (1b)$$

Note that CO_2, CO, CH_4, and NH_3 are the four major gas species emitted from peat fire (Hu et al., 2019a). Comparatively, CO_2 and CH_4 are the dominant greenhouse gases, but CO and NH_3 are toxic gases and can impact the atmosphere through the photochemical process (Hu et al., 2019a; Urbanski, 2014).

2.5. Control experiments

The baseline experiment of peat fire was conducted without any rain suppression, so that the burning characteristics were compared with those with different levels of rain suppression. To compare the required rainfall duration for extinguishing smoldering and flaming wildfires, the rain-suppression experiment for flaming wood cribs fire was also conducted. The wood crib was made of cylindrical wood rods with a length of 8 cm and a diameter of 1 cm (Lin et al., 2019a) (see Fig. S3), which aimed to mimic the common flaming fire on twigs and was similar to past studies (Rappsilber et al., 2019). The flaming wood crib had a burning area similar to the smoldering peat fire, thus, ensuring fair comparison. The wood cribs were ignited by a lighter for 1 min, followed by 1 min of self-burning before the artificial rain suppression. The extinguishing limit of the flaming wood crib was determined in the same way as the smoldering peat fire.

3. Results and Discussion

3.1. Effectiveness of fire suppression by rain

The effectiveness of rain of different intensities on suppressing peat fire is quantified against the rainfall duration (Δt), rainfall depth (d), mass loss of burning peat ($\Delta m''_p$), and carbon emissions per unit area of peat fire ($\Delta m''_C$) in Fig. 2. We found that the minimum rainfall intensity (I_{min}) to be roughly 4 mm/h (Fig. 2a), below which the peat soil could completely burnout like those without any rain suppression. Therefore, the smoldering peat fire may not be suppressed by a light rain regardless of the rainfall duration. Moreover, as expected, required suppression duration decreases with increasing rainfall intensity (Nmira et al., 2008).

For example, when the rainfall intensity increases from 30 mm/h to 100 mm/h, the required suppression duration decreases from 40 ± 3 min to 10 ± 1 min. An empirical correlation between the suppression duration and the rainfall intensity can be formulated as

$$\log_{10} \Delta t = -1.15 \log_{10} I + 3.3 \tag{2}$$

where common units of min for Δt and mm/h for I are used. The logarithm with base 10 is used in fitting with the R^2 coefficient of 0.99, and excellent linearity is shown in Fig. 2b.

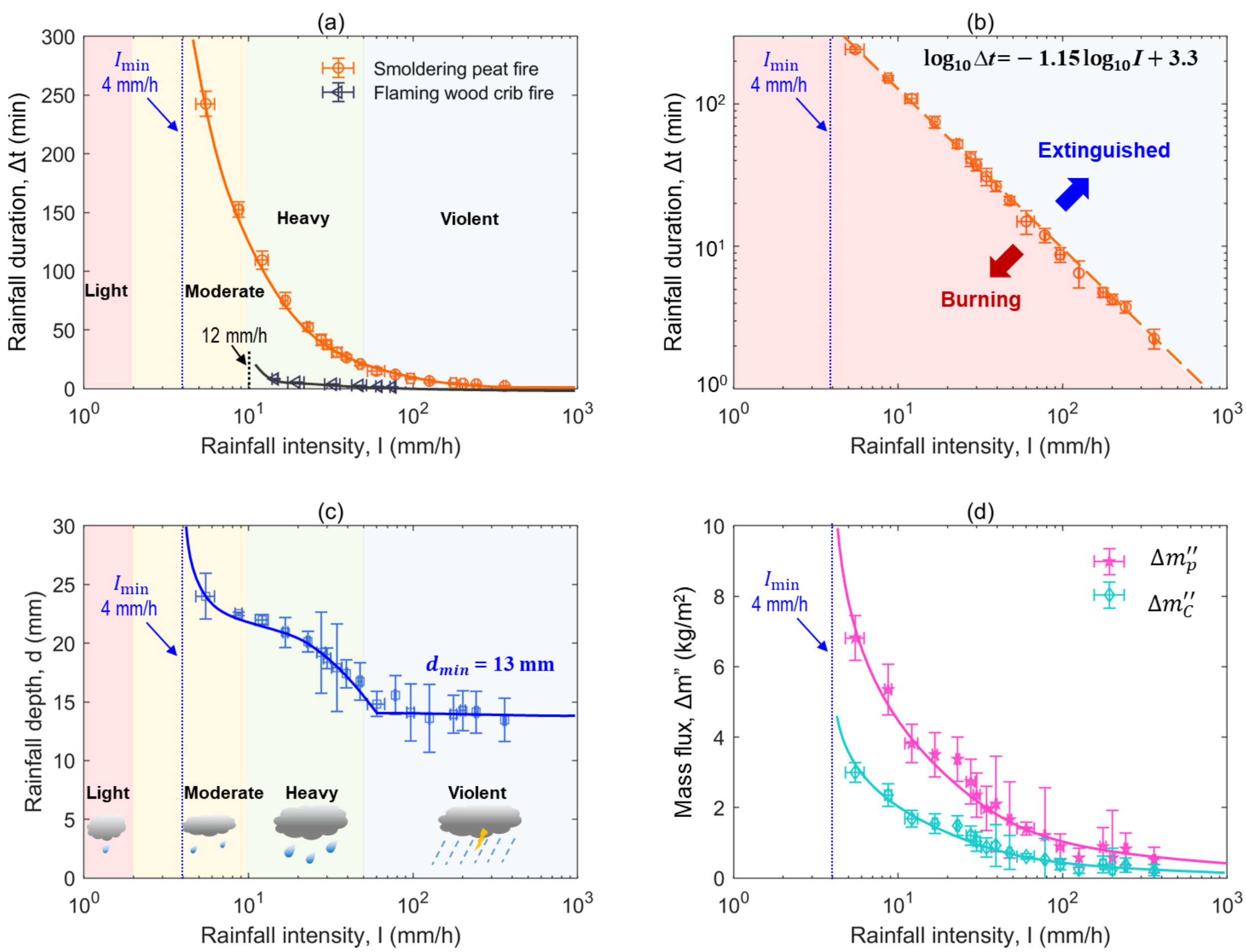


Figure 2. Limiting conditions for extinguishing smoldering peat fire by rain. (a) The rainfall intensity vs. duration, (b) base-10 logarithm of suppression duration, (c) rainfall depth, (d) minimum mass loss of dry peat and carbon

emissions, where the error bars show the standard deviation. The images and videos of fire suppression by rain are shown in *Supplemental Materials*.

Figure 2a further compares the required suppression duration between the smoldering peat fire and flaming wood-crib fire. Under the same rainfall intensity, the suppression duration of smoldering peat fire is much higher than that of flaming wood crib fire. For example, when the rainfall intensity is around 125 mm/h, the required suppression duration for smoldering peat fire is about 7 min, while for flaming wood crib fire, only 20 s is required for extinguishing the flame. For peat fire, the water in fuel beds tends to find the path of least flow resistance (Jacobsen et al., 2003; Mikalsen et al., 2018), and the peat soil becomes hydrophobic after high-temperature heating from the smoldering combustion (Moore et al., 2017; Perdana et al., 2018; Wu et al., 2020). Therefore, it is more difficult for rainwater to arrive and remain in the underground burning zone. In contrast, for the flaming wood crib, raindrops can reach and cool the burning wood more directly and effectively. An empirical correlation for rain suppression of the flaming wood-crib fire, $\log_{10} \Delta t = -\log_{10} I + 1.9$, can also be obtained, where the R^2 coefficient was found to be 0.92 (see more details in Fig. S4). The minimum rainfall intensity to suppress the flaming wood-crib fire was identified as about 12 mm/h (i.e., a heavy rain), which was much larger than 4 mm/h found for the smoldering peat fire. Because the power or heat release rate of flaming fire is much greater than that of smoldering fire, greater threshold for rainfall intensity is expected to suppress a flame.

As shown in Fig. 2c, once the rainfall intensity exceeds I_{min} (4 mm/h), the required rainfall depth also shows a negative correlation with the rainfall intensity, following a similar trend of required rainfall duration in Fig. 2a. In particular, when the rainfall intensity increases from 30 ± 1 mm/h to 40 ± 2 mm/h, the rainfall depth decreases from 19 ± 1 mm to 17 ± 1 mm. More importantly, when the rainfall intensity further increases, the rainfall depth gradually approaches a critical value (~13 mm) for the violent rain, which can be defined as minimum rainfall depth (d_{min}).

Figure 2d compares the mass loss of peat per unit area after successful suppression. As expected, the burning mass loss of peat decreases with the increase in rainfall intensity, indicating that more peat soils were consumed under lighter rain. For example, when the rainfall intensity increases from 30 mm/h to 100 mm/h, the mass loss decreases from 2.4 ± 0.6 kg/m^2 to 0.9 ± 0.3 kg/m^2 (see more details in Table S1). When the rainfall intensity is very small, rainwater will be quickly evaporated by the hot smoldering fire, and the rainwater cannot penetrate the burning zone, resulting in a maximum mass loss (Ramadhan et al., 2017). With a heavier rain, the burning zone is slowly penetrated and cooled by rainwater, meanwhile the smoldering fire continues to spread downward and burn out more fresh soil. With a violent rain, raindrops can flush over the soil layer to immediately extinguish the fire and minimize the burning of peat (see more details in Fig. 3 and S5). Figure 2d also estimates the corresponding carbon emissions per unit area from peat fire under different rainfall intensities, considering that the carbon content of this peat is about 44%. With the correction of rainfall influence, the prediction of carbon emissions from the peat fire can be improved and combined with the regional wildfire weather model (Coen and Schroeder, 2013).

3.2. Peat fire behaviors under rain suppression

Baseline experiments were conducted to determine the burning characteristics of the smoldering peat fire without the influence of rain. Once the peat was ignited and started to spread downward, a thin black char layer was formed on the free surface, which did not convert into white ash. The black char layer has also been observed in the field, because of large heat loss to the environment (Huang and Rein, 2017).

Below this thin char layer, there was a white ash layer as the char was further oxidized (Huang and Rein, 2019).

Figure 3a shows a group of thermocouple measurements of the baseline experiment, where the typical smoldering spread over a 15 cm-deep sample lasted for about 6 h. During the forced ignition by the coil heater, the temperature near the ignition zone (i.e., $T_{-5\text{ cm}}$ at 5 cm below the free surface) first increased and then remained stable at around 100 °C, indicating the robust on-going process of water evaporation. After a short period of drying, $T_{-5\text{ cm}}$ rapidly increased to a peak of around 500 °C. Once the coil igniter was off, $T_{-10\text{ cm}}$ (10 cm below the surface) first dropped but soon increased again, indicating that the smoldering fire becomes self-sustained (Huang and Rein, 2017). Meanwhile, both T_0 and $T_{-5\text{ cm}}$ decreased due to burnout, and the thermocouple started to record the gas temperature, showing a high-frequency fluctuation. Figure 3b show the temperature evolution of peat fire under a rainfall intensity of 3 mm/h for more than 500 min. Despite of some fluctuation, the temperature evolutions are similar to the baseline measurement, and the entire 15-cm deep peat was burnout before the rain stops. In other words, a rainfall of 3 mm/h cannot suppress the smoldering peat fire.

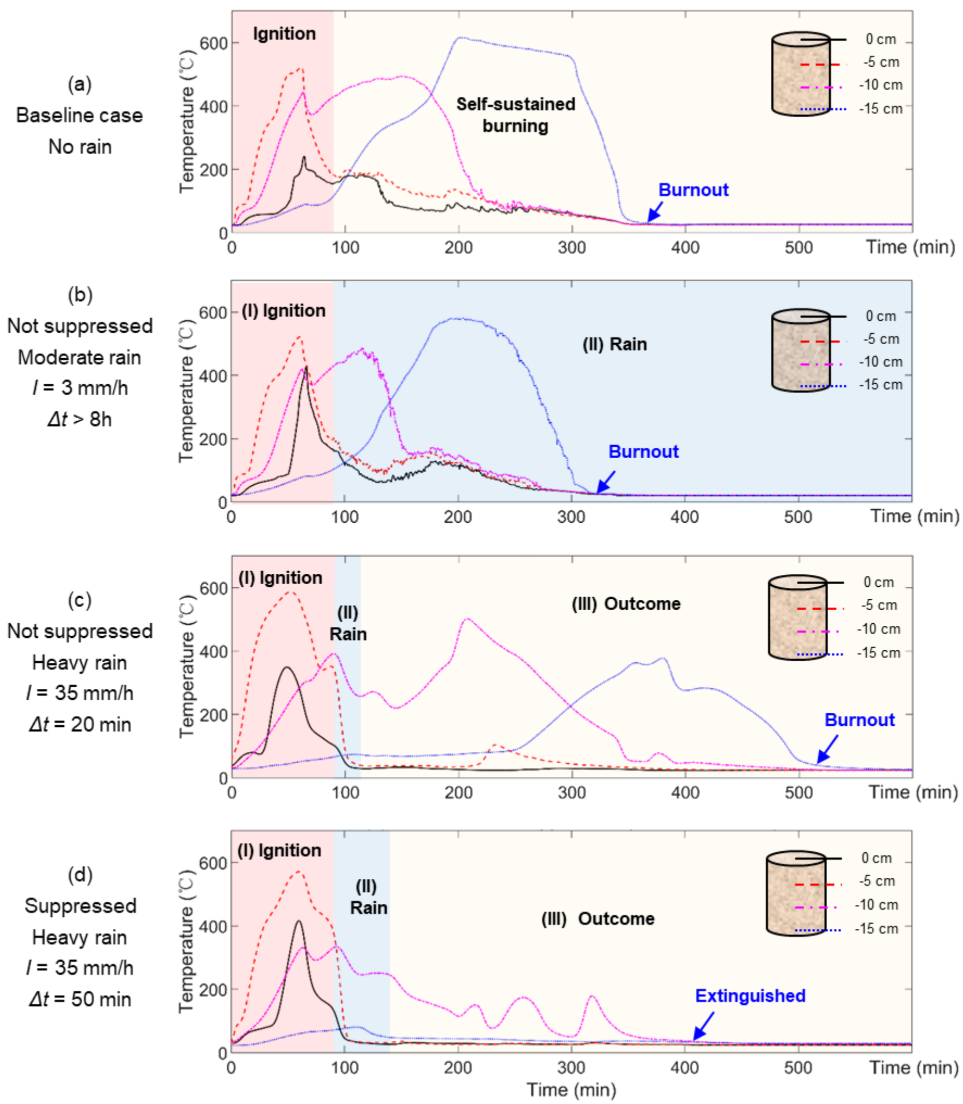


Figure 3. Temperature measurements of the baseline and rain-suppression fire experiment, (a) baseline experiment, (b) failed fire suppression with rainfall intensity of 3 mm/h for more than 500 min, (c) failed fire suppression with rainfall intensity of 35 mm/h for 20 min, and (d) fire suppression with rainfall intensity of 35 mm/h for 50 min.

Figure 3c-d compares the temperature evolutions of peat fire under a rainfall intensity of 35 mm/h (i.e., heavy rain) for 20 min (failed suppression) and 50 min (successful suppression). More temperature profile measurements can be found in Fig. S5. To better analyze the burning and suppression processes, we divided the temperature profile into three stages: (I) ignition and burning, (II) rain suppression, and (III) outcome. After the forced ignition for 60 min and following self-sustained burning for another 30 min, the surface of the peat sample shrank, exposing the thermocouples (T_0 and $T_{-5\text{ cm}}$). Once the simulated rain was activated (Stage II), those exposed thermocouples were directly cooled by raindrops to the ambient temperature. In the early stage of rain suppression, due to the intense water evaporation in the burning zone and the absorption of peat soils in the upper layer, it was difficult for raindrops to penetrate to deeper regions, so the decrease of $T_{-10\text{ cm}}$ was small. For the same reason, the temperature at the bottom ($T_{-15\text{ cm}}$) even increased initially.

For the failed fire suppression (Fig. 3c) after raining for 20 min, the visible white smoke was likely water vapor, because the measured temperature was still higher than 200 ℃. It was not possible to immediately determined by visual inspection whether the peat fire was suppressed or not, so that the in-situ detection of real underground peat fire remains a great challenge (Huang and Rein, 2019). With thermocouple readings, we found in Stage III the $T_{-10\text{ cm}}$ first fluctuated shortly, and then showed a sudden increase to above 500 ℃, indicating a failed fire suppression. Despite the top peat layer that was wetted and extinguished by rain, they would be soon re-ignited. Eventually, the entire peat sample was burnout like the base case in Fig. 3a, except that the burning duration increased to about 500 min. Note that a short rain duration can still wet the peat and slow down the fire spread, although it may not extinguish the peat fire. Therefore, after rainfall, human firefighting effort will become more effective to extinguish the persistent peat fire completely.

For the successful fire suppression (Fig. 3d), white smoke was also observed from peat after raining for 50 min. Afterward, despite some fluctuations, $T_{-10\text{ cm}}$ gradually decreased to ambient temperature, and re-ignition did not occur, because the minimum temperature for igniting smoldering peat fire of about 250 ℃ (Lin et al., 2019b) was not reached (also see thermal analysis in Fig. S6). Considering the self-ignition risk of peat (Restuccia et al., 2017), peat fire cannot be fully extinguished unless the sample temperature profile is lower than the self-ignition point. It is recommended that the suppression effort should be extended until the measured sample temperature was below 80 ℃ (Ramadhan et al., 2017). Setting a more sophisticated criterion for the successful suppression of peat fire needs more lab and field experiments.

3.3. Minimum rainfall intensity for extinguishing

For rainfall intensity lighter than 4 mm/h, the smoldering peat fire behavior is similar to that without rainfall, as compared in Fig. 3a-b. In other words, the rainwater will be directly evaporated by the hot burning zone on the surface layer (Fig. 4a), so that raindrops are not able to penetrate through the burning zone regardless of rainfall duration. As the rainfall intensity reaches the level of moderate and heavy rain (4-50 mm/h), the rainwater starts to penetrate and cool the burning zone (Fig. 4b). Thus, as the rainfall intensity increases, the required suppression duration and rainfall depth, as well as, the carbon emissions are reduced. For a violent rain (>50 mm/h), a large amount of rainwater quickly flushes over and cools down the burning soil layer, and eventually quenching the smoldering peat fire (Fig. 4c). With the extinction limits obtained in Fig. 2, it is possible to identify the effectiveness of rainfall in suppressing peat fire in situ, evaluate the probability of re-ignition after rain, and provide more information to guide the follow-up human firefighting activities.

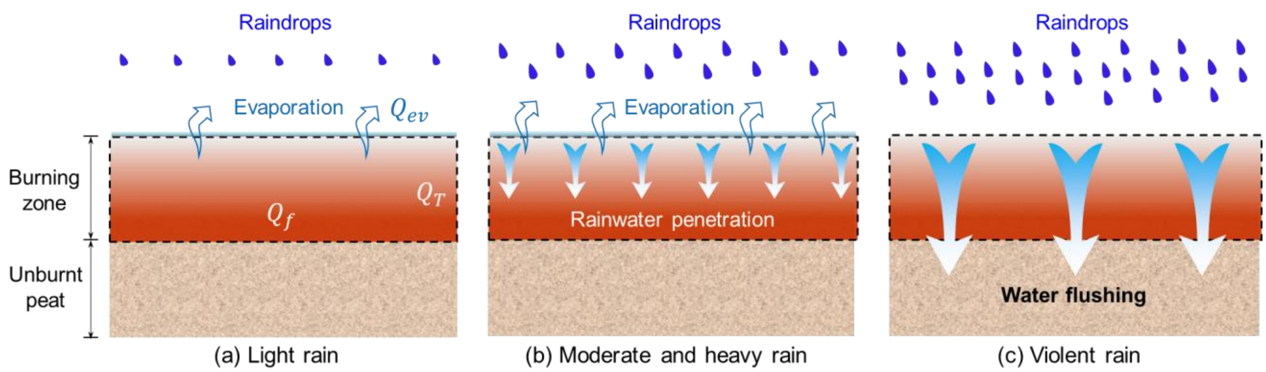


Figure 4. Different modes of rain suppression. (a) Light rain where all raindrops are evaporated by the smoldering peat fire, and (b) moderate and heavy rain where raindrops penetrate to the burning zone, and (c) violent rain where the rainwater flushes through the burning zone.

To scientifically understand the suppression limit of the peat fire, the minimum temperature to sustain the smoldering peat fire ($T_{min} \approx 250$ ℃) is defined (Lin et al., 2019b). Below this threshold or ignition temperature, the exothermic char-oxidation reaction becomes too weak to overcome the environmental cooling and maintain the peat fire. Then, an energy-conservation equation is proposed to explain the process of rain suppression. At the extinction limit, the heat released from the smoldering fire zone (Q_f) during rainfall and the extra thermal energy stored in peat (Q_T) should able to evaporate all raindrops (Q_{ev}) as

$$Q_f + Q_T = Q_{ev} \tag{3a}$$

which can be further expressed as

$$\dot{m}''_p \Delta H_{sm} \Delta t + \delta_{sm} \rho_p c_p (T_{sm} - T_{min}) = d \rho_w \Delta H_w \tag{3b}$$

where $\dot{m}''_p$ is the burning flux of peat fire, ρ_p is the dry peat density, ΔH_{sm} is the heat of smoldering combustion, δ_{sm} is the thickness of the smoldering reaction zone, c_p is the specific heat of peat, T_{sm} is the instant smoldering temperature, T_{min} is the minimum temperature for smoldering fire, d is the rainfall depth, ρ_w is the water density, and ΔH_w is the overall heat of vaporization of water.

The minimum rainfall intensity (I_{min}) occurs when the rainwater only balance the heat release without weakening the burning zone ($Q_c = Q_{ev}$), as shown in Fig. 4a. Otherwise, the burning zone will become smaller and eventually extinguish. Thus

$$\dot{m}''_p \Delta H_{sm} \Delta t = d \rho_w \Delta H_{ev} = I_{min} \Delta t \rho_w \Delta H_w \tag{4a}$$

By reorganizing, the minimum rainfall intensity ($I_{min,cal}$) can be calculated as

$$I_{min,cal} = \frac{\dot{m}''_p \Delta H_{sm}}{\rho_w \Delta H_w} \tag{4b}$$

where $\dot{m}_p'' = 0.2$ g/(m^2·s^1), ρ_w= 1000 kg/m^3, and $\Delta H_w = c_w(T_b - T_a) + \Delta H_{ev}$ = 2.4 MJ/kg are found from the literature (Huang and Rein, 2017; Lin et al., 2019b). The calculated minimum rainfall intensity is 3.3 mm/h, close to the experimental measurement of 4 mm/h.

3.4. Minimum rainfall depth

Once the rainfall intensity exceeds the minimum value, the extra rainwater will start to penetrate and wet the burning fire zone (Fig. 4b). With I_{min}, Eq. 3b can be expressed as

$$\delta_{sm}\rho_p c_p(T_{sm} - T_{min}) = (I - I_{min})\Delta t \rho_w \Delta H_w \tag{5a}$$

Then, we can estimate the required rainfall depth (d) given a rainfall intensity (I)

$$d = \varphi \frac{I}{I - I_{min}} \tag{5b}$$

where $\varphi = \delta_{sm}\rho_p c_p(T_{sm} - T_{min})/(\rho_w \Delta H_w)$ is a constant for the given peat soil. Therefore, the required rainfall depth decreases with the increasing rainfall intensity, agreeing with Fig. 2c.

When the rain becomes violent (I > 50 mm/h), the required suppression duration is very short ($\Delta t \to 0$), and the temperature of rainwater will not increase to 100 °C to trigger massive evaporation (see Fig. 4c). Thus, both the chemical energy and water evaporation can be neglected. Then, a minimum amount of rainwater (d_{min}) is required to directly quench the burning zone ($Q_T = Q_{ev}$) as

$$\delta_{sm}\rho_p c_p(T_{sm} - T_{min}) = d_{min}\rho_w c_w(T_w - T_a) \tag{6a}$$

where T_w is the temperature of rainwater after flushing through the burning zone. Therefore, the minimum rainfall depth can be expressed as

$$d_{min} = \frac{\delta_{sm}\rho_p c_p(T_{sm} - T_{min})}{\rho_w c_w(T_w - T_a)} \tag{6b}$$

Given that $\delta_{sm} \approx 0.1$ m, $\rho_p = 145$ kg/m^3, and $T_{sm} \approx 400$ ℃ measured from experiments (Huang et al., 2016; Huang and Rein, 2017), as well as, literature values of $c_w \approx 4.2$ kJ/(kg·K), $c_p \approx 2$ kJ/(kg·K) and $T_{min} = 250$ ℃ (Lin et al., 2019b), and $T_{w,max} = 100$ ℃, we can then calculate the upper limit of minimum rainfall depth to be 15 mm, which also successfully explains the experimental measurement of 13 mm.

Note that current fire-suppression experiments are conducted for the peat fire in the shallow soil layer up to 15 cm deep, which is the first step to understand the effectiveness of rain and other water-based strategies in suppressing peat fire. The peat fire in the field can also survive in the deep soil layer (Huang and Rein, 2019; Rein, 2013). These deep underground peat fires can be more difficult to suppress, requiring a longer rainfall duration and a larger rainfall depth. Therefore, more experiments will be conducted in the future to investigate rain suppression of deep underground peat fire with larger-scale field experiments, where the fire-suppression effectiveness by the varied rainfall scenarios will be explored.

4. Conclusions

In this research, we assess the underlying mechanism of rain in suppressing the peat fire in the shallow soil layer up to 15 cm deep through laboratory experiments. The minimum rainfall intensity to extinguish the peat fire is found to be roughly 4 mm/h, so that the persistent light rain cannot extinguish such smoldering wildfire. The required rainfall duration, Δt (min), for extinguishing peat fire decreases with the rainfall intensities, I (mm/h), as $\log_{10}\Delta t = -1.15\log_{10} I + 3.3$. For example, for a heavy rain of 30 mm/h, it takes at least 40 min to extinguish the smoldering peat fire near the ground surface. Such a required rainfall duration is much longer than that for a small flaming wildfire ($\log_{10}\Delta t = -\log_{10} I + 1.9$).

We also identify that the required rainfall depth to extinguish the peat fire gradually decreases with the rainfall intensity and approaches a minimum value of 13 mm under violent rain. As rainfall intensity increases, the carbon emission flux from peat fire decreases. Therefore, the short-term violent rain is most effective for extinguishing the persistent peat fire. This research helps evaluate the impact of weather on the development of peat fire and improve the prediction of global carbon emissions from peat fire with the use of regional weather model.

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CRediT author statement

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