

Laboratory study on the suppression of smouldering peat wildfires: effects of flow rate and wetting agent

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Abstract. The application of water, or water mixed with suppressants, to combat wildfires is one of the most common firefighting methods but is rarely studied for smouldering peat wildfire, which is the largest type of fire worldwide in term of fuel consumption. We performed experiments by spraying suppressant to the top of a burning peat sample inside a reactor. A plant-based wetting agent suppressant was mixed with water at three concentrations: 0% (pure water), 1% (low concentration), and 5% (high concentration), and delivered with varying flowrates. The results showed that suppression time decreased non-linearly with flow rate. The average suppression time for the low-concentration solution was 39% lower than with just water, while the high-concentration solution reduced suppression time by 26%. The volume of fluid that contributes to the suppression of peat in our experiments is fairly constant at $5.7 \pm 2.1 \text{ L kg}^{-1}$ peat despite changes in flow rate and suppressant concentration. This constant volume suggests that suppression time is the duration needed to flood the peat layer and that the suppressant acts thermally and not chemically. The results provide a better understanding of the suppression mechanism of peat fires and can improve firefighting and mitigation strategies.

Keywords: experiment, fire, firefighting, mitigation, peatland, smouldering, suppression, wetting.

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Introduction

Wildfires can be driven by two types of combustion, i.e. flaming or smouldering (Rein 2013). A flaming wildfire is the result of homogeneous reactions between oxygen and gaseous pyrolysis products such as the burning of some of the ground covering vegetation, while smouldering wildfire is the heterogeneous reaction between oxygen and solid char, such as the burning of peat (Rein 2016). Flaming wildfires are characterised by rapid spread rates (600 cm h^{-1}), high temperatures ($\sim 1200^\circ\text{C}$) and a visible flame sheet, and smouldering wildfires are characterised by a slow ($\sim 6 \text{ cm h}^{-1}$), low-temperature ($\sim 500^\circ\text{C}$), flameless form of combustion (Ohlemiller 1985; Rein 2016). In general, smouldering wildfires seem to be changing in terms of frequency, size and hazard in some parts of the world (Page *et al.* 2002; Turetsky *et al.* 2015; Walker *et al.* 2019). In terms of emissions, smouldering is more hazardous than flaming (Hu *et al.* 2018). Smouldering peat releases a large amount of ancient carbon that has not been involved in the global carbon cycle for centuries (Walker *et al.* 2019) and therefore contributes to climate change, leading to a further increase of frequency and size of smouldering wildfires (Rein 2013). Large-scale peatland fires are subject to suppression efforts but typically only stop when the rainy season arrives, e.g. peatland fires in Southeast Asia in 1997 and 2015 (Page *et al.* 2002; Huijnen *et al.* 2016),

illustrating the persistency of smouldering and difficulty in suppressing such fires (Rein 2013; Ramadhan *et al.* 2017; Lin *et al.* 2020). In pristine conditions, peatlands are naturally protected from burning because of their high moisture content, which can be up to 300% of dry basis mass in flooded condition (Moreno *et al.* 2011; Turetsky *et al.* 2015). Because of climate change and human activities, peatlands are drying in many places, which increases the susceptibility of peatlands to fire (Page *et al.* 2002; Turetsky *et al.* 2015).

Flaming wildfires are more common worldwide, spread faster (Ohlemiller 1985; Rein 2016) and cause more direct harm to lives and properties (McCaffrey and Rhodes 2009; Gibbons *et al.* 2012) compared with smouldering wildfires. Hence, most firefighting techniques are developed for flaming wildfires. The same techniques are also employed to fight smouldering wildfires, under the incorrect assumption that both fire types are similar. Techniques commonly used to suppress flaming wildfires include aerial attack by air tanker or helicopter, land attack with water by hose either for flanking the flame front or mopping up residual smouldering fuel, removing vegetation for firebreaks and backburning (Plucinski 2019). Land attack with water, aerial attack and firebreaks are commonly employed to fight smouldering peat fires as well. Different to flaming wildfires, firebreaks in smouldering fires can be made by removing the peat layer (not

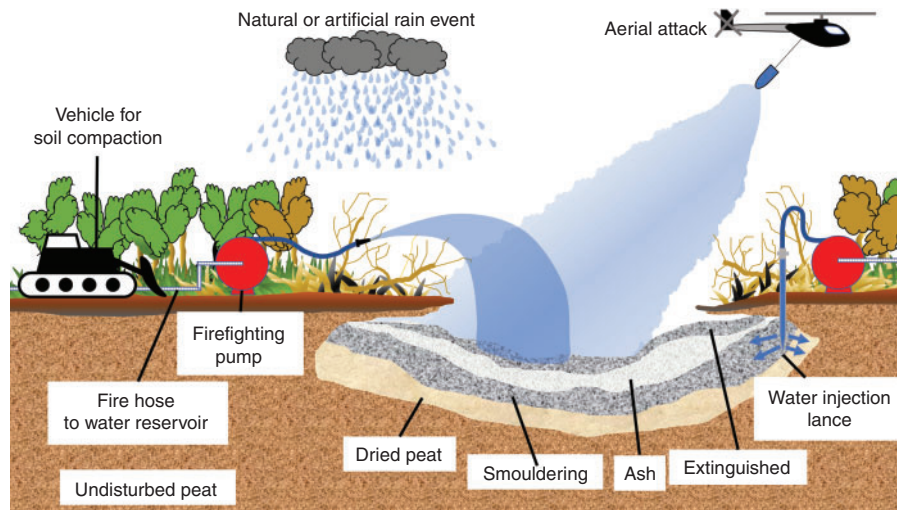


Fig. 1. Direct firefighting methods during peatland fires, including cooling and smothering. Cooling methods shown in this illustration are ground spray, aerial attack and injection lance. The smothering method shown here is through soil compaction to remove the natural oxygen channel network in the peatland soil. In addition, rain events, both natural and artificial, are also illustrated. Illustration by MA Santoso, CC BY.

only the surface vegetation) by digging a ditch along the fire perimeter (Rein *et al.* 2008; Davies *et al.* 2013), or by reflooding the fire area by diverting water from the nearest sources (Neal 2018; Pumps Journalist 2018). Moreover, other unique techniques have also been developed specifically to fight peatland fires. These techniques include soil compaction to reduce oxygen ingress underground (Moreno *et al.* 2011) and water injection to directly attack the fire (Hadden and Rein 2011; Santoso 2020). Another novel method developed to fight smouldering is by burying a cooling pipe (Mikalsen *et al.* 2019). Even though the latter study was conducted in wood pellets, it proved to be effective in suppressing subsurface fire, which is also a behaviour of fire spread in peat. Fig. 1 illustrates several methods employed in the suppression of peatland fires, and natural events, i.e. heavy rain, are also included as they have been shown to successfully suppress large peat fires (Page *et al.* 2002; Huijnen *et al.* 2016). The investigation of the suppression of smouldering peat fire due to rainfall was investigated by Lin *et al.* (2020). They conducted laboratory-scale experiments and varied the rainfall intensity, showing that a minimum rainfall intensity of 4 mm h^{-1} for at least 5 h is needed to successfully suppress peat fire. Another prospective method is by artificially inducing rainfall by seeding clouds with aerosols of dry ice, calcium chloride, calcium oxide and kitchen salt, or by sending salt flares into the clouds (Shukla *et al.* 2010). These techniques increase the water density and make water particle in clouds freeze. Recently, this technique was adopted to fight peatland wildfires in Indonesia (Sutikno *et al.* 2020). This method may help in reducing hotspots and improve air quality in the affected areas.

Owing to the subsurface nature of smouldering fires, it is much harder to detect and to access underground hotspots. As a result, an intuitive suppression approach may prove effective by directly channelling water into the subsurface hotspot with a water injection lance (Fig. 1). This method allows a targeted attack of smouldering hotspots. The efficiency of this method

was investigated in the laboratory for smouldering coal fires (Hadden and Rein 2011) and in smouldering peat field experiments (Santoso 2020), showing lower efficiency (more water required) than spray methods.

Reflooding peatlands by temporally diverting water streams or a municipal supply is generally effective by increasing the moisture content (MC) of the peat above the critical MC of smouldering (Frandsen 1997; Huang *et al.* 2015), thus preventing future ignition and fire spread. Even though flooding requires large volumes of water, up to billions of litres of water, it has been shown to effectively suppress peat fires. Two examples are the 2008 Evans Road Fire in North Carolina, USA, and the 2018 Lake Cobrico Peat Fire in Victoria, Australia. In the 2008 Evans Road Fire, up to ~ 7.5 billion L of water was pumped from nearby lakes to reflood the peatland (Gabbert 2008; North Carolina Division of Air Quality 2009; US Fish and Wildlife Service 2009). This fire was declared to be extinguished 7 months after the fire was started by a lightning strike (Mickler *et al.* 2017). In the 2018 Lake Cobrico peat fire, a 4-km pipeline connected to the nearest municipal water connection was laid, supplying ~ 65 million L of water that enabled flooding of the fire perimeter (Pumps Journalist 2018). This fire was extinguished after 2 months (Neal 2018).

Beside firebreak flooding, fire breaks by fuel removal can also be considered in controlling peatland fire spread. However, this effort may not be effective if the peatland watertable is very low (Usup *et al.* 2004; Bourgault *et al.* 2019) since the peat layer can be very deep and the trench would need to be more than 5 m deep (Page *et al.* 2011), rendering this effort a tedious task.

The subsurface spread of peatland fires is possible and is fed by oxygen diffusion deep below the ground owing to the porosity of peat (Rein 2016). Removal of the oxygen supply by compacting the soil has been suggested as an effective firefighting method, according to an investigation conducted during the 2009 smouldering peat fire in Las Tablas de Daimiel

National Park, Spain (Moreno *et al.* 2011). However, this method requires heavy machinery and access for such vehicles may be unavailable to peatlands owing to their geographic location. In summary, compared with soil compaction and fuel removal, cooling methods are the most feasible for suppressing peatland fires, including water spray, aerial attack, perimeter area reflooding and injection methods. The question is how much water is required for successful suppression.

Suppressant agents to fight wildfires

Suppression efficiency varies with the suppressant agents. The most utilised suppressants are water, firefighting foam, or mix of water and other suppressants (Plucinski 2019). Sand can also be considered as a suppressant because it is inert and highly dense but is more difficult to transport. In field conditions, the suppressant agent can be applied through the use of handheld firefighting equipment, fire trucks or aerial fleets (Plucinski 2019). In using firefighting agents, environmental safety is an important criterion. The development of environmentally friendly firefighting foams and agents and their effectiveness on both building and wildland fires have been investigated by several authors (Kennedy *et al.* 2015; Hinnant *et al.* 2017; Rakowska *et al.* 2017; Hinnant *et al.* 2020; Rivai *et al.* 2020; Subekti *et al.* 2020).

Foam suppression acts by smothering the smouldering, covering the surface of the fuel with a foam layer that prevents oxygen from accessing the fuel. In addition to its smothering effect, the foam layer also cools the surface of the fuel owing to the water content of the foam solution. Ratnasari *et al.* (2018) and Subekti *et al.* (2020) investigated the suppression time of peat fires using Class A fluorine-based foam and palm oil fatty acid-based foaming agent (FAP) foam respectively. Suppression time decreased with foam layer height while FAP foam performed more poorly than fluorine-based foam. In another report, Rivai *et al.* (2020) reported suppression times from applying various foam formulations derived from palm oil on 10-cm-deep smouldering peat. Foam stability can be an issue because the foam will be drained during the suppression effort (Kruglyakov *et al.* 2008). Since foam suppression relies on depriving smouldering of oxygen, once the foam is drained, it is no longer effective. This implies another difficult aspect of suppressing peat fires with foam since the required smothering holding time for smouldering can be days, weeks or months. This is in contrast to flaming wildfires, which may need hours (Rein 2016) and flaming liquid fires, which may only need minutes (Hinnant *et al.* 2020).

The use of fluorine-based foam to suppress wildfires is currently controversial owing to the environmental issues of per- and polyfluoroalkyl substances (PFAS), which are the main component of current commercial aqueous film-forming foam (AFFF) (Giesy and Kannan 2001; OECD 2013; USEPA 2014; Ruan and Jiang 2017). There is also an indication that long-chain PFASs, such as perfluorooctanoic acid (PFOA), can increase hydrophobicity (de Voogt *et al.* 2012), which by itself is a problem after peat fires (Perdana *et al.* 2018). If peat becomes hydrophobic after suppression with fluorine-based foam, restoration efforts by rewetting may become ineffective, leaving the peatland vulnerable to fires again in the next drought. Owing to

the environmental issue of fluorine, alternative fluorine-free surfactants have been developed, including hydrocarbon-based foam (Hinnant *et al.* 2020), FAP (Subekti *et al.* 2020) and fluorine-free wetting agent (Rakowska *et al.* 2017).

Smouldering peat fire suppression by means of water has been investigated by Ramadhan *et al.* (2017) in 10-cm-deep peat and Lin *et al.* (2020) in 15-cm-deep peat. Ramadhan *et al.* (2017) reported a suppression time of ~65 min with ~12 L h⁻¹ of water spray, while Lin *et al.* (2020) investigated water spray suppression at variable flow rates represented in rainfall rate unit (mm h⁻¹). The critical rainfall rate required to suppress peat fires reported by Lin *et al.* (2020) was 4 mm h⁻¹ for at least 5 h.

Wetting agents are substances that can reduce the surface tension of solid particles in a solid–liquid type suspension (Hao 2005). In contrast to foam that stays on the surface of the fuel, wetting agent can penetrate deep into the fuel. Owing to their lower liquid surface tension, wetting agent solutions penetrate up to 68 times faster than water through forest ground surface fuel (Rakowska *et al.* 2017). Peat fires can propagate in the shallow and deep layer of peat, leading to subsurface spread. Thus, surfactant ability to access the shallow layer and quickly reach the deeper peat layer is an important property for suppression efficiency. The effectiveness of foam on peat fire suppression has been investigated before, but no study has been conducted on the effectiveness of wetting agents on peat fires. In the present study, we aim to fill this gap by performing laboratory-scale experiments of peat fire suppression with both variable flow rate and environmentally friendly (fluorine-free) wetting agents. Upscaling calculation from lab-scale results in this study to field condition is also presented to assess the effect of wetting agent to the required amount of suppressant needed to suppress peat fire.

Material and methods

Our sample preparation protocol followed that in previous studies (Christensen *et al.* 2019; Hu *et al.* 2019). A commercially available peat was used (Shamrock Irish Moss Peat, Bord na Mona Horticulture Ltd) owing to its homogeneous properties and batch consistency in the long term. The elemental content of the peat on a dry mass basis was C/H/N/S of 54.1/5.1/1.3/0.5%, and the inorganic content (IC) was 2.5 ± 0.6% (Christensen *et al.* 2020). In this experiment, the MC of peat is ~100% (mass of water content over mass of dried peat). This MC is below the critical value for ignition of boreal peat when IC < 10% (Frandsen 1997; Huang *et al.* 2015) and represents drought peatlands (Usup *et al.* 2004). Samples were prepared by oven-drying peat at 80°C before adding water. The sample was mixed to ensure homogenisation and stored inside a sealed container for 24 h. Prior to the start of experiment, the sample was mixed well again. A subsample of 100 g was placed in an oven at 90°C for 7 h to measure the final MC (Christensen *et al.* 2019). The MC obtained in these experiments was 103.0 ± 6.8%, which corresponds to 204.4 ± 8.9 kg m⁻³ wet bulk density. A total of 19 kg of dry peat was used in the 49 experiments in this study.

An open-top reactor with internal dimensions of 20 × 20 × 10 cm was used (Huang *et al.* 2016) in which conditioned peat was deposited up to the rim. The reactor was built using ceramic insulation boards with thermal conductivity

(k) = $0.7 \text{ W m}^{-1} \text{ K}^{-1}$, density (ρ) = 310 kg m^{-3} and specific heat capacity (c_p) = $1090 \text{ J kg}^{-1} \text{ K}^{-1}$. The ignition protocol consisted of supplying 100 W for 30 min through an 18-cm coil heater mounted on one side of the reactor, which was 5 cm below the free surface. This ignition protocol can initiate self-sustained smouldering in peat with $\text{MC} < 160\%$ and $\text{IC} < 10\%$ (Hu et al. 2019). Fig. 2 shows the schematic of the experimental set-up. Measurements included in this experiment were mass loss (Mettler Toledo balance, resolution 0.01 g), visual and infrared (IR) imaging of the surface spread (GoPro Hero 5 and FLIR A655SC cameras) and temperature–time histories using thermocouples (12 K-type thermocouple (TC) array, $3 \text{ rows} \times 4$

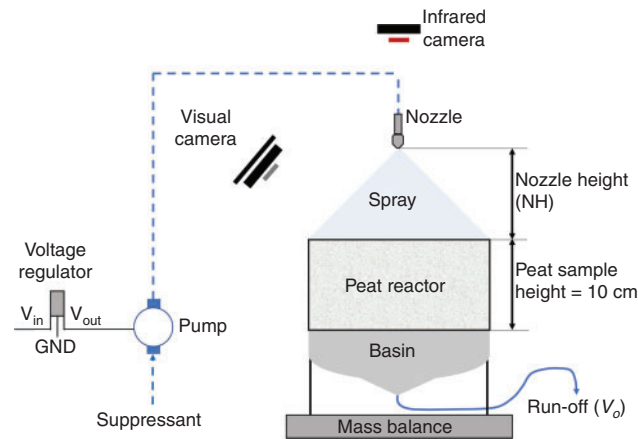


Fig. 2. Schematic of the suppression experimental set-up showing the diagnostics using infrared and visual camera, mass balance and measurement of runoff volume, and voltage regulation of the diaphragm pump to adjust suppression flow rate, along with nozzle height. GND is the reference point for voltage measurement.

columns (see also Fig. 5 and Fig. S1 in supplementary material)). To avoid fluid build-up inside the reactor and to imitate suppression on deeper soils, holes were made at the bottom face of the reactor to allow fluid flow into a basin connected to container (Fig. 2). At the end of each experiment, the volume of fluid in this container was measured and is denoted runoff volume (V_o).

An infrared camera was used to determine the timing for initiation of suppression. This was when the smouldering front arrived at the centre of the reactor such that the front was directly below the spray nozzle. Since the infrared image only represents surface smouldering, the addition of mass loss measurements provides comprehensive monitoring to ensure the initiation of suppression was consistent across all experiments. Fig. 3 shows that the average mass fraction at the initiation of suppression, i.e. the arrival of the smouldering front at the centre of the reactor, is $59.6 \pm 1.66\%$. This is equivalent to mass loss of 40.4% . The average time at the start of suppression (t_{sp}) is $303.6 \pm 49.3 \text{ min}$, across all 49 sets of conducted experiments. At the time that these two criteria were met, i.e. front below the nozzle and 40% mass loss, the temperatures of TC9 and TC10 were 400 to 550°C . This is discussed in the Results section. Smouldering was considered extinguished when all temperatures decreased below 50°C . This temperature criterion to identify extinguishment is a conservative value and has been used before in studies on smouldering coal (Hadden and Rein 2011). Once this was achieved, suppression was terminated and the suppression time was recorded.

Three different suppressant mixtures were studied: 0% (water only), 1% (low concentration (LC)), and 5% (high concentration (HC)) of fluorine-free wetting agent by weight in water. The wetting agent was ColdFire, produced by FireFreeze Worldwide, Inc. This wetting agent is a proprietary environmentally friendly formulation consisting of biodegradable anionic and non-ionic

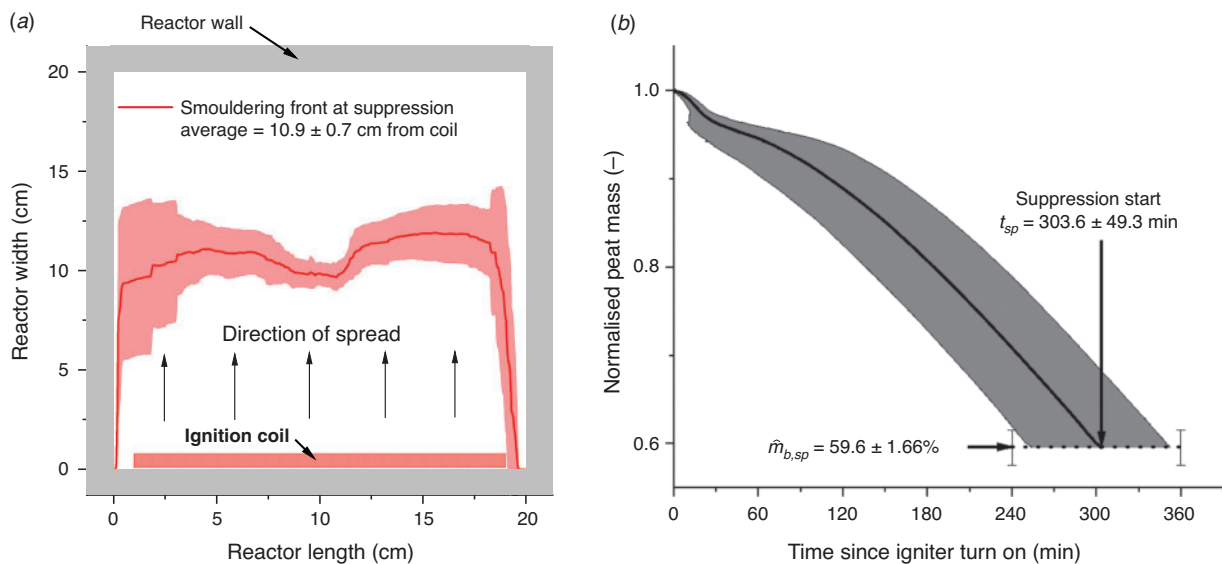


Fig. 3. (a) Top view of smouldering front location at the initiation of suppression. The red line indicates average front location at the start of suppression from IR footage, i.e. 10.9 cm , with standard deviation indicated by shade, i.e. $\pm 0.7 \text{ cm}$. (b) Average wet bulk peat mass (normalised to initial value) (line) and standard deviation (shading).

surfactants, organic compounds and minerals that have been tested to be free of PFAS (Firefreeze 2019). This wetting agent has liquid-to-air surface tension of $29.7 \pm 2.36 \text{ mN m}^{-1}$ (Rakowska *et al.* 2017), ~ 2.5 times lower than water's, which is 72.02 mN m^{-1} (Nikitas and Pappa-Louisi 1990). The complete physicochemical properties of the wetting agent can be found in Rakowska *et al.* (2017).

Suppression flow rates (\dot{V}_s) were varied by adjusting both the height of the nozzle and the voltage supply to the pump (Fig. 2). Parameters controlling the flow rate were measured using an

empty reactor on a mass balance. The flow rate was the rate of mass gained by the empty reactor. The flow rate decreased both with nozzle height and voltage (Fig. 4a). The increase in voltage increased pump pressure, which increased both volumetric flow rate and spray angle. Despite the increase in the volumetric flow rate, the increase in spray angle decreased the amount of water entering the reactor because the spray was wider than the reactor top area. The nozzle height and pump voltage were set before each experiment to obtain the desired flow rate based on the results shown in Fig. 4a. Suppression flow rate values were

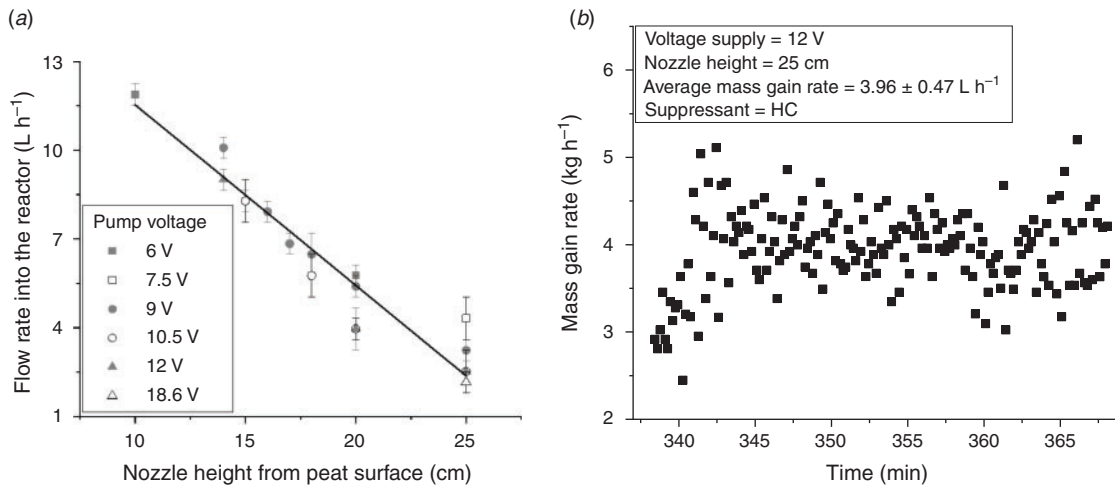


Fig. 4. Suppression flow rate resulting from changes to nozzle height and pump voltage. (a) Measurement of flow rate *v.* nozzle height and voltage supply. (b) Example of mass gain rate during suppression to confirm flow rate values, showing that the average suppression flow rate is $3.96 \pm 0.47 \text{ L h}^{-1}$, since the density of the wetting agent $\approx \rho_{\text{water}} = 1 \text{ kg L}^{-1}$ (Rakowska *et al.* 2017).

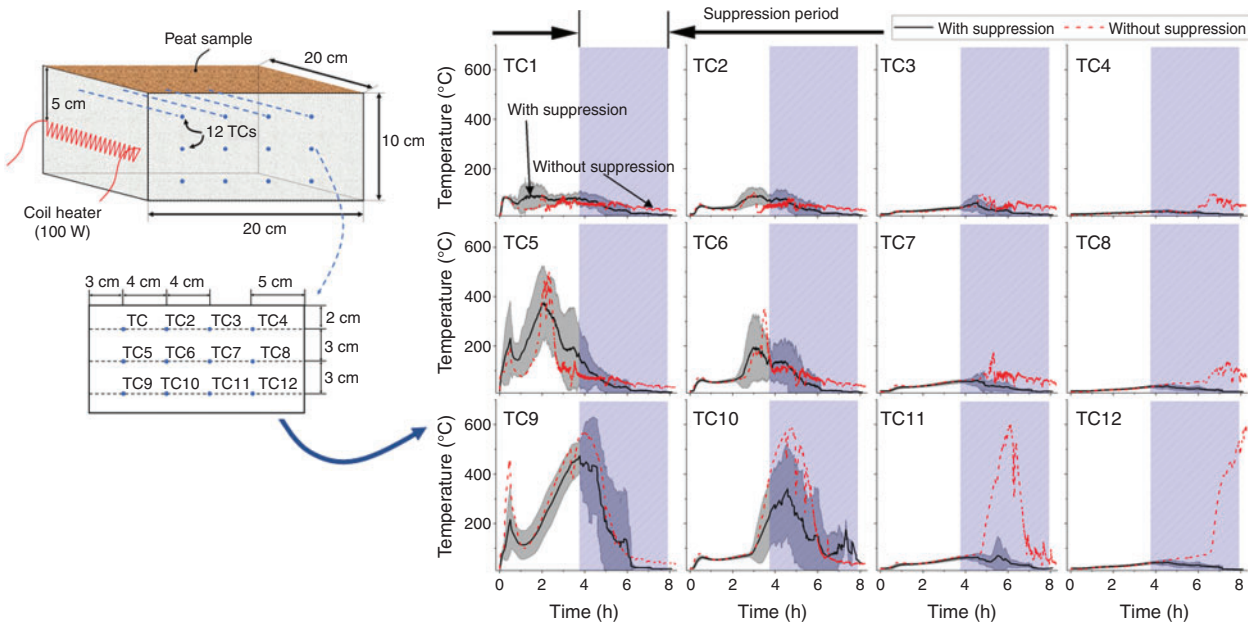


Fig. 5. Comparison of temperature profiles in experiments with and without water suppression. Red dashed line shows experiments without suppression; black solid line is the average profile from 21 experiments with water suppression (flow rate from 3.6 to 16.6 L h^{-1}). The grey and blue shades show the full data range and the suppression time period, respectively.

confirmed by data analysis averaging mass gain rate of the reactor due to the suppression flow into the reactor, from the start of the suppression to ~ 50 to 60% of the suppression time. Fig. 4b shows an example of mass gain rate from the start of suppression over the next 29 min, which is $\sim 60\%$ of the suppression time, in which the average of this mass gain rate corresponds to a suppression flow rate of $3.96 \pm 0.47 \text{ L h}^{-1}$. During this early stage of suppression, the peat was still smouldering. Because the mass loss from smouldering was negligibly small compared with the mass gain from suppression (~ 2 orders smaller than mass gain) and the decreasing burning rate due to smouldering being suppressed, mass loss from smouldering at this stage of suppression can be neglected. The rate of suppressant evaporation can also be assumed to be negligibly small, of the same order of sample mass loss due to smouldering.

Results of smouldering spread

Temperature profiles

Before suppression was initiated, horizontal spread was faster 8 cm below the surface, leaving a layer of peat on top, as evidenced by the low temperatures measured by the top thermocouples in Fig. 5. This unburnt surface layer stayed intact for some time, forming an overhang, which collapsed later. This has been observed previously by Huang *et al.* (2016).

Fig. 5 shows temperature profiles without suppression as a baseline behaviour for comparison (red lines) and average temperature profiles from 21 experiments with water suppression (black lines) in which flow rate was varied between 3.6 and 16.6 L h^{-1} . The ignition procedure is evidenced by the sharp increase in temperature measured by TC5 and TC9, also followed by a sharp decrease when the ignition procedure was stopped. Smouldering started at 5 cm depth from the top surface. From this point, i.e. TC5, smouldering then spread at a depth of ~ 8 cm, indicated by the trend of temperature increase from TC5 \rightarrow TC9 \rightarrow TC10 \rightarrow TC11 \rightarrow TC12 (red lines in Fig. 5).

In experiments with water suppression (black lines in Fig. 5), only the measured temperature of TC9 and TC10 was $\sim 400^\circ\text{C}$ at the start of the suppression, which is marked by the left side of the rectangular blue shading in Fig. 5. Thus, at the start of

suppression, the smouldering front was around TC9 and TC10 (up to 7 cm away from the ignition wall). Fig. 5 shows that smouldering propagation at this time was also well beyond the steady state, which can also be seen in the mass data in Fig. 3b (see also Fig. S2). A small bump of temperature increase at TC11 in experiments with suppression indicates that the leading edge of the drying front was probably located between TC10 and TC11, ~ 9 cm away from the ignition wall. As can be seen in Fig. 5, smouldering spread beyond TC10 was successfully prevented after water suppression across all 21 experiments.

The dynamics of smouldering fires can be studied by the temperatures reached and the thermal residence time (Hartford and Frandsen 1992; Certini 2005; Rein *et al.* 2008). Thermal residence time is the amount of time that a point in the sample is above a certain temperature threshold, e.g. 60 min of thermal residence time for 100°C means that a point in the sample was at 100°C or above for 60 min (Rein *et al.* 2008). The thermal residence time of TC10 in Fig. 6 shows that suppression decreases thermal residence time across the temperature range from 100 to 650°C compared with cases without suppression. It can be seen that compared with the effect of suppressant concentration, flow rate has a stronger effect on decreasing residence time. By increasing the flow rate from 0.6 to 7.6 L h^{-1} , thermal residence time decreases by ~ 1 h from 100 to 550°C (Fig. 6a). Considering the effect of the suppressant concentration, it can be seen that the LC affects thermal residence time almost in the same way as water, but further decreases residence time by 0.5 h only at temperatures above 300°C (Fig. 6b). HC has a stronger effect than LC in that the residence time decreases by ~ 0.5 h across all temperatures in comparison with water. In Fig. 6a, the standard deviations of LC thermal residence time are 0.6 h at low flow rate, 0.2 h at intermediate flow rate, and 0.12 h at high flow rate, whereas in Fig. 6b, the standard deviations of thermal residence time are 0.35 h for water, 0.2 h for LC and 0.03 h for HC.

Persistent smouldering

Fig. 7 shows a side-view schematic of the smouldering propagation based on temperatures in Fig. 5 and visual observation of the experiments (Fig. S2) and illustrating the location of TC10

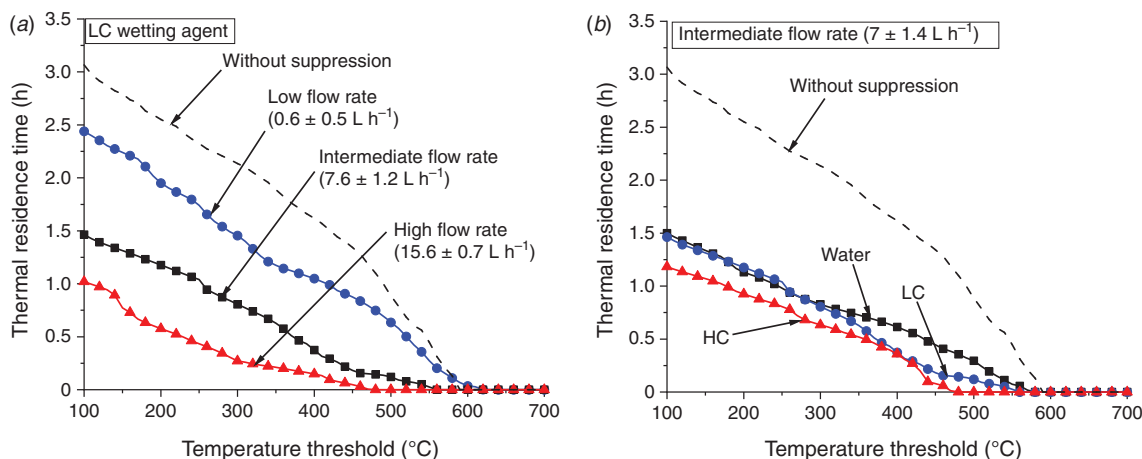


Fig. 6. Average thermal residence time *v.* temperature threshold with (a) LC suppressant at increasing flow rates; and (b) intermediate flow rate at increasing suppressant concentrations. The thermal residence time is the time from the start of ignition until termination.

close to the smouldering leading edge at the initiation of suppression. In *Ramadhan et al. (2017)*, a temperature threshold of 80°C anywhere in the sample was the suppression criterion. However, in the present study, 14 experiments out of 49 show the occurrence of persistent smouldering, represented by a temperature increase and continuation of spread during suppression. During this persistent smouldering, the temperature at TC10 was seen to increase up to ~220°C (approximately peat smouldering temperature (*Chen et al. 2011*)) and this increase occurred after this temperature had decreased to as low as ~66°C (*Fig. 8a*). In other cases, smouldering continuously spread despite ongoing suppression as indicated by a temperature increase at TC11 (*Fig. 8b*). Both cases show a potential of reignition if suppression was stopped at a temperature above 50°C. In another study, *Lin et al. (2020)* reported a reignition of peat at a temperature of ~60°C. We choose 50°C as a conservative threshold for successful extinction since no reignition was observed when 50°C was the criterion. Successful suppression can also be identified from surface infrared radiation; however, IR was unable to detect the occurrence of persistent smouldering at depth (*Fig. S3* and *Fig. S4*).

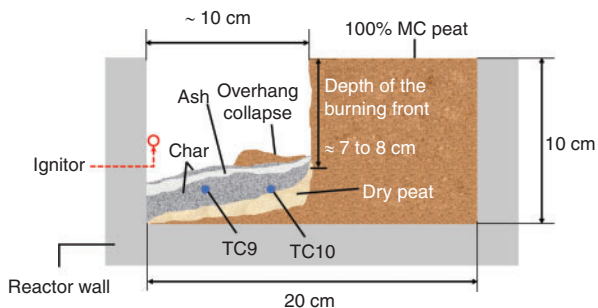


Fig. 7. Side-view schematic of the smouldering front at the start of suppression. TC9 and TC10 approximately indicate the trailing and leading edges of the char oxidation front.

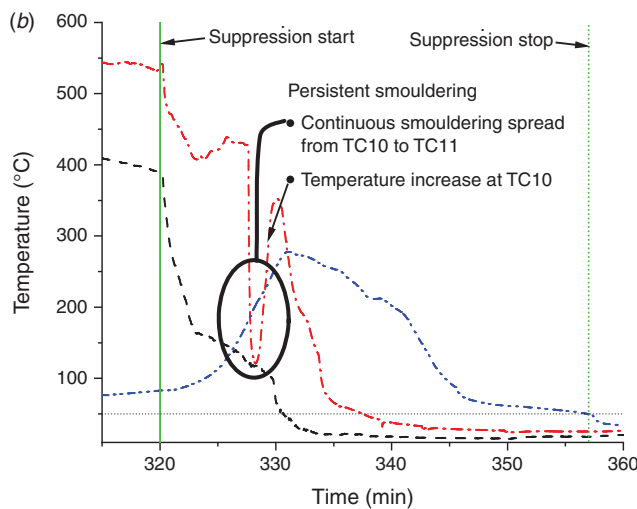
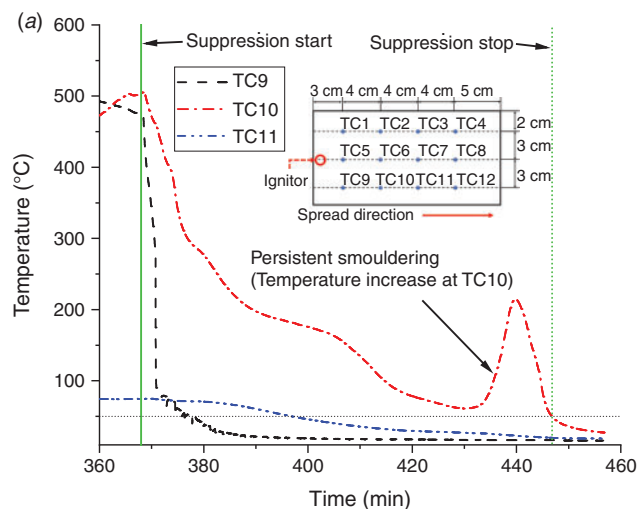


Fig. 8. Examples of persistent smouldering during suppression indicated by temperature profiles at the deep layer, i.e. TC9, TC10 and TC11. (a) Water at 4.3 L h⁻¹ flow rate; suppression time is 78.8 min. (b) Water at 7.2 L h⁻¹ flow rate; suppression time is 36 min.

Temperature anomalies in *Fig. 8a* can also be caused by the thermocouple tip being surrounded by the solution for a while, thus causing a temperature decrease, followed by a temperature increase once the enveloping solution has dried. Another possible cause for the increase in temperature is the collapse of an overhang that burned near a thermocouple (*Fig. 7*), causing a perturbation in the temperature curve, which is thus not as smooth as if there was no collapse. *Fig. 9* shows a summary of the occurrences of persistent smouldering (temperature increase at TC10 and continuation of spread to TC11) during ongoing suppression, showing a clear indication that these occurrences are less frequent with increasing flow rate and wetting agent concentration, with flow rate having the greater effect.

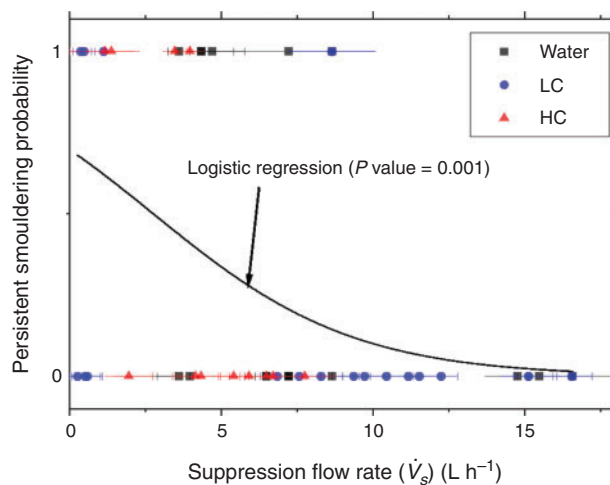


Fig. 9. Occurrences of persistent smouldering. A value of 1 on the y axis indicates that persistent smouldering was observed in the experiments conducted at a particular flow rate, while 0 means that persistent smouldering was not observed.

Uncertainty can be caused by the TC being enveloped by the solution and overhang collapse.

Results on suppression dynamics

Suppression time

As seen in Fig. 10, suppression time decreased with flow rate for all suppressant concentrations. The best-fit lines in Fig. 10 can be assumed to be a critical limit of suppression flow rate and time below which suppression is unsuccessful. In the range from 5 to 9 L h⁻¹, the average suppression time with LC was 39% lower than with water, while with HC, the suppression time was 26% lower than with water. Even though LC on average was faster than HC, the standard deviation of LC time was ~20 min, significantly greater than the 6-min standard deviation for HC. This means HC is more reliable in reducing suppression time than LC. For example, our data shows that a suppression time of ~70 min can be achieved by HC with a flow rate of 1.5 L h⁻¹ or a flow of 4.1 L h⁻¹ with water. With high flow rates (9 to 18 L h⁻¹), LC suppressant and water resulted in similar suppression

times (<40 min). However, to achieve ~60 min suppression time, HC suppressant required a lower flow rate compared with water, resulting in 63% lower pump power (pump power is proportional to flow rate (Gerhart et al. 2016)), which is a crucial consideration for field conditions where remote locations make power supply challenging. The range and trend of suppression time reported here agree with previous studies for water (Ramadhan et al. 2017; Lin et al. 2020), while the present study includes wetting agents. Longer suppression times in Ramadhan et al. (2017) can be due to the much lower MC in their samples, i.e. 15%. With Netherlands peat samples at 50% MC, Lin et al. (2020) reported that 0.16 L h⁻¹ water spray was the minimum flow rate for successful suppression, thus in agreement with the present study (Fig. 10).

Suppression column height and runoff

Fig. 11a shows the ratio of runoff (V_o) volume to the total suppressant volume (V_i) of the three fluids (water, LC and HC). Runoff can be caused by uniform penetration of the suppressant

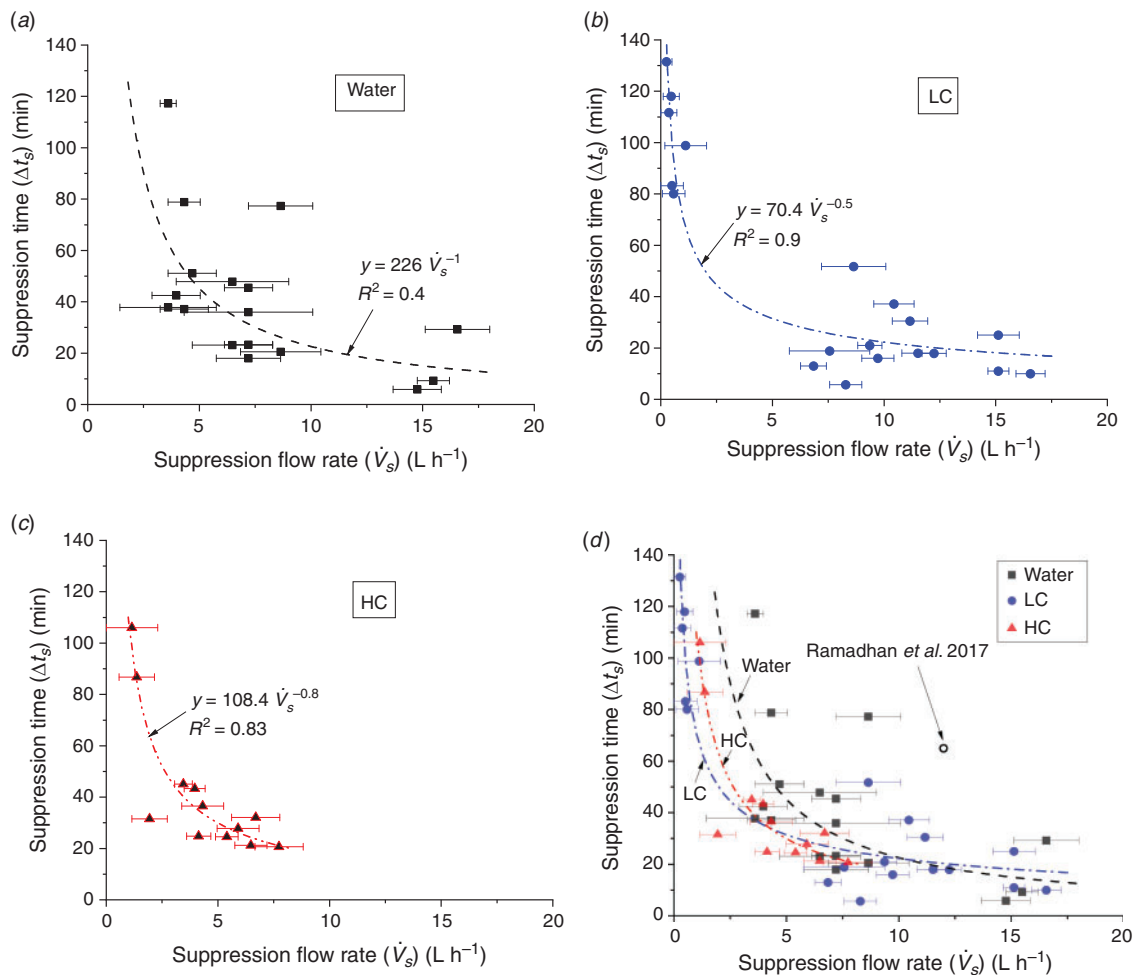


Fig. 10. Suppression time v. suppression flow rate. The best-fit lines represent a critical suppression limit for flow rate and suppression time below which suppression is not successful. (a) Water suppression; (b) LC suppression; (c) HC suppression; (d) all suppressants, and comparison with data point of suppression time from Ramadhan et al. (2017). The standard deviation for suppression time is too small to be included in the graph (± 10 s).

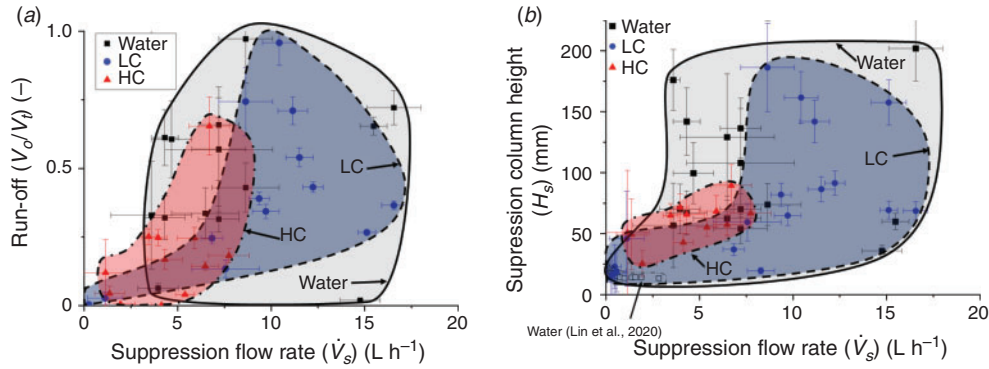


Fig. 11. Runoff and suppression column height. (a) The ratio of suppression runoff to the total volume of suppressant applied. (b) Suppression column height, the product of flow rate and suppression time divided by the reactor area (Eqn 1). The shaded areas for each suppressant agent are approximate estimation to assist visual observation.

or by channel formation. Uniform penetration is aided by the low surface tension enabling the suppressant to seep through the pores between soil particles. In this study, the wetting agent surface tension is ~ 2.5 times smaller than water surface tension. Higher runoff due to uniform penetration can aid suppression of deeper hotspots. For runoff due to channel formation, most of the suppressant flows through the same path, causing poor heat transfer and a smaller contact surface between the suppressant and the particle (Hadden and Rein 2011), thus decreasing suppression performance. Channels are formed when the surface tension of the suppressant is high and the suppressant encounters more resistance to seeping through the pores.

Fig. 11a shows runoff data for water, which are widely scattered, demonstrating no clear trend, and generally higher than wetting agent suppressants (both LC and HC) at flow rates below $\sim 7 \text{ L h}^{-1}$. Comparing runoff data in Fig. 11a with suppression time in Fig. 10d especially at flow rate below $\sim 7 \text{ L h}^{-1}$, the higher runoff of water than wetting agent suppressants is not accompanied by a shorter suppression time. This means that at low flow rates, water travels through the sample more quickly than wetting agent suppressants because of channelling, thus the longer suppression time. With wetting agent suppressants, runoff increases with flow rate. Comparing Fig. 11a with Fig. 10d, we see that the increase of runoff in wetting agent is accompanied by a significant decrease of suppression time. As the flow rate increases beyond $\sim 7 \text{ L h}^{-1}$, the runoff of wetting agent increases to the level of water, resulting in a shorter suppression time than water. This means that runoff in wetting agent is mainly caused by uniform penetration and that higher runoff is equivalent to better wetting over the whole sample.

Suppression column height or suppressant fluid volume per unit area can be calculated by using Eqn 1 where H_s is the suppression column height, \dot{V}_s is the flow rate, Δt_s is the suppression time, and A_r is the reactor area ($0.2 \times 0.2 \text{ m}$). By looking at the lower suppression column height and shorter suppression time (at flow rates below 7 L h^{-1}) of LC and HC compared with water (Fig. 10d and Fig. 11b), it can be seen that wetting agents increase suppression efficiency. Comparing Fig. 10d and Fig. 11b, the decrease of suppression time with

flow rate is followed by increasing suppression column height, which can have a positive effect on suppression performance if the runoff is caused by uniform solution penetration.

$$H_s = \frac{\dot{V}_s \Delta t_s}{A_r} \quad (1)$$

Fluid volume per mass of peat

The required volume of fluid to successfully suppress smouldering in 1 kg of peat (V_{sp}/m_{sp}) is calculated using Eqn 2 where V_{sp} is the total fluid volume, including the volume of suppressant applied ($\dot{V}_s \Delta t_s$) and the moisture content left when suppression was initiated ($V_{w,sp}$) but excluding runoff (V_o); and m_{sp} is the mass of the dry peat and residue (char and ash) when suppression was initiated, i.e. $299.3 \pm 18.5 \text{ g}$ (equivalent to $40.4 \pm 1.66\%$ mass loss). m_{sp} was calculated by estimating the water content at the start of the suppression ($m_{w,sp}$). By observing the average location of the front at suppression (L_{sp}), i.e. $10.9 \pm 0.7 \text{ cm}$ (Fig. 3a), the volume fraction of the unburnt sample (X_{sp}) can be estimated to be 0.46 ± 0.04 (Eqn 3, where L_r is the length of the reactor, which is 20 cm). Multiplying this volume fraction by the initial water content of the peat sample before ignition ($\frac{\text{MC} \cdot m_b}{1 + \text{MC}}$) results in $m_{w,sp}$ (Eqn 4, where m_b is the bulk mass of the sample before ignition). m_{sp} was obtained by subtracting $m_{w,sp}$ from the bulk mass data at the start of the suppression. The volume of water at the start of the suppression ($V_{w,sp}$) is obtained from the mass of the water ($m_{w,sp}$) and $\rho_w = 1 \text{ kg L}^{-1}$ (in Eqn 2). Runoff is excluded in this calculation because it escapes the sample and therefore is not absorbed.

$$\frac{V_{sp}}{m_{sp}} = \frac{\dot{V}_s \Delta t_s + \frac{m_{w,sp}}{\rho_w} - V_o}{m_{sp}} \quad (2)$$

$$X_{sp} = \frac{L_r - L_{sp}}{L_r} \quad (3)$$

$$m_{w,sp} = X_{sp} \frac{\text{MC} \cdot m_b}{1 + \text{MC}} \quad (4)$$

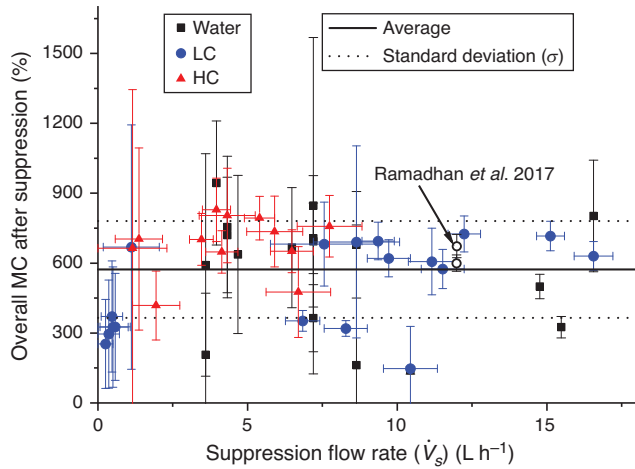


Fig. 12. Overall MC of peat after successful suppression according to Eqn 2, assuming $\rho_{sp} = 1 \text{ kg L}^{-1}$. The density of the wetting agent is similar to water (Rakowska *et al.* 2017), thus $\rho_{sp} = \rho_w$. The average value is $572.9 \pm 207.8\%$ of MC on a dry-mass basis.

This total fluid volume per mass of peat is quite constant despite the wide range of flow rates and suppressant fluids. In other words, with increasing flow rate, runoff increases, and the volume of suppressant that is actively suppressing the fire is $5.7 \pm 2.1 \text{ L kg}^{-1}$ peat. This value can be understood as a critical flooding point, demonstrating the amount of water required to flood peat fires for successful suppression. Fig. 12 reports the critical flooding point in term of MC percentage (conversion of V_{sp}/m_{sp} by multiplying it by ρ_w and 100% where wetting agent density (ρ_{sp}) is the same as $\rho_w = 1 \text{ kg L}^{-1}$ (Rakowska *et al.* 2017)), showing a value of $572.9 \pm 207.8\%$ MC is required to suppress the peat fire. This is almost twice the typical value of peatland in flooded pristine conditions, i.e. $\sim 300\%$ MC (Moreno *et al.* 2011; Turetsky *et al.* 2015).

This critical value suggests that the suppression time is the duration needed to flood the peat. In other words, suppression time is the time needed for the suppressant at a specified flow rate and concentration to flood the peat to that critical flooding point. This value is affected to a certain degree by runoff as well, since higher runoff corresponds to a longer necessary time to flood the peat. This means suppression is a thermofluids phenomenon in absorbing media, and that the suppressant acts thermally and not chemically. Thus, the effect of both suppressant concentration and flow rate is to accelerate fluid transport through porous media over the depth of the sample. The low surface tension of the wetting agent probably helps avoid channel formation. This critical flooding point could be a soil property and the value found here is valid for the peat type used in this study. Compared with the literature, this critical value generally agrees in order of magnitude with the value reported by Ramadhan *et al.* (2017), i.e. $\sim 6.4 \text{ L kg}^{-1}$ peat. The slightly different average to Ramadhan *et al.* (2017) might be explained by the fact that the reported value in that study was based on the mass of the peat before ignition, whereas the value reported in the present study is based on the mass of the peat and residue before suppression started.

Table 1. Data of minimum suppression height (mm) and runoff (%) from this study and available literature on peat fire suppression

Fluid	Minimum suppression column height (mm)	Runoff (%)
Present work – laboratory experiment (spray)		
Water	36 ± 5	2 ± 0.15
Low-concentration suppressant (1% weight in water)	14 ± 14	0.5 ± 0.45
High-concentration suppressant (5% weight in water)	26 ± 11	0.6 ± 0.2
Literature		
Water (Ramadhan <i>et al.</i> 2017) – laboratory experiment (Spray)	579 ± 30.8	N/A ^A
Water (Lin <i>et al.</i> 2020) – laboratory experiment (Spray)	13 ± 1.9	N/A
Water (Santoso 2020) – field experiment		
Successful suppression (Spray)	26.5 ± 9.2	N/A
Successful suppression (Spear injection)	842.5 ± 57.7	N/A
Unsuccessful suppression (Rain 1)	2.5 ± 0.1	N/A
Unsuccessful suppression (Rain 2)	4.8 ± 0.2	N/A

^AData are not available or not measured.

Even though higher runoff can indicate deeper suppressant penetration, the formation of channels, especially for water, is a concern because of less fluid participating in suppression. The constant critical flooding point confirms the two possible runoff mechanisms, i.e. channelling and uniform penetration. At low flow rate, the low runoff of LC and HC caused by uniform penetration resulted in shorter suppression times than water owing to faster flooding of the peat by LC and HC (Fig. 11a and Fig. 10d), whereas in case of water, the higher runoff at low flow rate is accompanied by a longer suppression time than LC and HC because the runoff was mainly caused by channel formation, causing most of the water to not contribute to peat flooding.

Upscaling to field conditions

Peat fire field experiments

In 2018, our group conducted field-scale experiments in Indonesia during which we ignited four peat fires, which burned for 4 to 10 days (Santoso 2020). Two rain events occurred during this time but the fires continued. The rainfall heights, equivalent to the suppression column height shown in Eqn 1, were 2.5 ± 0.1 and $4.8 \pm 0.2 \text{ mm}$ (Table 1). These values agree with our data because less than $36 \pm 5 \text{ mm}$ of water suppression would not suppress a peat fire. After 10 days, the four peat fires were suppressed in a controlled manner by means of water spray. The suppression times ranged from 17 to 42 min, and flow rates from 3000 to 4900 L h^{-1} , resulting in column heights from 26.5 to 36.7 mm . This range of suppression times agrees well with our laboratory measurements even though the flow rates were far higher. The two rainfall events correspond to 1.9 to 2.6 L h^{-1} for 50 min and 1.3 to 8.8 L h^{-1} for 17 min, and both fall below the critical suppression limit in Fig. 10a, thus too quick for successful suppression. Lin *et al.* (2020) reported that the minimum column rate to suppress peat fires is 4 mm h^{-1} , which is less than

rain events recorded in our field experiments, i.e. 5.6 and 8.3 mm h⁻¹. However, the minimum column rate should last for more than 5 h in order to successfully suppress peat fires (Lin *et al.* 2020), which is much longer than typical rainfall.

Table 1 shows a summary of suppression column height and runoff data for all currently available literature on peat fire suppression. It can be seen that the minimum suppression column height ranges from 13 to 36 mm, except for the two extremely high column height values from Ramadhan *et al.* (2017) of 579 ± 30.8 mm and from spear injection in GAMBUT (Santoso 2020) of 842.5 ± 57.7 mm.

Upscaling of laboratory results

Upscaling from laboratory data to the field can give an idea of the challenges of peat fire suppression in terms of flow rate and suppression time. Based on our data, we estimate the amount of suppressant fluid required to extinguish a hypothetical peat fire in the field with Eqn 5. It basically upscales the amount of required suppressant fluid from laboratory data ($\dot{V}_s \Delta t_s$) to a hypothetical field scale through the ratio of the fire area in the field to fire area in the laboratory. This equation assumes a uniform flow rate over an extended area of the wildfire, thus can be used to approximate the required volume of suppressant fluid for a relatively small peat fire area.

$$V_s = \dot{V}_s \Delta t_s \frac{A_f}{A_r} \quad (5)$$

where V_s is the required volume of suppression agent (L) (which is $\sim 5.7 \pm 2.1$ L kg⁻¹ peat in Fig. 12), \dot{V}_s is the suppression flow rate (L h⁻¹), Δt_s is required suppression time (h), A_f is fire area (m²), and A_r is the area of the reactor used in this study, i.e. 0.04 m² (at the start of suppression, half of the peat [surface peat] in the reactor had already burnt).

For example, the average suppression time for water at a flow rate of 4 L h⁻¹ in the laboratory reactor is ~ 63 min. Using Eqn 5, the amount of water required to extinguish, say, a 1-ha (1×10^4 m²) peat fire can be estimated to be of the order of 1 million L. If HC suppressant is used at the same flow rate, the average suppression time is 35 min, resulting in ~ 580 000 L of suppressant, approximately half the required volume with water.

Volumetric consideration can also be made in upscaling by including the depth of burn in Eqn 5, done by multiplying both fire area in the field and in the laboratory scale with their respective depth of burn. Taking the average depth of burn in peat fires from boreal and tropical regions, i.e. 39 cm (Santoso *et al.* 2019), and the laboratory-scale depth of burn in this study, i.e. ~ 8 cm, results in an ~ 5 fold increase of the amount of solution required to extinguish the hypothetical peat fire in the example above. This very high suppressant volume gives an idea of the difficulties of suppressing peat fires, as also reported from real peat fires incidents (Gabbert 2008; North Carolina Division of Air Quality 2009; Mickler *et al.* 2017; Pumps Journalist 2018).

Conclusions

We present suppression experiments on smouldering peat fires exploring the effect of three different concentrations of suppressant and variable flow rates. Suppression data are represented by

suppression time, runoff ratio, column height, and fluid volume per mass of peat. Flow rates decrease suppression time for all solutions explored. Using wetting agent as a suppressant, a 26 to 39% decrease in suppression time can be achieved, with HC performing more reliably in reducing suppression time. The use of a wetting agent could decrease the required flow rate by 63%, thus also reducing the required pump power by the same order, and significantly decrease the required volume of suppressant agent. An upscaling demonstration of the results in this study to the field, an example case of a small peat fire, shows that a 50% decrease in the required suppressant volume per hectare of fire could be achieved with wetting agents as suppressant.

The decrease of suppression time with flow rate is at the expense of higher runoff. The runoff is caused by channelling in water or uniform penetration by wetting agent. The uniform penetration by wetting agent is because it has ~ 2.5 times lower surface tension than water. Runoff by uniform penetration is a positive factor in suppressing deep fires.

The actual volume of suppressant that actively extinguishes the fires was found to be quite constant across different flow rates and suppressant agents. We called this value the critical flooding point, which is 5.7 ± 2.1 L kg⁻¹. This value being constant suggests that the wetting agent as suppressant acts thermally and not chemically.

We studied the occurrences of persistent smouldering despite ongoing suppression. The possibility of persistent smouldering decreased with increasing flow rate and suppressant concentration. The results presented here contribute to a better understanding on the mechanism of peat fires suppression, the role of flow rate and suppressant fluids, and the amount of resources needed to successfully stop peat wildfires.

Conflicts of interest

The authors declare no conflicts of interest.

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