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How to Build a Firebreak to Stop Smouldering Peat Fire: Insights from a Laboratory-Scale Study

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Abstract: Smouldering wildfire is an important disturbance to peatlands worldwide, and it contributes significantly to global carbon emissions and provides positive feedback to climate change. Herein, we explore the feasibility of firebreaks to control smouldering peat fires through laboratory-scale experiments. The dry-mass moisture content (MC) of peat soil varied from 10% (air-dried) to 125%. We found that smouldering peat fire may be successfully extinguished above the mineral soil layer, even if the peat layer is not entirely removed. There are two criteria for an effective peat firebreak: (I) adding water to make the peat layer sufficiently wet (> 115% MC in the present work), and (II) ensuring that the peat layer is thinner than the quenching thickness (< 5 cm). Criterion I may fail if the water table declines or the peat layer is dried by surface fires and hot weather, thus satisfying Criterion II is more attainable. A sloped, trench-shaped firebreak is recommended to guide water flow and help maintain high peat moisture content. This work provides a scientific foundation for fighting and mitigating smouldering wildfires and guides protective measures for field-scale peat fire experiments.

Keywords: *underground fire; wildfire fighting; peatland; quenching; soil moisture profile.*

Running Head: Firebreak for smouldering peat fire

Short summary

Firebreaks are constructed to isolate wildfires and protect humans and properties. This work explores the feasibility of firebreak in controlling smouldering peat fires and the scientific construction criteria.

Introduction

Smouldering fire is slow-moving, low-temperature, and flameless, and is the driving burning phenomenon in global peatlands and an important disturbance to the global ecosystem (Page *et al.* 2002; Turetsky *et al.* 2002, 2015; Rein 2013). Although peatland only covers 2-3% of Earth's land surface, it is a significant carbon sink, holding approximately 25% of the planet's terrestrial soil carbon, close to the carbon amount in the atmosphere (Gorham 1994). Therefore, peat fire is a global source of carbon emissions and the leading cause of regional haze events, especially in Southeast Asia and boreal regions (Page *et al.* 2002; Poulter *et al.* 2006; Moreno *et al.* 2010). In 2019, slash-and-burn activities in Indonesia accidentally resulted in peatland wildfires that burned for several months, producing a thick and hazardous smoke layer over Indonesia and nearby countries that posed severe health issues to a large population (Normile 2019).

In recent decades, global warming has increased fire frequency and severity in peatlands; therefore, fire regimes have changed (Liu *et al.* 2010; Mack *et al.* 2011; Kohlenberg *et al.* 2018). Once ignited, despite extensive rain or other firefighting attempts, smouldering peat fire may burn for months and even for years (Ballhorn *et al.* 2009; Rein 2013; Lin *et al.* 2020). Many research efforts have been targeted to understand the characteristics of smouldering peat fire, such as combustion chemistry (Huang and Rein 2014), ignition (Frandsen 1987, 1997; Lin *et al.* 2019), fire spread (Huang *et al.* 2016; Prat-Guitart *et al.* 2016; Huang and Rein 2017, 2019; Yang and Chen 2018; Christensen *et al.* 2020; Palamba *et al.* 2020) and emissions (Heil and Langmann 2004; Poulter *et al.* 2006; Rein *et al.* 2009; Aurell *et al.* 2016; Black *et al.* 2016; Wakhid *et al.* 2017; Hu *et al.* 2018, 2019). However, compared with these profound studies on ignition and fire behaviour, very few studies are available to control and extinguish these persistent smouldering wildfires (Lin *et al.* 2020).

With respect to the fire triangle, three methods can be applied to extinguish a fire, namely starving (by removing the fuel), smothering (by removing the oxygen), and cooling (or quenching by removing the heat) (Quintiere 2006). To suppress large-scale peat fires, except for cooling, neither starving nor smothering is practical (Lin *et al.* 2020; Lin and Huang 2021). In real fire scenarios, if the peat is sufficiently wet with dry-mass moisture content (MC_p) higher than 100~200%, it can be protected by its own moisture, which could be defined as the *peat fire threshold* (Frandsen 1987, 1997; Huang and Rein 2015, 2016; Prat-Guitart *et al.* 2016). Today, water is still the most widely-used cooling agent in fighting peat fires (Blake *et al.* 2012; Ramadhan *et al.* 2017; Lin and Huang 2020). However, water is not always accessible near the fire scene, and firefighting operations are risky due to the extreme heat and smoke (Saharjo 2019). In practice, building a firebreak or barrier could be more effective in controlling and mitigating the hidden peat fires (Migalenko *et al.* 2018), as illustrated in Fig. 1. For example, to suppress a peat fire in Scotland in 2008, the Fire Service and Regional Army dug a trench as the firebreak which was 5 m wide and 0.5–2 m deep (down to the mineral soil layer) around the perimeter of the fire by excavating peat soils (Rein 2013).

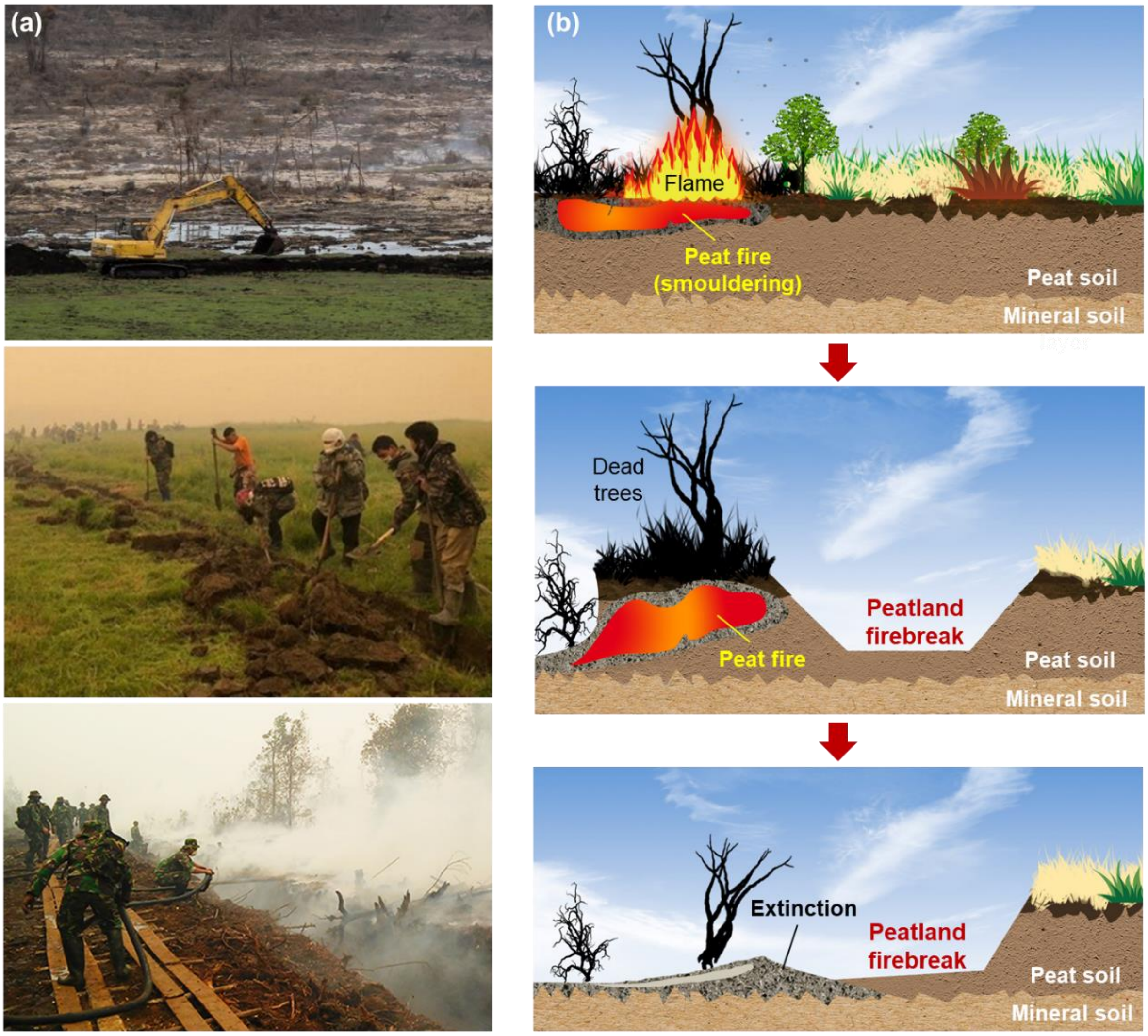

Fig. 1 (a) Practices of making a firebreak to control peat fires (Credit: Rob Gunstone, Ignacio Villaverde), and (b) schematics of smouldering fire in peatland and the concept of making a trench-shaped firebreak.

The firebreak, also known as the fireguard, is built to prevent the fire from escaping existing burning regions, which is widely used in the fire protection of wildland-urban interface (WUI) and prescribed fires (Weir *et al*. 2015; DFES 2016). A conventional firebreak is a strip of land denuded of all flammable materials. It may be constructed with a grader, plough, excavator, or just a shovel before or during the wildfire (Wilson 1988). Such a firebreak is designed based on the knowledge of flaming ignition to prevent flame spread and the proliferation of firebrands, so it may not be effective in controlling smouldering wildfires (Purnomo *et al*. 2021).

Considering the massive scale of peatlands and underground fires, digging a trench into the peat soil layer to make a firebreak is a quite costly process in practice (see Fig. 1). If the trench is too shallow and a thick peat layer remains, the smouldering fire can still cross the firebreak. One the other hand, if the trench is made too deep, valuable time and human resources are wasted, especially during an urgent peat fire event. As the thickness of the peat layer varies in the field, it is challenging to design and build a firebreak for peatlands in the scale of km that balances the effectiveness and cost. To the best of the authors' knowledge, no study has explored the feasibility and reliability of firebreaks in controlling smouldering peat fires; thus there is a significant knowledge gap.

This work aims to explore the applicability and minimum requirements of a firebreak for smouldering peat fires through laboratory-scale experiments. A trench-shaped firebreak was built above a mineral sand layer to mimic a real firebreak in peatlands. The maximum thickness of the remaining peat layer was explored under the principles of cooling or quenching, (I) by peat moisture and (II) by underlying mineral layer. The research outcomes provide a scientific foundation for underground wildfire fighting and the design criteria for the protective measures of large-scale peat fire experiments in the field.

Experimental methods

Ideally, for a firebreak, if all organic peat soils are entirely removed, and only the mineral soil layer remains, the smouldering fire can be well confined. However, the real thickness of the peat layer is not uniform, and the soil moisture profile and inorganic content vary greatly with locations. Moreover, it is practically impossible to quickly identify the peat layer's thickness or remove it completely. Nevertheless, even if the peat layer is not entirely removed, as long as the remaining peat layer is wet and thin enough, the smouldering fire can be quenched by its moisture or the bottom mineral soil layer (Miyanishi and Johnson 2002; Lin and Huang 2021). Thus, the laboratory experiments aim to determine the remaining peat layer's maximum thickness to break the smouldering peat fire successfully.

The tested organic-rich (~97%) peat soil was moss peat from Estonia (see Fig. 2a), which had been used in a series of previous studies (Lin *et al.* 2019, 2020; Lin and Huang 2020, 2021). Such a high-organic peat soil has the highest smouldering fire risk, which defines the worst peat fire scenario. Therefore, the criteria for breaking smouldering fire in this peat can guarantee effectiveness in other peat soils with lower organic contents. The peat soil was first oven-dried at 90 °C for 48 h, and the dry bulk density was measured to be 145 $\mathrm{kg{\cdot}m^{-3}}$. The element analysis shows a mass fraction of 44.2 (C), 6.1 (H), 49.1 (O), 0.5 (N), 0.1(S) % (Lin *et al.* 2019). Once the dried peat was exposed to ambient, it immediately absorbed the air moisture to reach a new equilibrium with $MC_p \approx 10\%$, defined as the air-dried peat. To obtain the desired MC_p, the oven-dried peat was mixed with the corresponding amount of water (Christensen *et al.* 2018; Lin *et al.* 2019). Afterwards, the sample was shaken and left in a sealed box to equilibrate and homogenate. For wet peat samples, the MC_p ranged from 25% to 125%, with an interval of 25%, where the uncertainty was within 5%.

A top-open smouldering reactor was designed to mimic a trench-shaped firebreak, as shown in Fig. 2b. All sides of the reactor were made of metal mesh to provide support and sufficient oxygen to the soil layer. Below the peat layer, there was a 1-cm layer of fine mineral sand plus a brick to simulate the mineral soil layers. The dry bulk density of sand was approximately 1,500 $\mathrm{kg{\cdot}m^{-3}}$. The sands with three different moisture contents (MC_s) were selected to vary the bottom cooling condition: (i) weak cooling

$MC_s \approx 0\%$ (dry sand), (ii) medium cooling $MC_s = 15\%$ (wet sand), and (iii) strong cooling, $MC_s = 30\%$ (saturated sand). Note that sand is ten times denser than peat soil, so the absolute mass of water in mineral sands with $MC_s = 15\%$ is still higher than that in peat soils with $MC_p = 125\%$.

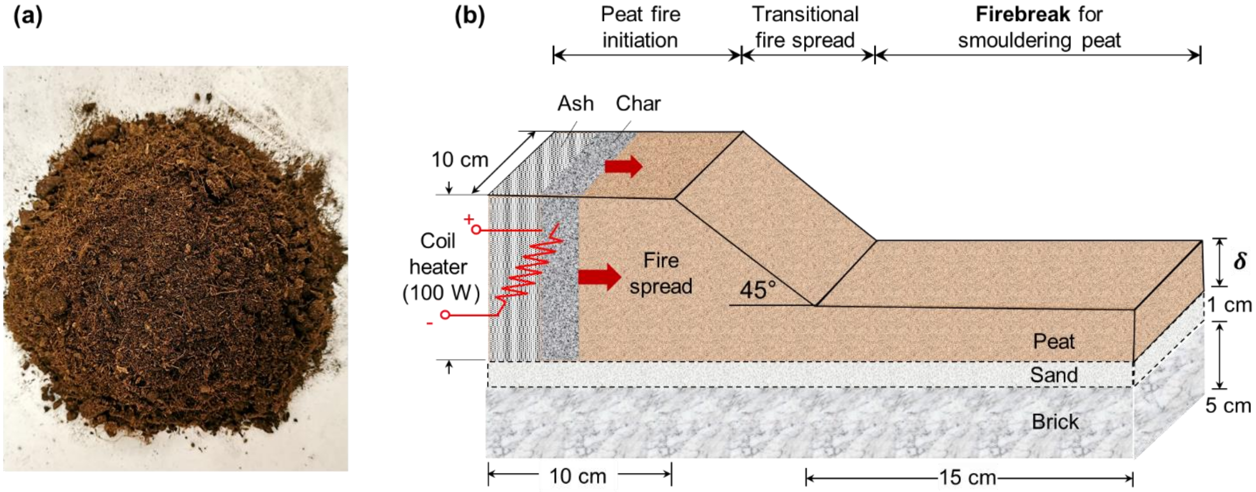

Fig. 2 (a) Photos of moss peat soil tested in this experiment, and (b) schematics of the experimental design.

A 10-cm coil heater was buried 5 cm below the top free surface and attached to the left-hand side to initiate a consistent and robust smouldering fire. The ignition protocol was set at 100 W for 30 min, which was strong enough to initiate a robust smouldering fire (Huang *et al.* 2016). Initially, the peat sample thickness was 10 cm, and the peat soil was left to burn and spread laterally for 10 cm to self-stabilize (see Fig. 2b). Considering the structural safety and stability of firebreaks in the field (Duncan *et al.* 2014), instead of a right-angle transition to the lower-level firebreak section, a sloped wedge transition section (45°) was designed to prevent landslide.

The effective length of the simulated firebreak was 15 cm, and the thickness of the peat layer (δ_p) was varied from 1 cm to 9 cm, referring to our previous work (Lin and Huang 2021). If smouldering fire successfully spread for 15 cm without clear deceleration but ultimately burned through the peat layer, the tested thickness was then gradually decreased at an interval of 2 cm until successfully breaking/quenching the fire. Then, the maximum thickness of the peat layer allowed for the firebreak (δ_p^*) could be obtained. Afterwards, the influence of the soil moisture profile (i.e., both MC_p and MC_s) was also explored. Throughout these experiments, the ambient temperature was 23±2 °C, and the relative humidity was about 50 ±10%. For each scenario, tests were repeated at least twice, and for tests near the limits, three or four repeating tests were conducted to ensure repeatability. Our results showed excellent repeatability roughly because of the use of commercial peat soil with uniform density, particle size, and organic content (Lin and Huang 2020). In total, about 250 experiments were conducted to explore the minimum requirements of an effective firebreak.

Results and Discussion

Phenomena of peat fire spread and extinction

As the peat moisture content was increased to 125%, the spread of smouldering peat fire was no longer sustained, regardless of the thickness of the peat layers (see Video S1). In the literature, fire extinction due to high peat moisture content (Quenching Type I) has been widely observed, and the maximum value of MC_p varies with the type of peat soil burned and the wildfire conditions (Frandsen 1987, 1997; Huang and Rein 2016; Prat-Guitart *et al*. 2016). For this specific peat soil, the maximum peat moisture or the *fire threshold* is about $MC_p \approx 115\%$. Note that for downward fire spread, the maximum MC_p could be higher because of the heat insulation provided by the top ash layer (Benscoter *et al*. 2011; Zaccone *et al*. 2014).

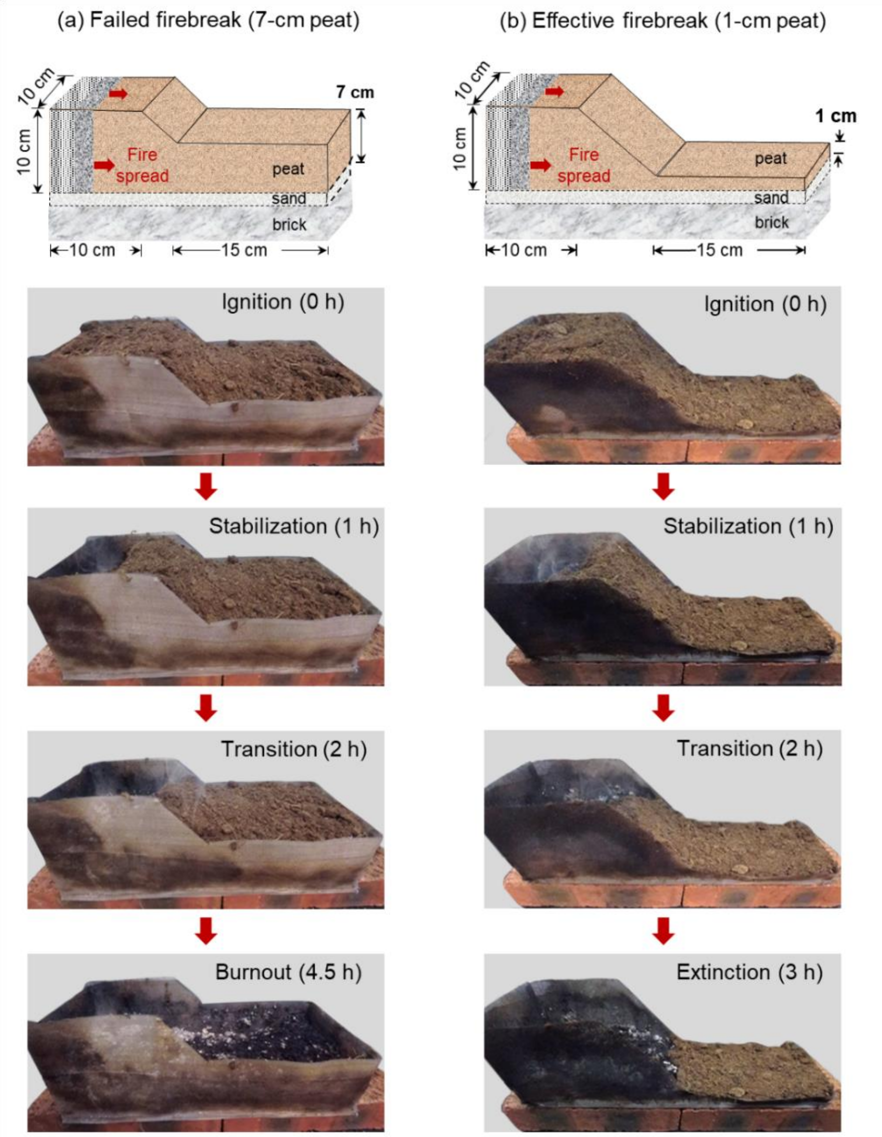

Fig. 3. Snapshots of the smouldering peat fire spread in the laboratory-scale firebreak, (a) failed firebreak with 7-cm thick peat layer, 50% MC_p, and 30% MC_s (Video S2), and (b) successful firebreak where fire extinction due to cooling with 1-cm thick peat layer, 50% MC_p, and 30% MC_s (Video S3).

Figure 3 compares the effect of remaining peat-layer thicknesses (δ_p) on breaking the smouldering peat fire. After the 0.5-h ignition process, a robust smouldering fire gradually spread forward for 10 cm before passing through the transitional wedge section. Then, in the transitional area, the fire front would slow down and self-adjust. Afterwards, the smouldering fire entered the firebreak section and attempted to spread. For the failed firebreak with a thickness of 7 cm, 50% $MC_{p,}$ and 30% MC_s (Fig. 3a and Videos S2), the smouldering fire successfully spread forward without a clear deceleration process. Eventually, the organic peat layer was consumed and turned into ash. Further extending the firebreak length over 15 cm, the smouldering fire could still spread across the firebreak. In other words, this firebreak could not stop/break the peat fire, because the remaining layer of organic soil in the firebreak was not thin enough to be quenched by the mineral layer.

As the remaining thickness of peat layers was decreased to 1 cm (Fig. 3b and Videos S3), the smouldering fire could no longer spread after passing through the transition section. Instead, the smouldering fire front was entirely stopped and extinguished within 5 cm into the firebreak. Therefore, as long as the remaining peat layer is thin enough, the smouldering fire could be quenched by the underlying cold mineral soil layer (Quenching Type II). The scientific principle of the smouldering quenching process was demonstrated previously (Lin and Huang 2021).

Limiting conditions of peatland firebreak

The experimental outcomes of firebreaks are summarized in Fig. 4a-c with different peat-layer thicknesses (δ_p) and soil layer moisture profiles (MC_p and MC_s), where '○' and '×' represent the spread and extinction of smouldering fire, respectively. First of all, no fire was sustained if the peat moisture was above 115% (Quench Type I).

Secondly, the quenching (or breaking) of smouldering peat fire also occurred if the thickness of the peat layer (δ_p) in the firebreak decreased, due to the cooling from the underlying mineral soil layer (Quenching Type II). As the mineral layer got wetter or the value of MC_s increased, a thicker peat layer was needed to maintain the fire spread, because of the increased cooling from the bottom mineral layer, as shown in Fig. 4a-c and further compared in Fig. 4d. Specifically, for air-dried peat (MC_p = 10%), the dry mineral soil layer was difficult to quench the peat fire (Fig. 4a), unless the peat layer was entirely removed. On the other hand, for a saturated mineral soil layer, the smouldering fire can be well isolated, even if the peat layer above increased to 6 cm with a moisture content larger than 75% (Fig. 4c).

Moreover, both quenching effects emerged for smouldering spread over a wetter peat layer. Then, the maximum peat thickness allowed to remain in the firebreak (δ_p^*) increased with the moisture content of peat (MC_p) and substrate mineral sand (MC_s). In other words, a wetter soil profile made the quenching of smouldering fire easier. For example, when the mineral sand layer was saturated, as MC_p increased from 10% to 100%, the value of δ_p^* increased from 1 cm to 7 cm. Therefore, in the practice of digging the break against the peat fire, as long as the remaining peat layer in the firebreak is wet and less than 5-10 cm (depending on soil types), the firebreak will be relatively effective.

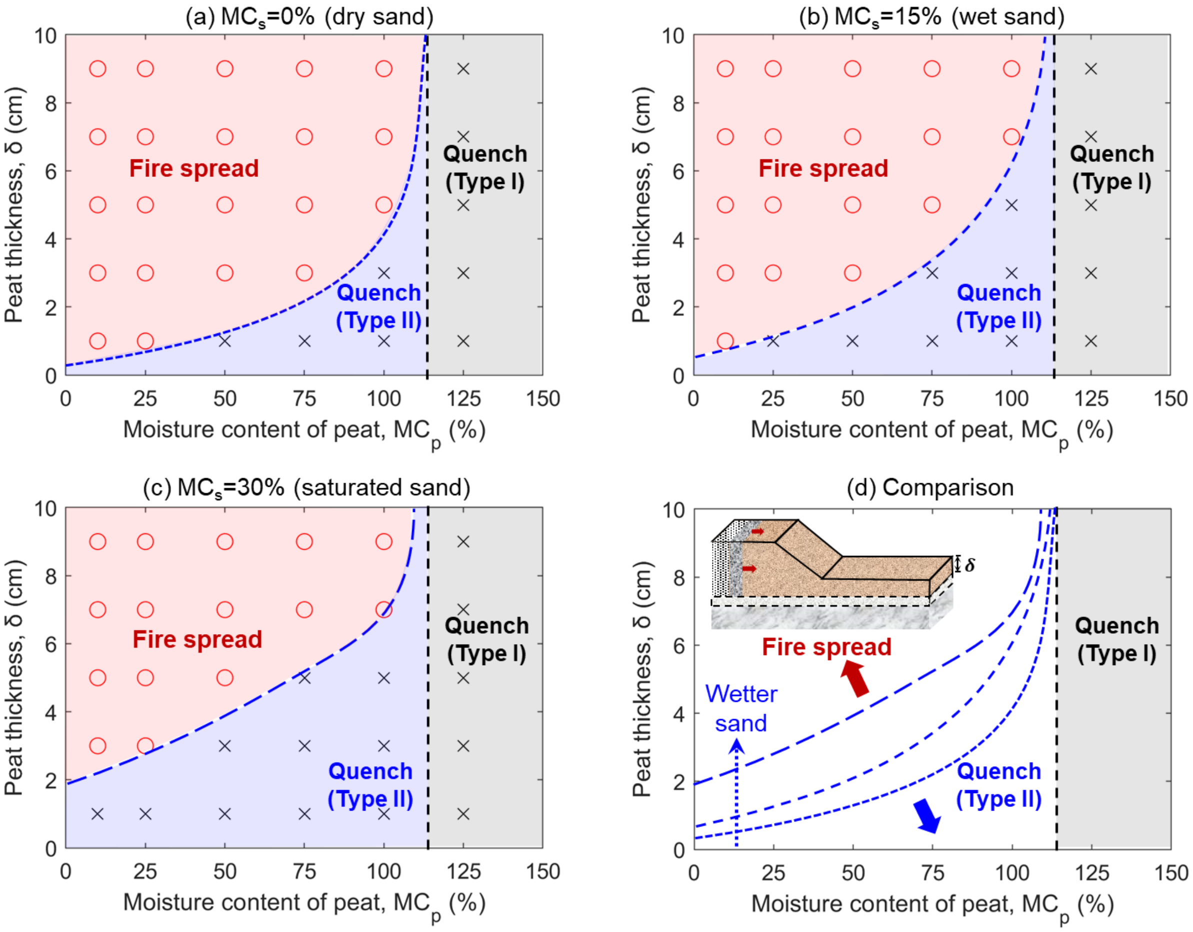

Fig. 4. Experimental outcomes of the peat fire spread in the firebreaks with different MCs of peat soils and inorganic sands (fire spread '○' and quenching '×').

Heat transfer analysis

To scientifically understand the influence of the soil moisture profile on the required thickness of smouldering firebreaks in peatlands, an approximate and simplified heat transfer analysis based on the energy conservation equation can be adopted. The smouldering region in the firebreak is chosen as the control volume, similar to Lin and Huang (2020a). Figure 5 illustrates the energy balance for a horizontally propagating smouldering front within the firebreak where the peat layer has a thickness of δ_p. At the extinction limit (δ_p^*), the net heat released from the smouldering fire region ($\dot{Q}_{sm}$) should just overcome the heat loss to the ambient atmosphere ($\dot{q}''_\infty$) and conduction to the bottom mineral soil layer ($\dot{q}''_{cond}$), as well as enabling the evaporation of the peat moisture ($\dot{Q}_{ev}$). That is,

$$(\dot{q}''_\infty + \dot{q}''_{cond})\Delta x = \dot{Q}_{sm} + \dot{Q}_{ev} = \dot{m}''_F \delta_p^* (\Delta H_{sm}^* - MC_p \Delta H_{ev}) \tag{1}$$

where Δx is the length of the smouldering front that is comparable to δ_p^* (Lin and Huang 2021); $\dot{m}''_F$ is the mass-loss flux of burning peat; and ΔH_{sm}^* is the heat of smouldering combustion of peat, where the combustion process is weak and incomplete at the near-extinction temperature of 250~300 °C.

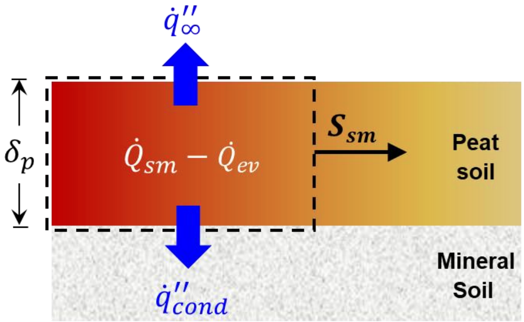

Fig. 5. Schematics for the energy balance for a horizontally propagating smouldering front.

If the entire peat and mineral layers are dry, the fire risk within the firebreak is the highest, although such a scenario may be rare in nature. Thus, smouldering fire can spread across the firebreak even with a very thin peat layer. This thinnest limit of the peat layer ($\delta^*_{p,min}$) is

$$(\dot{q}''_{\infty} + \dot{q}''_{cond})\Delta x = \dot{m}''_F \delta^*_{p,min} \Delta H^*_{sm} \tag{2}$$

By dividing Eqn 1 by Eqn 2, we have

$$\delta^*_p = \delta^*_{p,min} + \frac{\delta^*_{p,min}\Delta H_{ev}}{\Delta H^*_{sm} - \mathrm{MC_p}\Delta H_{ev}}\mathrm{MC_p} \tag{3}$$

where the maximum peat moisture for smouldering (or the limit of Quenching Type I) is

$$\mathrm{MC_{p,\,max}} = \frac{\Delta H^*_{sm}}{\Delta H_{ev}} \tag{4}$$

Eqn 3 predicts that as the peat becomes wetter (i.e., a larger $\mathrm{MC_p}$), the limiting thickness of the firebreak first increases almost linearly. When the peat moisture approaches the limit of Quenching Type I ($\mathrm{MC_{p,max}}$), the thickness of the peat layer becomes irrelevant, which agrees with the test data in Fig. 4.

The influence of sand moisture is reflected by the bottom heat conduction ($\dot{q}''_{cond}$), which is used to evaporate the water of the sand layer within a thermal-penetration thickness of δ_s as

$$\dot{q}''_{cond}\Delta x = \dot{m}''_w \delta_s \Delta H_{ev} = \rho_s S^*_{sm} MC_s \delta_s \Delta H_{ev} \propto MC_s \tag{5}$$

where $S^*_{sm} \approx 0.1$ mm/min is the minimum spread rate of the peat fire (Lin and Huang 2021). By substituting Eqn 5 into Eqn 2 and 3, we have

$$\delta^*_p \propto \delta^*_{p,min} \propto MC_s \tag{6}$$

Therefore, as the bottom sand moisture content (MC_s) increases, the smouldering fire is more vulnerable to extinction, even if the thicker peat layer remains. In short, the proposed heat-transfer analysis successfully explains the experimental results in Fig. 4d.

Implications of peatland firebreak in practice

Ideally, as long as $\mathrm{MC_p}$ is beyond the *fire threshold* (or it is sufficiently wet), the smouldering fire can be effectively isolated and even self-extinguished, which is regarded as a successful peatland firebreak based on Criterion I. However, in the real peat fire scenario, wetting the peatland by rain or firefighting water spray may become invalid, considering a peat fire can last for weeks or even months.

On the other hand, a wet soil layer can be quickly dried by surficial flaming front or slowly dried by sunshine and hot weather. If the peatland firebreak is dried before the peat fire is entirely suppressed, it can no longer isolate the burning area or break the smouldering peat fire.

Therefore, the most effective and reliable peatland firebreak needs to satisfy Criterion II, that is, removing the majority of peat layers and ensuring the thickness of the remaining peat layer in the firebreak is less than 5 cm. Then, without removing the entire peat soil layer, the firebreak can prevent the hidden peat fire from creeping cross the firebreak and escaping from the burning zone, regardless of the weather change. Moreover, the sloped, trench-shaped firebreak is recommended, as the sloped wedge creates a transition to weaken smouldering intensity, slow down fire spread, and avoid landslide or collapse (Duncan *et al.* 2014) in situ. The trench-shaped firebreak can also guide the water to flow into the firebreak like the drainage systems (Kanwar *et al.* 1986), which helps maintain a high water table and keep the peat soil layers wetter than the *fire threshold*.

The proposed design criteria of peat firebreaks can be applied to control real smouldering wildfires and offer a protective measure for field-scale peatland fire experiments. For peatland managers and firefighters, different layers of fire protection measures may be considered. Note that as the peat is heterogeneous in nature, the borderline of the quench/spread curves has some uncertainty. Therefore, it is recommended to sample peat soils and conduct small-scale experiments to identify their *fire threshold* in terms of moisture contents ($MC_{p,\max}$). Then, the thickness of the peat layer and moisture profile of the entire soil layer at different locations should be determined, so that different fire zones with similar fire hazards may be divided. Afterwards, referring to the criteria in Fig. 4, precautionary firebreaks can be created along with the areas with a thin and wet peat layer to minimize the cost and workforce. Finally, the trench-shaped firebreak can be quickly constructed by excavating the minimum amount of peat layer and adding a minimum amount of water, which saves the firefighting resource and maximizes efficiency. However, this firebreak method would not be simply upscaled for flaming wildfires, as firebrands may easily break through most firebreaks. Large-scale peat fire experiments in the field and more firefighting practices are required to develop scientific guidelines for peat firebreaks.

Conclusions

In this work, we conducted bench-scale peat fire experiments to explore the scientific foundation and design criteria for constructing peatland firebreaks. We found that the smouldering peat fire can be successfully isolated above the mineral soil layer, even if the peat layer is not completely removed. There are two criteria for an effective peat firebreak: (I) adding water to make the peat layer sufficiently wet (> 115% MC in the present work), and (II) ensuring the peat layer is thinner than the quenching thickness (< 5 cm). Criterion I may fail if the water table declines or the peat layer is dried by the hot weather and surface fires; thus, satisfying Criterion II is more reliable.

Moreover, the sloped, trench-shaped firebreak is recommended to avoid a landslide and guide the water flow to keep the peat layer wet. This work provides a scientific foundation for fighting and mitigating underground wildfires and guides protective measures for field-scale peat fire tests. Future research should quantify the influence of inorganic content and ambient temperature on the design of peatland firebreaks and verify the effectiveness of firebreaks in real peatland wildfires.

Acknowledgment

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Supplemental materials

Video S1 Effective peat firebreak (criterion I) with a thickness of 7 cm, where MC_p=125%, MC_s=30%.

Video S2 Failed peat firebreak with a thickness of 7 cm, where MC_p=50%, MC_s=30%.

Video S3 Effective peat firebreak (criterion II) with a thickness of 1 cm, where MC_p=50%, MC_s=30%.

https://www.youtube.com/playlist?list=PLyVe5fL3rmdTW2SLXHSoFw_3bY9p0WgAk

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