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Persistent Underground Smouldering Fire in Deep Peat Layer

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Keywords

Smouldering; peat fire; underground fire; wildland fire; fire spread

Abstract

Peatlands are essential terrestrial carbon pools. Due to climate change and human activities, peatlands are more prone to large-scale fires than ever, especially deep underground fires. However, most current smouldering researches focus on small-scale smouldering behaviour in relatively shallow layers, posing a research gap. This work explores in-depth (up to 60 cm) smouldering behaviour, such as persistence, propagation and emission. The commercial organic peat soil from Netherland was chosen for lab experiments. Reactors with good thermal insulation conditions were built to simulate the natural smouldering environment. Experimental results demonstrate that smouldering underground fires can sustain in deep soil layers for more than a week without any additional oxygen supply. Because of the competition of oxygen supply and heat losses, a critical depth of 55 cm for smouldering propagation was obtained, below which smouldering cannot self-sustained propagate. This work will help connect lab-scale experiments with natural underground smouldering peat fires and understand smouldering dynamics in deep soil layers.

1. Introduction

Peatland, as a type of wetland, accumulates a considerable amount of organic matter decomposed from vegetation material (Hugron et al. 2013). Peatlands are essential terrestrial carbon pools, storing one-third of the world's soil carbon (500-600 Gt C), as much carbon as surface vegetation globally, and may be of similar magnitude to the atmospheric carbon pool (~850 Gt C) (Ballhorn et al. 2009; Turetsky et al. 2015).

Due to climate change and human activities, peatlands are more prone to large-scale fires than ever before (Jolly et al. 2015; Lin et al. 2021a). Especially, at certain times and in certain areas, such as hot, dry summers and regions with a high diversity of plants, the fire risk is significantly increased (Evtyugina et al. 2013). Frequent peat fires have caused serious ecological and climatic damage, as well as significant economic losses. For example, in 2019, the slash-and-burn activities in southeast Asia (Goldstein et al. 2020) resulted in mega-scale peatland wildfires that burned for several months, leading to severe air pollution and causing many health issues to residents (Normile 2019). Peat fires are started by flaming fires in forests, lightning strikes, and human activities and are dominated by smouldering combustion. Smouldering wildfire requires less ignition energy than flaming combustion and can persist in wetter and lower oxygen conditions. Once ignited, smouldering can propagate vertically and horizontally in a deep and wide soil layer, thus sustaining the largest and most persistent fire on Earth (shown in Fig. 1). For such underground fires, it's challenging to detect and extinguish them. Even though fires on the soil surface was extinguished, hidden underground smouldering fire may spread at a very low propagation rate and re-spreading to the surface in some conditions (Rein 2013). However, this kind of in-depth smouldering behaviour is poorly understood. Smouldering wildfire and the relevant ecological problems have attracted much research attention. Still, most of them focus on smouldering propagation in relatively shallow soil layers in terms of smouldering ignition, propagation (Huang and Rein 2017, 2019), extinction (Lin and Huang 2021; Lin et al. 2021b), and firefighting (Ramadhan et al. 2017; Santoso et al. 2021). So far, there is a lack of both lab-scale and field-scale smouldering research to reveal the in-depth smouldering propagation behaviour, thus bringing a considerable knowledge gap.

This study aims to conduct a lab-scale series of in-depth smouldering experiments to understand the deep-layer smouldering propagation behaviour. This work will help better connect small-scale laboratory experiments with natural underground smouldering peat fires.

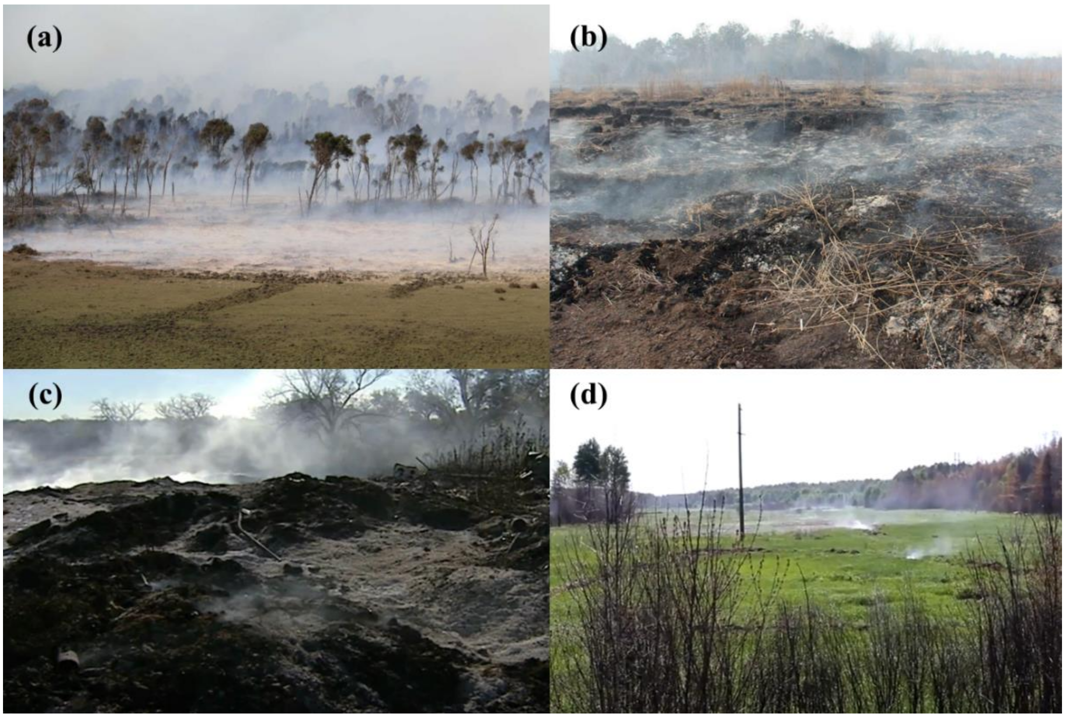

Figure 1- Underground smouldering fire in (a-b) Southeast Asia, (c) North America, and (d) Eastern Europe

2. Methodology

2.1. Peat sample

The commercial moss peat sample from Estonia with high organic content (~97%), uniform density, and homogenous particle size was chosen in this study. Before the tests, the peat soil was first oven-dried at 90 ºC for 48 h to reach an equilibrium with the air of MC = 10% (Huang and Rein, 2017). The measured peat bulk density and porosity were 145 ± 10 kg/m^3 and 0.90 ± 0.01. Elemental analysis shows that its mass fraction of C/H/O/N/S is 45.6/6.0/48.0/0.5/0.3%, respectively.

2.2. Experimental setup and procedure

Fig. 2 shows the schematic diagram of the experimental setup for the peat fire initiation and spread. In order to simulate a natural peat underground fire, the smouldering reactor needs to have good insulation. The smouldering reactor in this study was built of 1 cm-thick insulation ceramic fibreboards to contain the peat sample and had different heights (30 cm – 60 cm). The aluminium foil was attached to the outer surface of the insulation board to reduce the radiative heat loss. The top of the reactor was open to supply oxygen and release emissions. An array of K-type thermocouples with an interval of 3cm was inserted into the reactor to record the temperature history at a different height. The coil ignitor inserted into the sample was used to initiate the smouldering combustion.

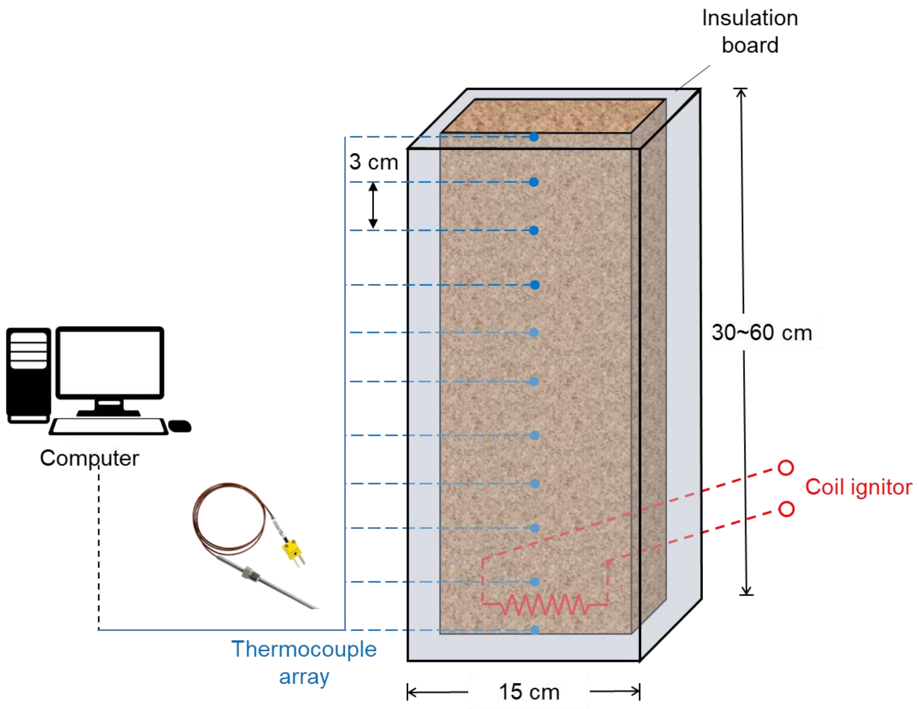

Figure 2- Experimental setup for in-depth smouldering peat fire

In order to initiate the peat and form a robust smouldering front, the ignition protocol was fixed at 100 W for 60 min. The tests are stopped until all peat has returned to room temperature for 2 hours, which indicates the end of smouldering. The test started with ignition at the bottom. Subsequently, tests with different reactor heights were conducted, and all the tests were repeated at least twice to ensure repeatability.

3. Results and Discussion

3.1. Smouldering phenomenon and critical depth

Fig. 3 shows the thermocouple measurements of (a) smouldering propagation and (b) no propagation in reactors with different depths of 50 cm and 60 cm, respectively. Taking (a) as an example, the ignition was started from the bottom (-50 cm). After 60-min heating, the temperature at the corresponding height exceeds 250 ºC, which is the minimum smouldering temperature and suggests a robust smouldering front formation. Afterward, it shows that smouldering propagated upward with a very low propagation rate (~4 mm/h). A noticeable change occurred after 3.5 days. Smouldering no longer continued to propagate upward but instead propagated downward with a similar propagation speed and higher smouldering temperature (> 400 ºC). Then the smouldering fluctuated around the bottom before final extinction. Notably, a peat layer of 50-cm depth maintained continuous smouldering combustion for about a week.

A completely different phenomenon occurs if the depth is increased to 60 cm (Fig. 3 (b)). The temperature near the bottom (-60 cm) still exceeded 250 ºC after 60 min heating, but no smouldering propagation was observed. Even though a few thermocouples near the bottom showed a short-term temperature increase, this is probably the effect of heat transfer since the duration was short and the temperature was low. Repeated tests have demonstrated that at this depth, even if the ignition power is further increased or the ignition time is extended, no smouldering propagation can be observed.

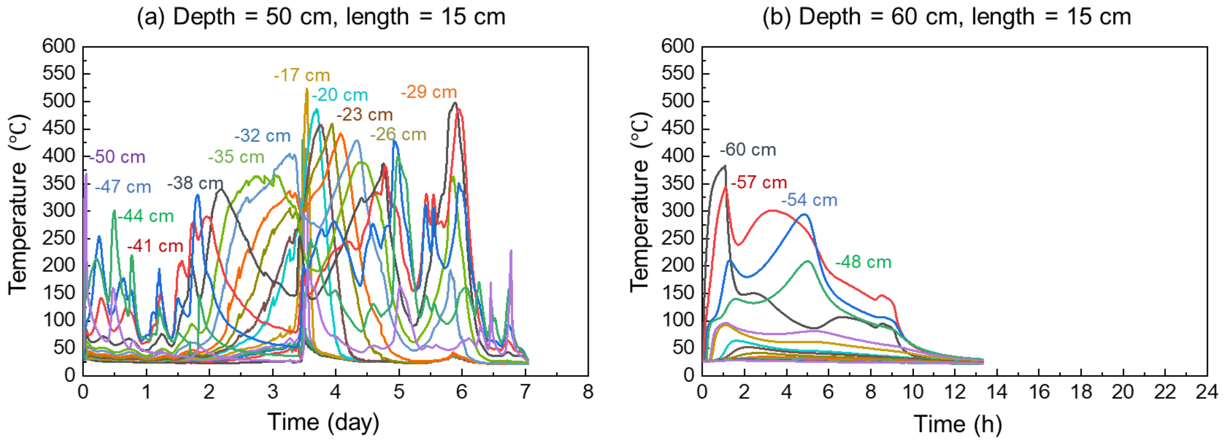

Figure 3- Thermocouple profiles in different depths. (a) shows a typical smouldering phenomenon while (b) indicates no smouldering propagation after ignition (The negative sign means that the thermocouple is below the reactor's top free surface).

3.2. Critical depth

Experimental results show that at this reactor size (length = 15 cm), smouldering can only propagate when the depth is less than 50 cm. Continue to deepen the depth, even if smouldering is still able to be ignited under a strong ignition, it cannot self-sustained propagate. Thus, the critical smouldering depth for this reactor size is 55 cm.

Critical depth exists due to the limitation of the oxygen conditions. Oxygen can only be provided by diffusion into the deep peat layers, and it may not be sufficient to support the oxidation processes necessary for smouldering below the critical depth. According to Darcy's law,

$$q = \frac{k}{\mu L} \Delta p \qquad \text{(Eq. 1)}$$

where q is airflow flux (or the air supply per unit area) in (m/s), k is the permeability of the porous medium in m^2, μ is the dynamic viscosity of the fluid in (Pa·s), and Δp is the pressure drop in (Pa) over a given distance L (m). Thus, given a heat transfer condition and minimum oxygen supply for the oxidation process of smouldering, the critical depth for smouldering can be determined. Future research could explore the critical smouldering depth in different insulation conditions or even smouldering in field-scale.

4. Conclusions

In this work, we conducted a series of lab-scale experiments to investigate the in-depth smouldering peat fire. We experimentally demonstrated that smouldering underground fires could sustain in deep soil layers for more than a week without any additional oxygen supply. In the current experimental setup, a critical depth of 55 cm for smouldering propagation was obtained, below which smouldering cannot self-sustained propagate. However, reducing heat loss, such as using a reactor of a larger size, will make smouldering sustain in a deeper peat layer. This work will help better connect small-scale laboratory experiments with natural underground smouldering peat fires and understand smouldering behaviour in deep layers.

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