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Critical Conditions for Flaming Peat Fire in Wildland

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Abstract

Smoldering peat fire is one of the largest and longest fire phenomena on Earth, but whether peat can support a flaming wildfire like other surface fuels is still unclear. Our experiments demonstrate the pilot flaming ignition of peat soil with moisture up to 100%. After flame extinction, conventional smoldering peat fire can be sustained, indicating that flame can spread over peat under external heating to rapidly increase the size of peat fire. Compared to smoldering ignition, flaming ignition of peat is more difficult, requiring a higher minimum heat flux. The propensity for flaming increases with a drier peat and a larger external heating. For the flaming ignition criteria, defining a constant mass flux is inappropriate for moist peat. On the other hand, the critical mass flux at flaming ignition point increases with heat flux but is insensitive to the moisture content. This research helps to understand the development of peat fire and the interaction between flaming and smoldering wildland fires.

Keywords: Peatland; Smoldering; Piloted ignition; Ignition energy; Moisture; Critical heat flux

1. Introduction

Catastrophic wildfires in recent years reveal a dramatic increase in size, frequency and duration because of climatological and human factors (Lin *et al.* 2019), particularly in United States, Australia, Indonesia and many European countries (Gibson *et al.* 2018). In particular, smoldering wildfires in peatlands are the largest and longest fire phenomena on Earth and contribute greatly to the global emission of greenhouse gasses (Rein 2013). Although peatlands only cover 3% of the Earth land surface, they store around 25% of the planet's terrestrial organic carbon, i.e., approximately the same mass of carbon in the atmosphere (Gorham 1994). More importantly, the annual release of ancient carbon from peat fires is approximately equivalent to 15% of human-made emissions (Page *et al.* 2002; Ballhorn *et al.* 2009; Turetsky *et al.* 2015).

Peat soil is an accumulation of incompletely decomposed vegetation residues, and it is carbon-rich and formed in anaerobic conditions (Page *et al.* 2002). Peat is also a porous and charring natural fuel that prone to smoldering combustion like plastic foams and coals (Rein 2013). Previously, most researches in the literature have focused on the smoldering characteristics of a peat fire. However, because most natural fuels can support both smoldering and flaming fires, it is logical to expect that peat soil can also support a flaming wildfire. If flame can spread over peat soil, the size of peat fire can expand much faster than the expected creeping smoldering spread. So far, no research has studied the critical conditions of flaming ignition of peat and the propensity for a flaming fire spreading on peatlands, so there is a big knowledge gap. Previously, many ignition

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theories have been proposed based on the critical mass flux (Drysdale 2011). These theories work reasonably for common dry polymer materials but become less reliable for complex wildland fuels (McAllister 2013) thus, requiring a better ignition criterion.

In this work, the flaming ignition with a pilot source and smoldering ignition of peat is investigated under varying MCs (10 ~ 100%) and radiant heat fluxes (5 ~ 90 kW/m^2). The ignition delay time, mass flux and minimum heat flux are quantified for both flaming and smoldering ignition of peat.

2. Experiment

2.1.Apparatus and Peat Sample

All ignition experiments were conducted using the cone calorimeter (FTT iCone Plus) (Babrauskas 2016). The cone-shape heater can provide a constant heat flux to the sample area of 10 cm ×10 cm. The schematic diagram of experimental apparatus is illustrated in Fig. 1 (a).

The carbon-rich peat soil tested in the experiment is the moss peat from Netherland (Fig. 1b), and it has an organic matter of about 96%. The peat was first oven-dried at 90°C for 48 h, and the oven-dried bulk density of peat is 145 kg/m^3 (MC → 0%). When the oven-dried peat was in contact with air, it quickly absorbed ambient moisture and reached a new equilibrium with about 10% MC, defined as the air-dried peat (Huang *et al.* 2016). In order to obtain other MCs, the oven-dried peat was mixed with water by following the same process in (Huang *et al.* 2016). For example, 2 kg of 100% MC peat can be produced by mixing 1 kg of dry peat with 1 kg of water. Afterward, samples were shaken to enhance the mixing process and left into the sealed boxes for homogenization for at least 48 h. Another two targeted MCs for peat were 50% (drought) and 100% (wet).

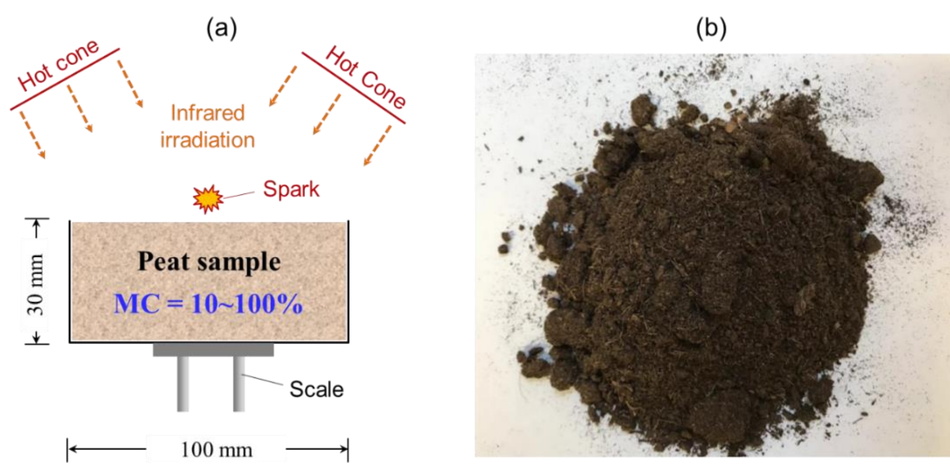

Figure 1. (a) Schematic diagram of the cone calorimeter and sample, and (b) photo of moss peat sample.

3. Results and discussions

3.1 Peat's propensity for flaming and smoldering

By plotting the ignition time of flaming ($t_{ig,f}$) and smoldering ($t_{ig,sm}$) versus radiant heat flux in Fig.

2, the propensity of air-dried and wet peat for flaming and smoldering ignition can be quantified. Like all other ignition phenomena, the required heat time is decreased with the increasing radiant heat flux. More importantly, as the heating duration and heat flux decrease, there are three ignition regions, (I) piloted flaming ignition, (II) smoldering ignition, and (III) no ignition. Clearly, longer heating duration and larger heat flux are required to pilot a flame attach to the peat soil. Therefore, the propensity of peat soil for smoldering is greater than that of flaming (Lin *et al.* 2019). This behavior is very similar to the low-density PU foam (Hadden *et al.* 2014; Rein 2014), while unlike the high-density redwood, probably because peat has a relatively small bulk density (160 kg/m^3 for air-dried peat) and a similar open-pore structure like PU foam.

For the air-dried peat (MC = 10%) in Fig. 2(a), under the same radiant heat flux, only a slightly longer heating duration is required for flaming than for smoldering. Moreover, both ignition forms are relatively easy to achieve (i.e., very small Region II), and the minimum heating flux for flaming ignition is $\dot{q}''_{min,f}$ = 7.5 ± 0.5 kW/m^2, and for smoldering ignition, it is slightly smaller as $\dot{q}''_{min,sm}$ = 6.5 ± 0.5 kW/m^2. However, for the wet peat (MC =100%) in Fig. 2(b), the minimum heat flux for smoldering ignition ($\dot{q}''_{min,sm}$) approaches to 6.5 kW/m^2 that is the same as the air-dried peat in Fig. 2(a), because the wet peat will be eventually dried by the long-term heating. On the other hand, the minimum heat flux for flaming ignition ($\dot{q}''_{min,sm}$) increases significantly to 55 kW/m^2. For the Region II with the heat flux between 6.5 and 53 kW/m^2, only a smoldering ignition can take place, and even if the spark is kept during the continuous heating, the flame will not occur until the peat is burnt out by smoldering. Therefore, as the peat MC is increased, the propensity for flaming is decreased significantly.

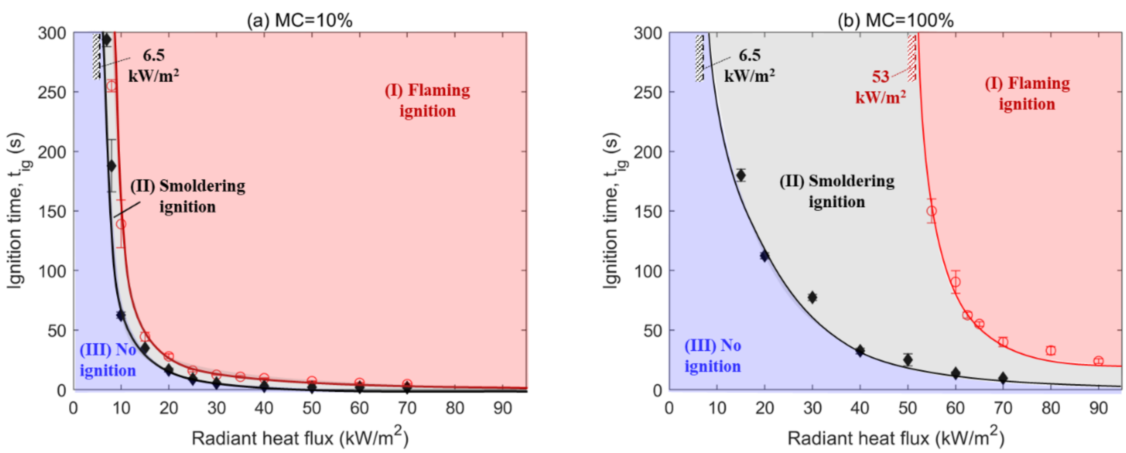

Figure 2. The ignition delay time for piloted flaming ignition and smoldering ignition for (a) air-dried peat sample (MC = 10%), and (b) wet peat sample (MC = 100%), where three ignition regions are identified.

3.2 Critical Mass Flux for Flaming Ignition

For the piloted flaming ignition, the critical mass flux (or mass loss rate per unit area, $\dot{m}''_{ig,f}$) is considered as the most fundamental criterion. It is because the value of mass flux is more related to the profile of fuel concentration and the flammability region above the fuel surface (Drysdale 2011). Fig. 3(a-c) shows some examples of the measured mass flux time evolution during the entire ignition and burning process of peat, where the symbol indicates the moment of the piloted flaming ignition and the critical mass flux. The scrutiny reveals very different locations of the ignition moment in the mass flux curve of different MCs. It is particularly clear in Fig. 3(c) that the flaming ignition occurs in the ascending period for the air-dried peat (MC = 10%), near the peak mass flux for the drought peat (MC = 50%), and in the descending period for the wet peat (MC = 100%). For any wet fuel, the measured overall mass flux includes both the water vapor and the pyrolysis gas. Because of the low evaporation point, the mass flux of water vapor most likely contributes to the initial stage as well as the peak in the total mass flux.

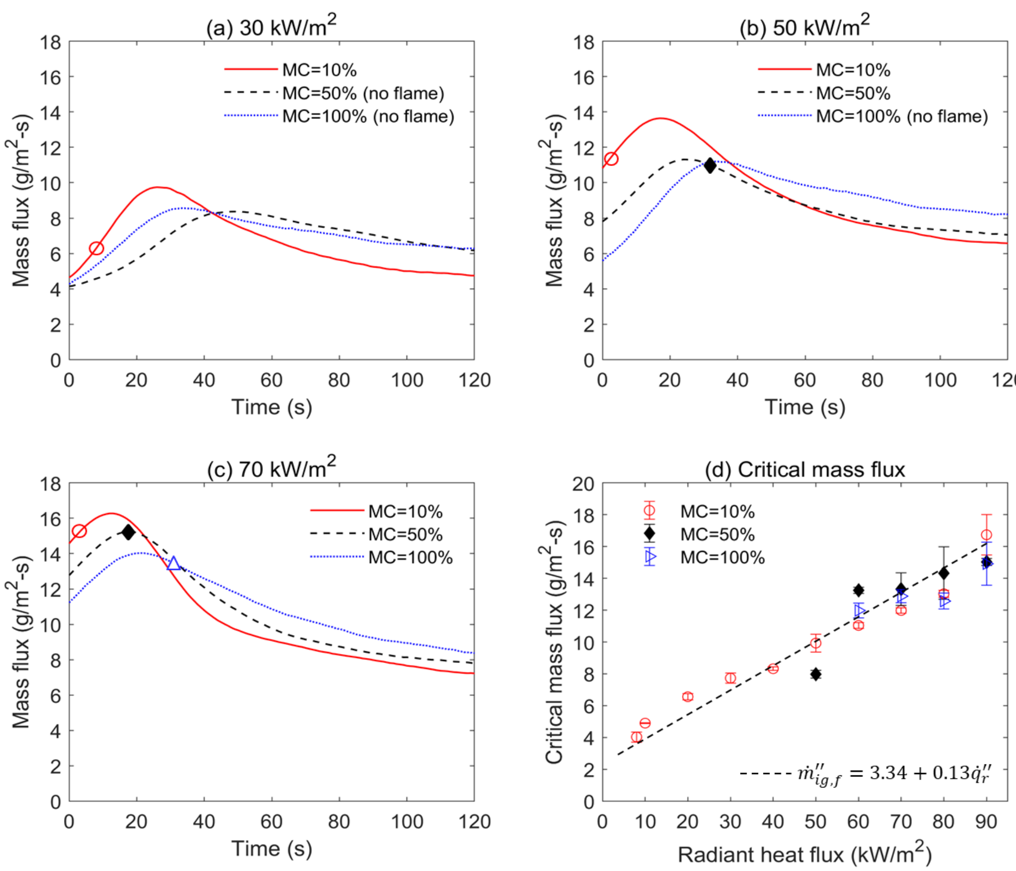

Figure 3. Time evolution of mass flux under the radiant heat flux of (a) 30 kW/m^2, (b) 50 kW/m^2, and (c) 70 kW/m^2, where the symbol indicates the moment of the piloted flaming ignition of peat, and (d) critical mass flux for piloted flaming ignition under all radiant heat fluxes and peat MCs.

The intensity of water vapor flux can alter the flammability limit at the location of the pilot spark. When the heat flux is relatively small, for example in Fig. 3(a-b), a large flux of water vapor will prevent the flaming ignition, while the pyrolysis gas is not large enough. At the same time, the continuous heating initiates a robust smoldering fire that dominates the following burning process. However, gas products from smoldering emission (mostly H_2O, CO_2, and CO (Hadden *et al.* 2013)) is not large and flammable enough to pilot a flame. Therefore, throughout the heating process, the mixture near the spark never reaches the lower flammability limit unless $\dot{q}''_{min,f}$ is reached. This is the fundamental reason why the minimum heat flux for flaming ignition as well as the area of

Region II increases with the fuel MC in Fig. 2(a).

Figure 3(d) summarizes the average critical mass flux of repeating tests under various MC and radiant heat flux. Interestingly, the critical mass flux is found to increase almost linearly with the radiant heat flux up to 90 kW/m^2. Then, an empirical correlation can be fitted for all data points of different MCs as

$$\dot{m}''_{ig,f} = 3.4 + 0.13\dot{q}''_r \quad (1)$$

where $\dot{m}''_{ig,f}$ has a unit of g/m^2-s, and $\dot{q}''_r$ has a unit of kW/m^2. The R^2 coefficient is found to be 0.97, indicating an excellent linearity. So far, the reason for such a trend has not been well explained yet. As the peat MC increases from 10% to 100% in Fig. 3(d), the minimum mass flux for flaming ignition ($\dot{m}''_{min,f}$) is also increased from 4.3 g/m^2-s to 10.4 g/m^2-s. More importantly, under the same radiant heat flux, the critical mass flux is found to be insensitive to the peat MC, which has not been observed before. All these abnormal phenomena suggested that care should be taken in using a fixed critical mass flux to describe the flaming ignition of wet wildland fuels.

4. Conclusion

In this experimental work, we found that peat soils can support a flaming wildfire, like leaves, twigs and barks, even when the peat moisture content (MC) is as high as 100%. Piloting a flame on peat is found to be more difficult than starting a smoldering peat fire, requiring a higher minimum heat flux.

The moisture significantly lowers the flammability of peat soil. As the MC increases from 10% (air-dried) to 100% (wet), the minimum heat flux of flaming ignition increases from 7.5 kW/m^2 to 53 kW/m^2, and the minimum flaming ignition energy increases from 0.3 MJ/m^2 and to 2.0 MJ/m^2. The critical mass flux of flaming ignition is found to be insensitive to peat MC, but increase linearly with the heat flux, as $\dot{m}''_{ig,f} = 3.4 + 0.13\dot{q}''_r$. These phenomena suggest that the defining a constant mass flux is inappropriate for wet wildland fuels.

In our future work, experiments will be conducted to quantify the ignition temperature and rate of flame spread over peat soil. Also, numerical simulations will be performed to understanding the minimum heat flux, critical mass flux, and the interaction between flaming and smoldering peat fire.

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