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Experimental study of the formation and collapse of an overhang in the lateral spread of smouldering peat fires

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ABSTRACT

Smouldering combustion is the driving phenomenon of wildfires in peatlands, and is responsible for large amounts of carbon emissions and haze episodes world wide. Compared to flaming fires, smouldering is slow, low-temperature, flameless, and most persistent, yet it is poorly understood. Peat, as a typical organic soil, is a porous and charring natural fuel, thus prone to smouldering. The spread of smouldering peat fire is a multidimensional phenomenon, including two main components: in-depth vertical and surface lateral spread. In this study, we investigate the lateral spread of peat fire under various moisture and wind conditions. Visual and infrared cameras as well as a thermocouple array are used to measure the temperature profile and the spread rate. For the first time the overhang, where smouldering spreads fastest beneath the free surface, is observed in the laboratory, which helps understand the interaction between oxygen supply and heat losses. The periodic formation and collapse of overhangs is observed. The overhang thickness is found to increase with moisture and wind speed, while the spread rate decreases with moisture and increases with wind speed. A simple theoretical analysis is proposed and shows that the formation of overhang is caused by the spread rate difference between the top and lower peat layers as well as the competition between oxygen supply and heat losses.

1. Introduction

Smouldering wildfires in peatlands are the largest combustion phenomenon on Earth, and contribute considerably to annual greenhouse gas emissions [1]. Peatlands cover 2–3% of the Earth's land surface, and are most abundant in boreal and tropical regions. They are important ecosystems for a wide range of wildlife habitats supporting biological diversity, hydrological integrity and storing 25% of the world's soil carbon [2]. Annually, peat fires release large amounts of ancient carbon roughly equivalent to 15% of the man-made emissions [3,4], and result in the widespread destruction of ecosystems and regional haze events, *e.g.* recent megafires in Southeast Asia, North America, and Northeast Europe [1,3]. Moreover, climate change might dry peatlands and increase the extend and depth of smouldering fire, creating a positive feedback to the climate system [5].

Peat is an important organic soil. It is a porous and charring natural fuel, thus prone to smouldering [1,6]. Smouldering combustion is the slow, low-temperature, flameless burning of porous fuels, and the most persistent type of combustion phenomena [6–8]. Smouldering involves heterogeneous reactions, and is sustained by the heat released when oxygen directly attacks the fuel surface. It is especially common in solid fuels like polymers, coal and organic soils with tendency to charring [6], differing from high-temperature homogenous flaming combustion. Once ignited, natural smouldering fires can burn for very long periods of time (*e.g.* months and years) despite extensive rains, weather changes, or fire-fighting attempts [1].

Two mechanisms control the spread of smouldering combustion: oxygen supply and heat losses [6,8]. Peat fires can be initiated by flaming fires, lightning strikes or embers. The probability of ignition depends on the moisture content (MC[1]), inert content (IC[1]), and other chemico-physical properties [9,10]. Afterwards, smouldering spreads laterally along the free surface and vertically

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[1] Moisture content (MC) is defined here in dry basis as the mass of water divided by the mass of a dried soil sample, expressed as %. Inorganic content (IC) is defined here in dry basis as the mass of soil inorganic matter (minerals) divided by the mass of a dried soil sample, expressed as %.

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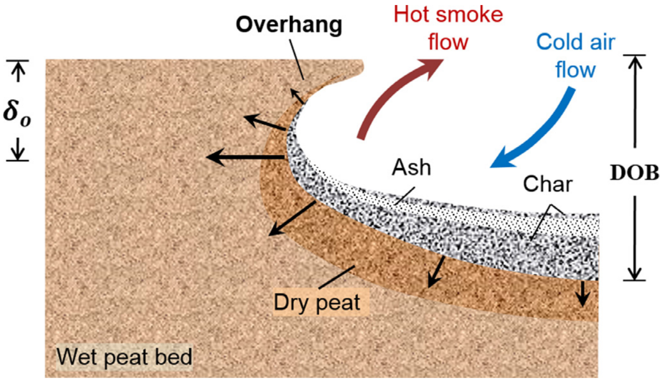

Fig. 1. Schematic diagram of smouldering spread laterally along the surface and vertically in-depth with an overhang and depth of burn (DOB).

in-depth, both dominated by forward smouldering [1,9], as shown in Fig. 1.

Compared to flaming wildfires, the fundamental chemistry and dynamics of smouldering wildfires are not as well understood, with only a limited number of studies found in the literature. Palmer [11] conducted a series of pioneering experiments on the smouldering combustion of dust and fibrous materials. Ohlemiller [12] studied the two-dimensional (2D) profiles for smouldering spread of dry wood fibres. Various thermal-analysis at mg-scale [13,14] has investigated the smouldering chemistry and found the existence of a multi-front (drying, pyrolysis and oxidation fronts) structure [9]. Frandsen [15] studied the ignition thresholds for various bench-scale soil samples, and found a correlation between critical MC and IC, recently verified computationally in [10]. Hadden et al. performed a bench-scale peat experiment, and revealed the competing roles of the pyrolysis and oxidation reactions in the formation and consumption of char [16]. In actual field peat fires, smouldering has been found to consume peat up to depths in excess of several meters [3,4,17]. The depth of burn (DOB) and critical MC for extinction have been investigated experimentally [18–20] and numerically [21]. The fire has been found to spread faster at a depth than at the free surface ("overhang" phenomenon, see Fig. 1) [22–24], which has not been explained or studied until now. The formation and collapse of the overhang dictates the ultimate lateral spread of smouldering fire, its horizontal footprint and the damage to the soil ecosystem.

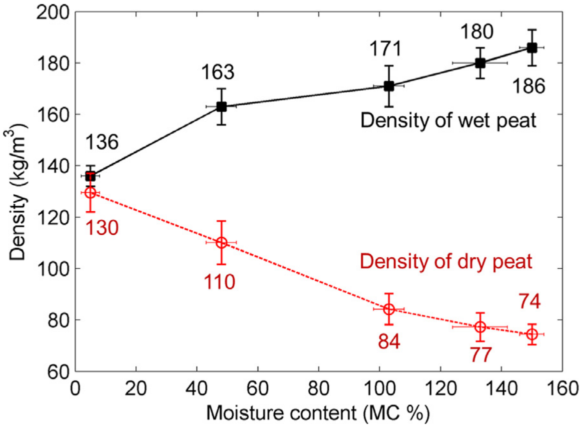

Fig. 3. Density of wet peat (i.e. mass of peat and water/total volume) and density of dry peat (i.e. mass of peat/total volume) vs. moisture content (MC) with experimental uncertainty.

In this work, lateral fire spread over bench-scale moss peat samples is investigated in the laboratory under different moisture and wind conditions. This experimental study focuses on the lateral spread and the periodic formation and collapse of the overhang. The influence of MC and environmental wind is quantified, and analyzed through a simple heat transfer model.

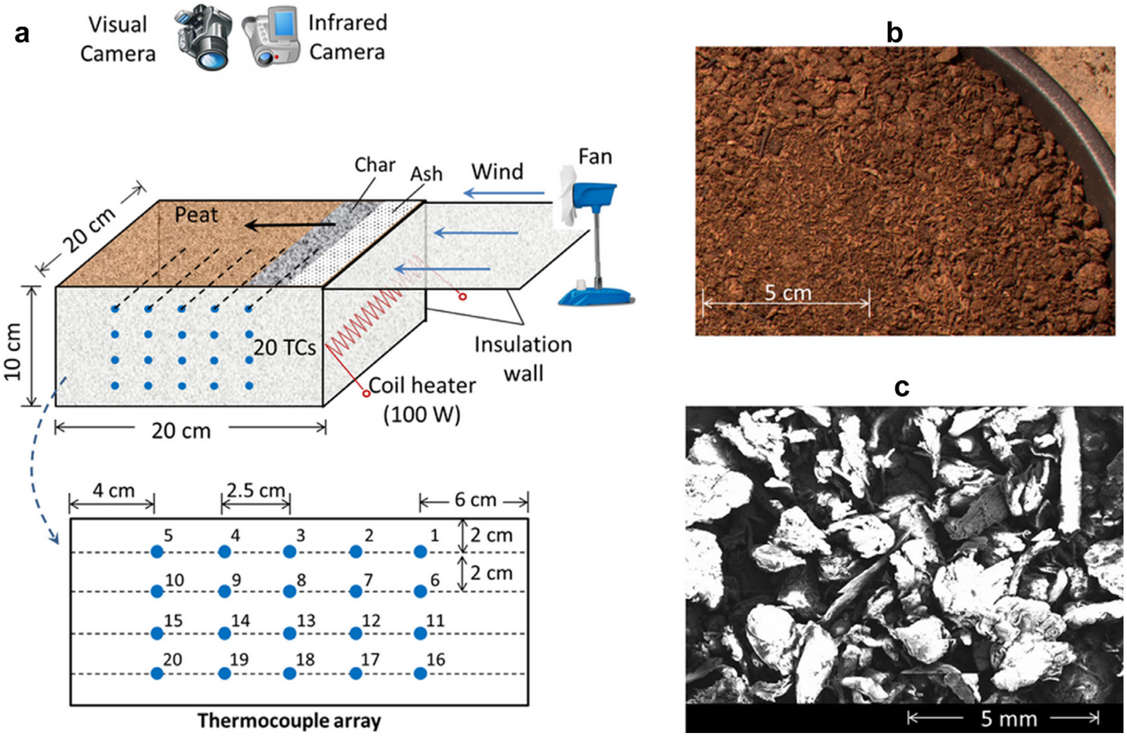

Fig. 2. (a) Diagram of the experimental setup and the arrangement of thermocouples array; (b) visual image of peat sample; and (c) scanning electron microscopy imaging of peat particles.