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Arctic fires and smouldering combustion: influence of soil and air temperature on fire spread

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Abstract

Recent wildfires in Arctic regions have burned unprecedented swaths of land, demonstrating a detrimental change in the arctic fire regime and release large amounts of ancient carbon that have been stored for millennia in the organic soils into the atmosphere. These events highlight the vulnerability of these biomes to climate change and the importance of protecting them. Arctic fires are poorly understood and difficult to be detected due to their remote location. Here, we present a novel rig capable of studying smouldering arctic fires at the lab scale by reducing environmental and soil temperatures. The rig consists of a chamber with low air temperatures, a reactor with a temperature-controlled base to imitate the influence of permafrost, and the fuel sample of organic soil with preconditioned temperatures. The smouldering of organic soil was investigated across a range of realistic temperatures in the Arctic: -7 °C, 2 °C, and 21 °C. The experimental results show that smouldering can be sustained in soil temperatures below the freezing point of water. While insignificantly affect spread rate, the range of temperature in this study was found to have profound effect on the depth of burn, increasing by up to 66% as base temperature decreased from 21 to -7 °C. The critical moisture content above which smouldering is not self-sustain was found to be between 110% and 120% which is lower than the value in the literature because the lower temperature of the reactor base in this study resulted in higher heat losses than the reactor in the literature. As the average soil temperature increases with climate change, the critical moisture content will increase and may lead to more frequent fires in the Arctic. This study is the first experimental work on smouldering Arctic wildfires with findings that can improve our understanding on the effect of cold temperatures, and presents a novel methodology to investigate Arctic fires at laboratory scale.

1. Introduction

In pristine condition, the organic soil in peatland is protected from fire, due to the cold and high moisture conditions (Turetsky *et al*. 2015). With global warming and land-use changes, the condition of peatland is disturbed and can lead to the drying of the organic soil. Once dry, the soil can be ignited and burn for weeks to months (Page *et al*. 2002) because the fire of the organic soil is governed by smouldering combustion, which is the slow, low temperature, flameless burning of charring porous fuel, and the most persistent type of combustion phenomena (Rein 2016). The difficulty in peat fire mitigation has been reported to requires abundant resources of million to billion L of waters that was often difficult to fulfil, leading to the persistent emission of carbon (Ramadhan *et al*. 2017).

In the Arctic, there are reports of fires that were ignited during the summer, survived the winter season by burning underground, and returned to the surface once the snow has melted (Rein and Huang 2021). Such fires that resurface after winter season have been referred to as overwintering fires. In the summer, both flaming and smouldering are part of the wildfire. The flames of the wildfires will be extinguished by rainfall, cold weather or firefighting. However, smouldering hotspots can survive below ground and not be quenched by water or winter because of the insulation effect of the topsoil and snow cover. In the Spring, the overwintering fires grow helped by the dry conditions and warmer temperatures (Scholten *et al*. 2021).

Smouldering dynamics have, primarily, been studied to understand wildfires in tropical and temperate peatlands. Lin *et al*. (2021) investigated the critical MC to ignition in regard to temperatures in the Arctic. However, no laboratory experiments have explored the dynamics of smouldering wildfires in the Arctic, such as spread rate and burning depth. Here we introduce a novel experimental set-up to address this gap by conducting experiments varying both temperature and MC to understand their effects on the dynamics of smouldering wildfires in the Arctic.

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2. Method

The effect of temperature on smouldering dynamics was explored by using a novel rig developed by Christensen (2020). The rig was designed to control three parameters: the ambient air (or chamber) temperature (T_c), the soil temperature (T_0), and the temperature of the bottom boundary of the reactor (T_b) in which the peat was burned. To control the air temperature, a large chamber with an internal dimension of 120 × 80 × 80 cm was constructed using vermiculite and lined with a fibreboard insulating material (Figure 1). A 40 × 40 cm extraction hood was mounted through the top of the chamber with a variable speed mechanical fan installed to control the extraction rate of the smoke from the smouldering samples. A fine metal mesh (0.5 mm) skirt extends down from the hood, as illustrated in Figure 1, to reduce any significant air currents from developing which would affect the smouldering dynamics. The experiments were conducted inside the mesh skirt. A compressed airline was passed through a vortex tube which directed cold air with adjustable temperature (T_i) through an inlet at the bottom of the chamber. A thermocouple was placed within the mesh cage at the same height as the top edge of the reactor to measure T_c. T_c was varied from ~20°C down to ~10°C by adjusting T_i down -7 ± 2°C.

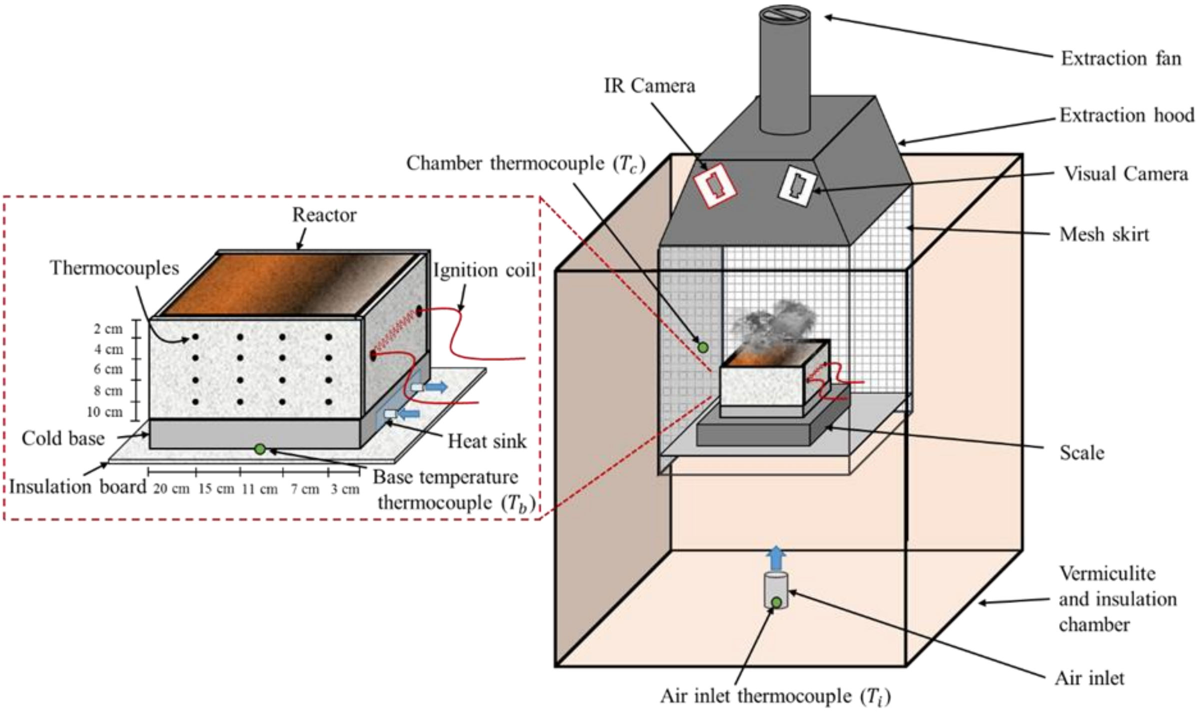

Figure 1- Illustration of the Experimental Low-temperature Smouldering Apparatus (ELSA). Left figure shows key features of the reactor which is filled peat soil. The internal dimension of the reactor measures 20 × 20 × 10 cm. On the right, key features of the rig are highlighted. The dimensions of the chamber are 120 × 80 × 80 cm.

The reactor has internal dimensions of 20 × 20 × 10 cm (Figure 1). The walls were constructed from an insulating fibreboard (k= 0.7 W·m^{-1}·K^{-1}, ρ= 310 kg·m^{-3}, c_p= 1090 J·kg^{-1}·K^{-1}). The bottom of the reactor was a thin aluminium plate so to allow for the effective conduction of heat. To control the temperature of the bottom boundary of the reactor, an aluminium base (22 × 22 × 2.5 cm) was placed. The base was designed with an inset heat sink through which a temperature-controlled water – glycol mixture was pumped. The temperature of the mixture was varied by a benchtop recirculating chiller (Polyscience LS-series compact chiller). A thermocouple was mounted to the base to measure the temperature at the interface between the base and the aluminium plate (T_b) as indicated in Figure 1.

A commercial peat (Shamrock Irish Moss Peat, Bord na Móna Horticulture) was used due to its accessibility, material consistency and frequent use in literature (Huang *et al*. 2016), allowing for improved isolation of peat soil variability and comparison to literature results. This soil has a C/H/N/S proportion of 54.1/5.1/1.3/0.5% by mass respectively, and an inherent inorganic content of 2.5 ± 0.6% (Hu *et al*. 2019). Sample preparation was conducted according to Christensen *et al*. (2019). The peat was dried at 80 °C until no mass loss was observed in measurements of 6 h apart. Water was added to the dried peat to achieve a desired MC, and the peat was put in a sealed container to homogenise for 24 h. MC is considered as the mass of the water divided by the mass of the dry matter. The MC was verified by taking a 100 g subsample of the peat and drying it in an oven at 90°C for 6 hours (this was found to sufficiently dry sub samples of any moisture content). Where the initial temperature of sample (T_0) was required to be altered, the reactor and sample was placed in a fridge or freezer for at least 12 hours before starting the experiment.

The samples were ignited using an 18 cm, helically wound nichrome coil, 1 cm in diameter through which 100 W of power is supplied, which has been shown to be a strong ignition source (Huang *et al*. 2016). A scale is used to measure the mass of the sample every minute. 16 thermocouples were inserted along the centreline of the reactor at 3, 7, 11 and 15 cm from the ignition side and at 2, 4, 6 and 8 cm depths, as illustrated in Figure 1. This is a similar thermocouple array to that used in (Huang *et al*. 2016). Both infrared (FLIR Duo R) and visual cameras (GoPro) were mounted above the reactor to capture the behaviour and spread of the smouldering.

To explore the effect of soil temperature on smouldering dynamics, three temperature conditions were targeted: below zero, near zero, and room temperature. This covered a range of temperatures from frozen conditions to summer conditions in Arctic regions, where the active layer is warm. Temperature condition (T_{cond}) was defined as a set of three temperatures set up: base temperature (T_b), chamber temperature (T_c), peat soil initial temperature (T_0). Table 1 shows T_{cond} setup in this work. Experiments with MC of 50% and 100% were conducted at all three condition temperatures, with one to three experiments conducted per soil condition.

Table 1- Summary of average temperatures for the three temperature conditions (T_{cond}) in this study: below freezing point (-7°C), at freezing point (2°C), and at room temperature (21°C). The uncertainties reported here are the standard deviation of measured temperature across all experiments at the given condition temperature.

Condition temperature (T_{cond})	Below freezing point	Freezing point	Room temperature
	-7°C	2°C	21°C
Base temperature (T_b)	-6.8 ± 0.6°C	2.1 ± 1.3°C	20.7 ± 0.3°C
Chamber temperature (T_c)	10.1 ± 1.4°C	9.5 ± 2.2°C	21.8 ± 1.5°C
Initial soil temperature (T_0)	-11.3 ± 1.5°C	3.8 ± 0.4°C	18.0 ± 0.1 °C

3. Results

Figure 2a presents the spread rates measured using the IR images and shows a slightly decreasing relationship with decreasing condition temperature. This is likely due to the increased sensible energy required to heat the fuel at low temperatures and to melt the frozen MC. Figure 2b shows that MC has a more substantial effect on spread rate than condition temperature, with horizontal spread rates decrease with MC. For samples with 50% MC, the spread rate decreased 14% between 21°C and -7°C conditions. This difference increased to 18% in samples of 100% MC. As such, condition temperature was found to have a minor but insignificant influence on horizontal spread rates as confirmed by a nonsignificant linear regression ($p>0.05$), but was significantly influenced by MC as confirmed by a significant 2-sample t-test ($p<0.05$).

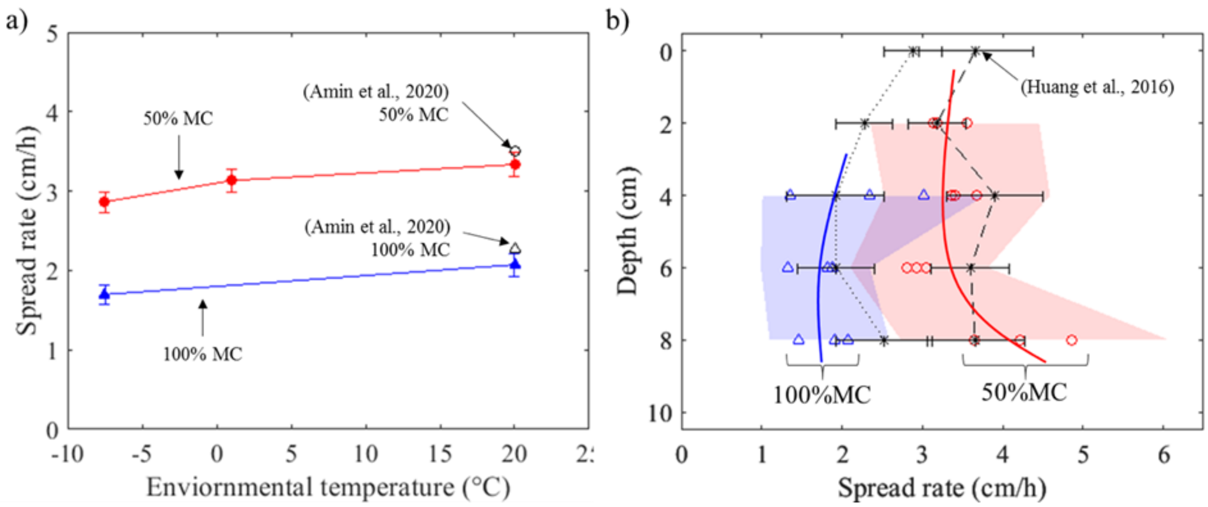

Figure 2- a) illustrating the effect of condition temperature on spread rate, measured using infrared (IR) imaging, in sample of 50% and 100% moisture content (MC). Results are also compared against IR spread measurements of a

similar reactor with an insulated base at room temperature presented by Amin et al. (2020). IR data was not available for samples with 100% moisture at 2°C. b) showing the effect of depth on spread rate on both samples with 50% and 100% MC at various temperature conditions and compared to spread rates presented by Huang et al. (2016). Error bars are based on uncertainties in measurement. Triangle and circle symbols represent spread rate from samples of 100% MC and 50% MC. Blue and red lines are approximate trends of horizontal spread rate with depth from samples of 100% MC and 50% MC. Temperature at 2 cm depth in samples of 100% moisture never exceeded 100°C and so could not be measured. Data from Huang et al. (2016) are represented by black lines: dotted line for sample of 100% MC and dashed line for sample of 50% MC.

The depth of burn is found by linearly interpolating between the peak temperatures of adjacent thermocouples and finding the location of the 200°C threshold. The burning depths in this study are presented in Table 2 along with the burning depth found in (Huang *et al*. 2016). Two effects are noticeable in the depth of burning in regard to both condition temperature and MC. Firstly, decreasing condition temperatures increases the burning depth, with a linear model confirming the significance of this trend ($p<0.05$). At 50% MC the burning depth increased by 66% between 21°C and -7°C, while in samples of 100% MC the increase was 13%. This change in depth of burning is likely due to the additional energy required to melt and heat the soil causing the optimal balance between oxygen supply and heat losses to exist deeper within the soil. Secondly, comparing the depth of burning estimated here to that presented by Huang *et al*. (2016) who conducted experiments at room temperature, using the same source of peat and a similar reactor but with an insulated bottom face, it is evident that the effect of the energy loss through the base results in shallower burning depths. This difference is enhanced with MC.

Table 2- Estimated burning depth by using 200°C as an indicator of char formation and linearly interpolating between peak temperatures measured by thermocouples. Depth of burning measured by Huang et al. (2016), is also presented for comparison.

	Depth of burning (cm)			
	-7 °C	2°C	21°C	Huang *et al*. (2016)
50% MC	2.5 ± 0.2	1.8 ± 0.3	1.5 ± 0.3	3 ± 1
100% MC	5.4 ± 0.6	4.6 ± 0.2	4.8 ± 0.5	9 ± 1

Additional experiments were performed to explore how the condition temperature influenced the critical MC of ignition in this work. It was found that smouldering could be successfully sustained in MC of 110% however would fail at 120%. This was true across all condition temperatures, and is lower than the value of 160% MC found by Hu *et al*. (2019) who used the horizontal reactor with an insulated base.

4. Conclusions

In this work, we have studied the smouldering dynamics of peat fire in the Arctic using a novel experimental rig able to separately control the temperature of the ambient air (10 to 21°C) and bottom boundary of the smouldering sample (-7 to 21°C). The initial temperature of the peat sample was varied from -11 to 18°C. We found that the range of ambient air, bottom boundary, and initial soil temperatures in this study have insignificant effect on spread but reduce burning depth up to 66% as the bottom boundary temperature decreased from 21 to -7°C. The critical moisture content to ignition in this study was found to be between 110 and 120% which is lower than the value in the literature (160%). This study is the first experimental work on smouldering Arctic wildfires with findings that can improve our understanding on the effect of cold temperatures on the smouldering dynamics of peat fires, and presents a novel methodology to investigate Arctic fires at laboratory scale.

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