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Experimental and numerical characterisation of the smouldering combustion of peat

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Abstract

Smouldering peat fires are a major source of greenhouse gas emissions. As the climate warms, the frequency and severity of peat fires will continue to increase, with a single large fire event contributing as much CO2 to the atmosphere per day as an industrialized country. Estimates of the amount of CO2 released by peat fires contain large uncertainties, driven by overwhelming uncertainty in the mass of peat consumed in these fires. The present work addresses uncertainties in peat fire dynamics and smouldering through an iterative experimental and modelling process. Presented here is a first step towards predicting greenhouse gas emissions. Experiments focus on capturing the mass burnt in a smouldering peat fire and describing the smouldering—pyrolysis and oxidation—process. Mass loss rate is found to vary as a sample is tested in lateral spread vs downward spread configurations. A one-dimensional model of peat smouldering is implemented, with initial qualitative results presented here, showing the drying of wet peat and the pyrolysis front. These results represent the current work in progress on this effort. Further work will compare experimental and simulation results for additional parameters of interest, and simulations will be used to inform which soil parameters to explore experimentally.

1. Introduction

The smouldering of organic soils is a key wildfire hazard across the globe with peat fires burning primarily in boreal regions in the northern hemisphere (e.g., Siberia, Canada, Alaska) and tropical regions (e.g., Southeast Asia). Boreal peat (at northern latitudes from Europe to the Arctic) stores over 400 Gt of carbon (Beaulne *et al.* 2021), which can be released to the atmosphere if the peat is ignited. As the climate warms, the frequency and severity of peat fires will continue to increase. The timescales of this release (days) compared to the timescales for the formation of peat (millennia) mean it has a significant potential to drive climate change. Estimates of the amount of greenhouse gases (GHGs) released by peat fires contain large uncertainties, driven by overwhelming uncertainty in the mass of peat consumed in these fires (Rodríguez Vásquez *et al.* 2021).

Sustained smouldering is dominated by two processes: pyrolysis and oxidation. The pyrolysis process is controlled by heat transfer through the soil and is therefore influenced by its moisture content (MC), the composition of the peat (specifically the quantity of inert material/inorganic content (IC)), and the heat losses to the environment. The oxidation process is governed by the diffusion of oxygen through pyrolyzed soil regions. These two processes produce different carbon-based emissions. Therefore, to elucidate the contribution of peat fires to GHG emissions, we must (1) be able to predict the mass of peat consumed, and (2) have detailed knowledge of the processes and dynamics of the smouldering combustion.

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Recent efforts have been made to understand the process of smouldering combustion to better understand the hazards posed by this wildfire process. Previous work on peat fires has used commercial peat to analyze gas emissions (Hu *et al.* 2020) and the chemical reactions involved in the ignition and spread of smoulder (Hadden *et al.* 2013) in the laboratory. The influences of MC (Amin *et al.* 2020; Huang and Rein 2017; Lin *et al.* 2020), wind and slope (Christensen *et al.* 2020), density (Krieger Filho *et al.* 2020), and depth of peat (Lin *et al.* 2021) on spread rate have been studied. A one-dimensional (1-D) model has been developed (Huang and Rein 2015; Huang and Rein 2019; Huang *et al.* 2015) and used to understand the relationship between depth of smouldering and MC. This model has been used to explore the effects of MC, IC, and peat properties on critical ignition conditions (Huang and Rein 2015; Huang *et al.* 2015). Limited work has been done in the laboratory using natural peat as the medium under investigation, though work has been done with peat from near Edinburgh, Scotland (Rein *et al.* 2009).

Here, we present initial steps towards providing more accurate estimates of GHG emissions from peat fires. The experiments explore key 3-D effects, such as specimen size and orientation. Initial results are presented from quasi-1D simulations, based on the model created by Huang and Rein. As part of an iterative experimental and modelling process, the experiments will be used to validate the model and expand it to 2-D and 3-D, while the model will be used for physics elucidation and to explore the experimental parameter space to inform which experiments to perform.

2. Experimental set up

To explore the competing effects of heat transfer and oxygen diffusion on peat smouldering, a series of one-dimensional opposed flow smouldering experiments were undertaken in the laboratory. Two cuboidal peat sample sizes of cross-sectional area 625 and 2,500 mm^2 (25- and 50-mm side lengths) and total length of 300 mm were studied in the vertical downward and lateral orientations, as shown in Figure 1 below. An open boundary condition was used in all cases to allow the free flow of oxidiser into the reaction zone by constructing sample holders from woven stainless-steel mesh with hole size of 0.96 mm (~46% open area). An electrical nichrome coil was used for ignition, supplying a power of 50 W for 5 min. Commercially harvested sphagnum moss peat was used as the feedstock. Prior to testing, the peat was dried in batches for at least 48 hours at 80°C. The bulk density of peat was fixed at 350-400 kg/m^3. The approximate mass of peat for the three sample sizes tested is 50 and 200 g.

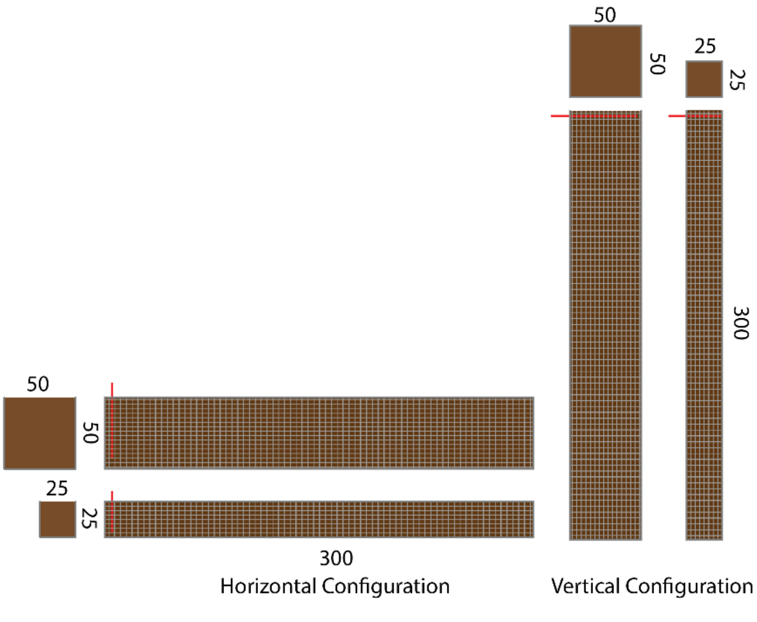

Figure 1- Schematic of experimental setup for lateral (horizontal configuration) and downward (vertical configuration) spread experiments for both sample sizes. All dimensions are in mm. The red line represents the ignition location.

Real time mass measurements were made during the experiment and the mass loss rate (MLR) was calculated and smoothed using a 51-point Savitsky-Golay filter with a second order polynomial. Temperature measurements were made at the centreline of the sample using 0.25 mm diameter K-type thermocouples. These are used to track the position of the pyrolysis and smouldering fronts as a function of time. The propagation rate was recorded using time-lapse imagery which was processed computationally.

3. Experimental results and analysis

The smouldering process is characterised using the mass and MLR data, which can capture the effects of both pyrolysis and oxidation. Propagation rate data and temperature data will be included subsequently to elucidate the smouldering front characteristics.

3.1. Experimental mass and mass loss rate data

The mass of the sample as a function of time is presented in Figure 2a. As the sample dimension increases, so does the duration of the smouldering, as the mass of peat has also increased. Orientation of the specimen impacts the duration of the smouldering process for a given propagation direction. The smouldering propagation direction also appears to change the smouldering dynamics. Vertical downwards smouldering is characterised by a period of relatedly high MLR per unit cross section (Figure 2b) after ignition (25-100 minutes) and then a period of lower MLR (100-150 minutes), which is anticipated to represent the transition from primarily pyrolysis to long-time oxidation. The longitudinal smouldering, on the other hand, is characterised by a quasi-steady MLR, suggesting that steady state propagation has been achieved.

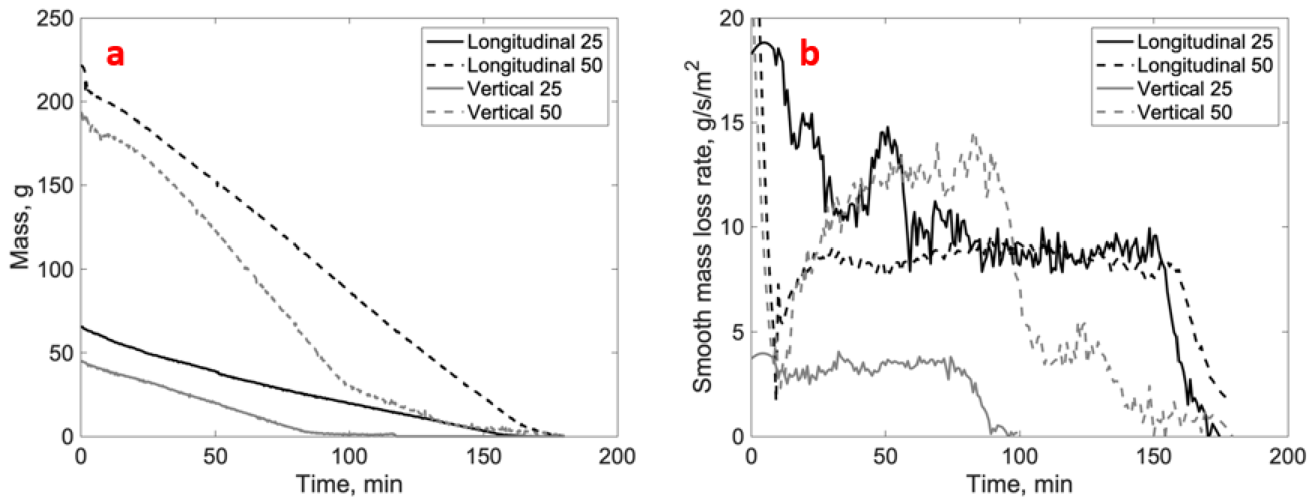

Figure 2- Sample mass (left) and mass loss rates (right) as a function of time for cuboidal samples with 25- and 50-mm sides.

4. Computational modelling

The quasi-1-D model used here is based on the work of Huang *et al.* (2015) and Huang and Rein (2015), in which a 1-D model of peat smouldering was developed in GPyro. A version of their model has been implemented in Sierra Thermal/Fluids: Aria, a generalized Galerkin finite element method code (Notz *et al.* 2016). The governing equations are solved both in the solid phase and in the gas phase for continuity, continuity of species, and enthalpy. We use Darcy's law for flow through a porous media to calculate the gas phase velocity. The ignition source is modelled as a constant 800°C temperature on the top end of the peat column. Boundary conditions on the cool end assume convective and radiative heating to an ambient environment. Material properties of the solid phase species were taken from Huang and Rein (2015). A 5-step reaction mechanism, developed in Huang and Rein (2014), is used to describe the peat smouldering process, with kinetic parameters for each reaction taken from Huang and Rein (2015). To account for the experimentally observed collapse when a peat column burns, the model solves the quasi-static conservation of momentum.

The model is run for 30,000 s on a lateral column of peat 400 mm long and 100 mm x 100 mm square. A 1-D problem is approximated in Aria by creating a mesh with elements in only one direction (i.e., a stack of blocks).

The element edge length along the column of the peat is 2 mm. Time is advanced implicitly using adaptive time stepping based on problem difficulty and error control, with a minimum of 1^{-9} s and a maximum of 1 s.

Initial modelling results, presented in Figure 3, show notional agreement with lateral spread experiments. A snapshot of one of the experiments shows black char and ash behind the smouldering front. Modelling results show the drying front (in red) and leading edge of the pyrolysis front (in blue). Experiments and simulations are compared at an arbitrary time. While further work is required to verify and validate the model, initial results are promising.

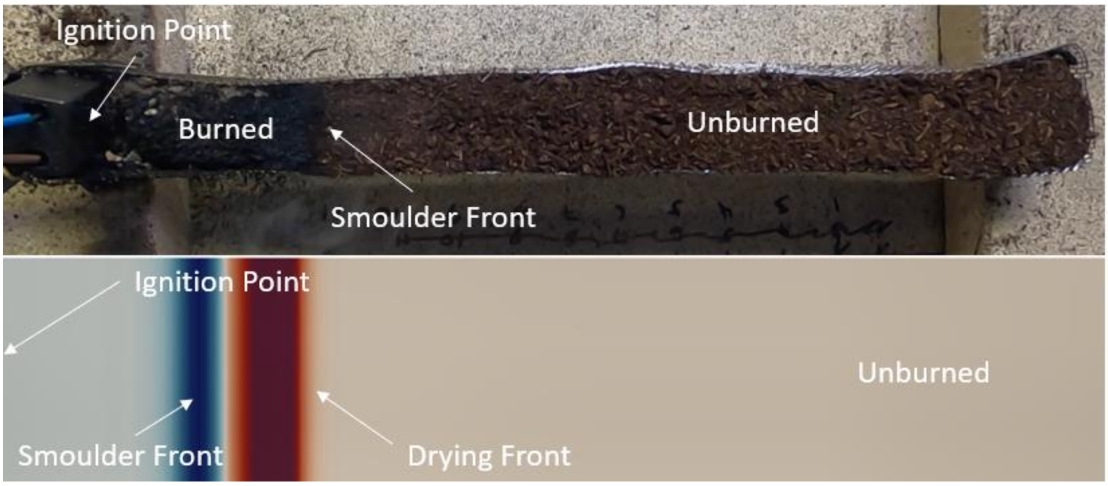

Figure 3- Top: Lateral peat spread experiment, smouldering direction left to right; Bottom: simulated peat smouldering, where red represents the drying front and blue represents the pyrolyzing front

5. Conclusions and application

The present work shows the first steps of an iterative modelling and experimental process aimed at ultimately predicting GHG emissions from smouldering peat fires. The experimental MLR results show areas of pyrolysis versus oxidation, correlating with expected carbon emissions. More detailed modelling results will be presented after verification with literature and validations with the experiments has been completed. A limitation of this model is the 1-D assumption as peat smouldering, particularly in field environments, is spatially heterogeneous. While the current computational model is 1-D, the code base is fully 3-D, allowing for easy expansion to higher dimensions in future work. Further work will include the iterative experimental/computational design process described.

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