

Influence of Soil Conditions on the Multidimensional Spread of Smouldering Combustion in Shallow Layers

Eirik G Christensen¹, Nieves Fernandez-Anez², Guillermo Rein^{1*}

¹Department of Mechanical Engineering, Imperial College London, London, SW7 2AZ, UK

²Western Norway University of Applied Sciences, Haugesund, 5528, Norway

**Corresponding author, Email g.rein@imperial.ac.uk*

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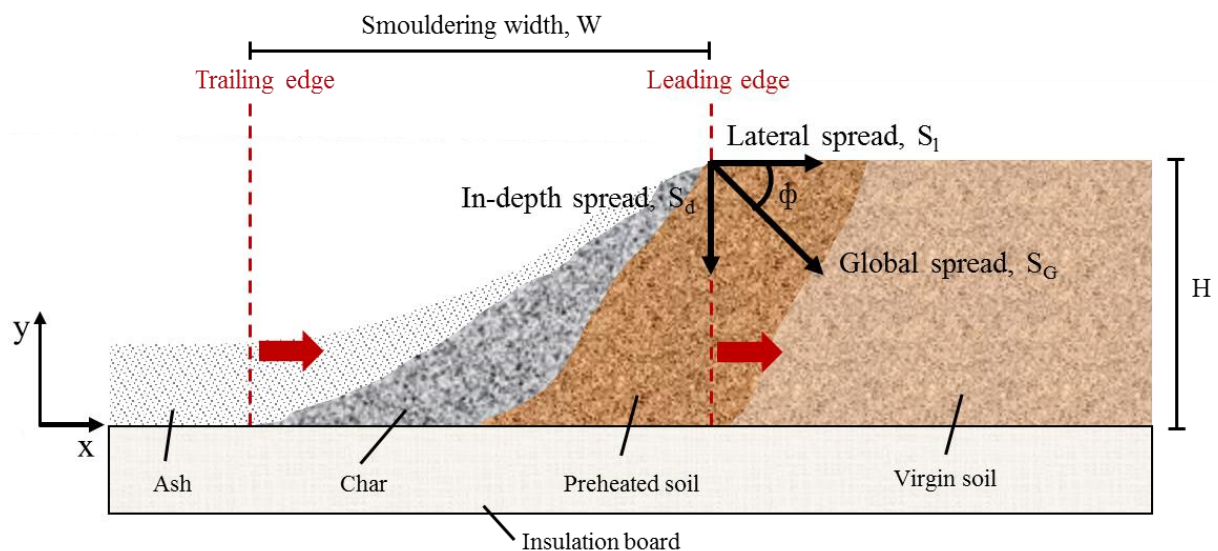
Abstract

Smouldering peatland fires are capable of burning vast amounts of organic soils, resulting in the release of greenhouse gases into the atmosphere, as well as a significant deterioration of air quality causing major regional crises known as haze events. Fundamental understanding of smouldering fire spread is essential for the development of mitigating technologies. In this paper, we have systematically conducted 63 experiments studying the individual and combined influence of two key factors affecting multidimensional smouldering spread in organic soils: moisture content (MC) and inorganic content (IC). Both lateral and in-depth smouldering spread were investigated using a novel shallow reactor. This shallow depth allows a greater number of experiments to be performed in a short period of time compared to deeper samples. Lateral spread was found to decrease linearly with moisture content ($R^2 > 90\%$); while in-depth spread rate increased linearly up to 300% from moisture contents of 0% to 140%. Increased inorganic content linearly decreased the lateral spread rate but had little influence on in-depth spread in drier samples. Interestingly, in wetter samples, in-depth spread was in fact sensitive to inorganic content. A novel approach combining lateral and in-depth spread rates as vector components, revealed that the global spread is independent of moisture content, with an average spread rate of 8.7 and 8.4 cm/h for 2.5 and 40% IC, with changes in direction according to moisture content; going in-depth for wet soils, and laterally for dry soils. Similarly, increasing the IC encouraged downward spread for wet samples. We also report observations of a bifurcation of lateral spread, where spread would locally extinguish where the in-depth spread was greater than the lateral spread. These findings provide previously unknown insight into the relationship between lateral and in-depth spread in smouldering fires, ultimately improving the fundamental understanding of such fires.

1 Introduction

Smouldering is the low temperature, flameless, heterogeneous form of combustion that occurs in porous char-forming media [1]. An example of an abundant fuel which burns in this way is an organic soil, such as peat. Peat is formed over centuries to millennia by the natural accumulation of organic matter in regions where the rate of decomposition is lower than the rate of growth. This is common in regions that are very wet or cold such as Indonesia and Siberia respectively [2]. Peat stores great quantities of carbon around the globe; it is estimated that 1670 Pg [3] and 89 Pg [4] are stored in permafrost and peatlands, respectively. Smouldering wildfires provide a pathway for this sequestered carbon to be released into the atmosphere as greenhouse gases and contribute to climate change [5-7]. An example of this is the 1997 peat fire in Indonesia, which released the equivalent of 13-40% of annual global fossil fuel emissions that year [8]. In addition to the positive feedback mechanism between

smouldering wildfires and climate change [5], their low burning temperatures ($\sim 600^{\circ}\text{C}$) create weakly buoyant smoke plumes, rich in harmful particle matter and gases, that can be pushed into populated regions by wind and causing severely negative health impacts [9-11] and significant economic losses. Combined with the fact that they are both easier to ignite [12], and more difficult to extinguish than flaming fires, requiring far more water to suppress [13] (often even surviving heavy rains and fire-fighting efforts), make smouldering wildfires a global challenge. It is therefore unfortunate that thus far, smouldering fires have received minimal attention in the research community, because the fundamental understanding of smouldering wildfires is essential to develop suppression strategies, early detection systems, and inform policy makers to better manage lands and prevent future fires.



Lateral spread is known to decrease with moisture [19-22], owing to the latent heat of water evaporation requiring energy and time to dry the soil. Additionally, in wet peat, lateral spread rates are faster below the surface than at the top. This results in a phenomena known as overhang, where deeper layers of peat are consumed more rapidly than those closer to the surface, creating a section of peat that overhangs a void. Eventually, the overhang loses its structural integrity and due to its weight, it collapses and accelerates the burning. Smouldering propagation is then characterized by periodic cycles of overhang formation and collapse [21]. The depth of this overhang increases with MC [21] until a critical MC is reached, and

smouldering can no longer be sustained because the energy required to dry the soil is greater than that provided from the char oxidation [14].

In contrast to lateral spread, in-depth spread increases with MC as observed experimentally in [23]. Huang and Rein [23] explained that this is because of the faster oxygen transport due to swelling. IC, on the other hand, slightly decreases in-depth spread, according to both experiments and modelling [24, 25]. Notably, as the fire moves downward, in-depth spread rate decreases with depth due to the accumulation of ash above the oxidation zone reducing the oxygen supply [23, 24, 26].

As highlighted above, all research to date has focused on lateral and in-depth spread individually. In this paper, for the first time, these spread components are combined to understand the dynamics of a global spread rate. The influence of both MC and IC are studied in combination and individually, in a comprehensive study. The experimental set-up makes it feasible to conduct a much larger number of experiments, due to the reduced experimental time required, and gain insights that are not possible with deeper reactors [27]

2 Method

2.1 Experimental Setup

Small scale experiments were conducted using a shallow open-top reactor with an internal dimension of 40 x 40 x 1.6 cm (Figure 2). The reactor was built using insulating ceramic boards ($k=0.7$ W/mK, $\rho=310$ kg/m³, $c_p=1090$ J/kgK). Commercial milled Irish Sphagnum peat (Shamrock Irish Moss Peat, Bord na Mona Horticulture) was used, due to its batch consistent properties in the long term, ease of accessibility, and frequent use in scientific literature [20-23]. The peat contained 54.1/5.1/1.3/0.5% mass fraction of C/H/N/S respectively; its inherent IC was of 2.5 ± 0.6 %, measured through the use of a muffle furnace by heating the sample to 1000 °C and recording the mass every hour until there was no mass lost between subsequent measurements. Before conditioning, peat was dried in an oven at 80 °C [27, 29] until no mass loss was seen in measurements 6 h apart. The dry soil was then sieved at 8.5 mm to remove excessively large material and to improve the homogeneity of the fuel. To condition the peat, controlled quantities of sand and water were added to alter the IC and MC respectively. The sand used was fine, washed, commercial sand (Hanson Play Pit Sand), similar to that used in [29]. Both IC and MC are calculated on a dry basis (Eqs 1 and 2).

$$MC = \frac{m_w}{m_p + m_s} \% \quad (1)$$

$$IC = \frac{m_s + IC_0 m_p}{m_p + m_s} \% \quad (2)$$

Where m_w is the mass of the water (g), m_s is the mass of the added sand (g), IC_0 is the inherent inorganic content of the unconditioned peat (%), and m_p is the mass of the unconditioned peat (g). The range of soil conditions used can be grouped into three series: MCx, ICx and mixed. The MCx series consisted of samples with no additional IC added, and target MC of 0 to 160 % in increments of 20 %, with an addition set at 110%. The ICx series was modified by solely altering the IC, while maintaining a minimum MC (< 5%). Seven IC values were explored between 2.5 (IC_0) and 90 %. Finally, the mixed series, had both IC and MC modified. The IC was fixed at 40 %, and MC between 0 and 80% in increments of 20% as well as an additional set at 70 % were targeted. Each soil condition was studied 3 times, resulting in a total of 63 experiments. A 100 g subsample was taken from each batch of conditioned soil and dried at

90°C for 7 h, to verify the MC [27]. This drying time was found to be sufficient to completely dry all subsamples.

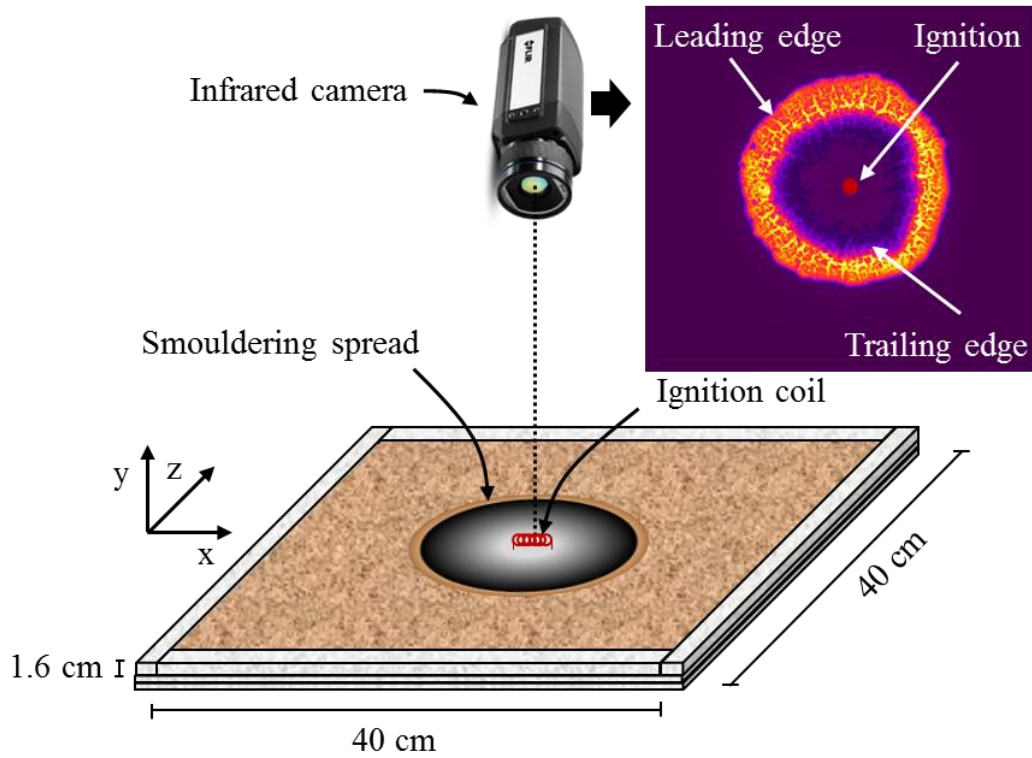


Figure 2 - Illustration of the experimental setup, displaying a central ignition using a wound coil and key features observable in IR imaging.

Samples were prepared by filling the reactor with the conditioned soil and levelling the surface of the sample to the rim of the reactor walls, removing any excess material without compacting or tamping, creating a flat and repeatable sample thickness of 1.6 cm. The mass of the sample was measured using a mass balance (± 0.1 g) so that the bulk and organic density could be calculated. The organic density (ρ_o) is the density of organic material in a sample and was calculated using Eq. 3; where m is the mass of the sample and V is the volume of the sample (2560 cm^3). It was found that the organic densities measured here matched well with measurements of the samples presented by Huang and Rein [23] (Figure 3a). The organic density decreases with MC as shown in Figure 3a, indicating that the peat swells with the addition of water, while it is relatively insensitive to IC up to 75% after which it sharply decreases. This suggests the sand is accommodated in the pore space between the peat particles (Figure 3b) at low ICs.

$$\rho_o = \frac{m(1-IC)}{V(MC+1)} \quad (3)$$

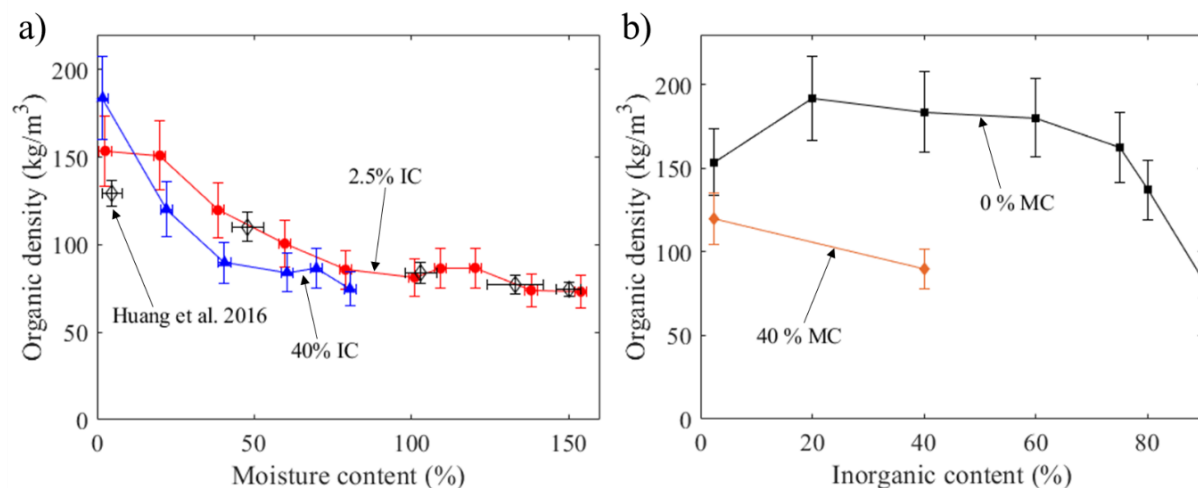


Figure 3 - Measurements and the relationship between organic density and soil properties, a) showing the influence of moisture content b) the effect of inorganic content on the organic density. Error bars are calculated from measurement uncertainties.

The samples were ignited at the centre of the reactor using a helical coil, 1 cm long, with a diameter of 1 cm, and made of a 0.5 mm thick nichrome wire. 20 W were supplied to the sample through the coil for 30 min. This is a greater flux than used in literature, which is typically 100 W for 30 min across an 18 cm helical coil [21, 27, 28, 30]. For this reason, the ignition protocol can be considered a reliable and strong ignition source, sufficient to ignite all samples studied. The experiments, from ignition to burnout, lasted between 2 and 5 h.

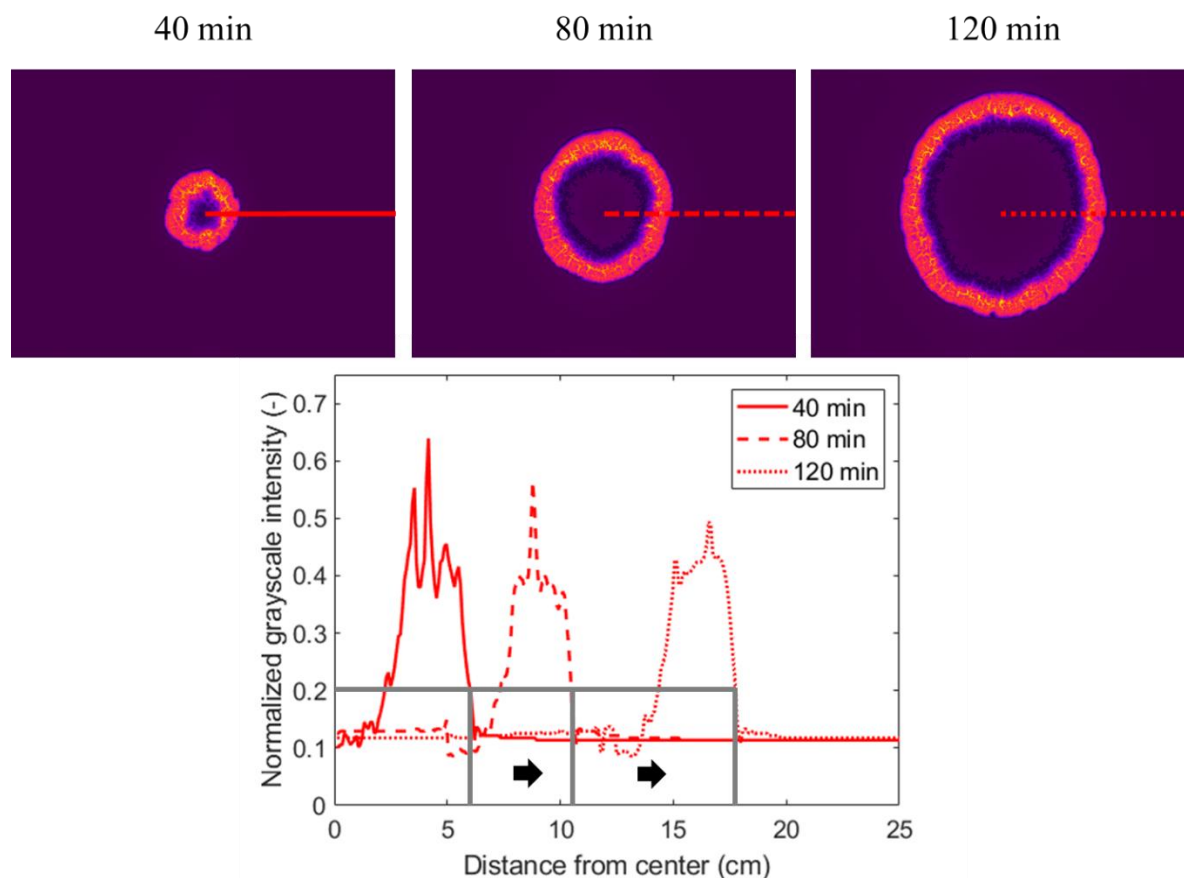


Figure 4 – Illustrating the method of IR image analysis using example images from a sample with 40% MC and 2.5% IC. The plot present the pixel intensity profile from the same transect at 40, 80 and 120 min after ignition (top images) and how using a normalized pixel intensity value of 0.2 was used to track the leading edge (gray line).

Smouldering spread was monitored by taking time lapse images with an IR camera (FLIR A655sc) at a frequency of 1 frame per minute, placed directly above the centre of the reactor; example videos of the acquired time lapses can be seen in S1. From these images the leading and trailing edge could be clearly observed (Figure 2). Measurements of the leading edge provided the lateral spread rate while the trailing edge was used to calculate the in-depth spread rate by dividing the thickness of the soil bed (H_0) by the smouldering residence time (t_R). We define residence time as the time difference between the trailing edge and leading edge reaching any given location. The assumption made in this calculation is that all of the fuel is consumed. However, in all cases where the sample successfully ignited, the residual mass at the end of the experiment was within ~5% of the mass due to the IC.

$$S_d = \frac{H_0}{t_R} \quad (4)$$

It is also important to note that, the bottom boundary influences the in-depth spread, but the trend in behaviour is valuable for insight and understanding the fundamentals of smouldering dynamics. Additionally, the shallow depth of the reactor minimized the influence from the effects of overhang as smouldering is maintained near the surface.

2.2 IR image analysis

For analysing the spread, the images were converted to gray scale and 60 equally spaced transects were drawn radially from the centre of the ignition coil. Each transect returned a pixel intensity profile as shown in Figure 4, which shows the pixel profile of an example transect at different time steps. These pixel values were normalized to the range 0 to 0.15 W/cm²-steradian, and an arbitrarily low threshold value of 0.2 was selected and used to define the location of both the leading and trailing edge. Their movement was tracked every 10 min. The results are insensitive to the specific threshold value due to the steep gradients of the intensity profile. The value 0.2 was selected as it was suitably close to the minimum heat flux measured by the IR camera to capture the smouldering fronts, while also high enough to reduce the influence of noise. The scale of each pixel was defined by using the length of the reactor and dividing by the corresponding number of pixels.

Although this method measures transient behaviour, it was found that the self-sustaining spread is steady, as shown in Figure 5, indicating that average values are a good representation of the results and will therefore be used in the discussion. The results of the lateral spread rate are averaged between 35 min (5 min after the end of ignition) and the time at which the smouldering front reached 17 cm from the coil (3 cm from reactor walls) to avoid any influence of the boundary. In the case of in-depth spread, which considers both the leading and trailing edge, values are averaged from when the trailing edge passed 2 cm from the coil to avoid any sensitivity to the ignition or IR signal from the hot coil.

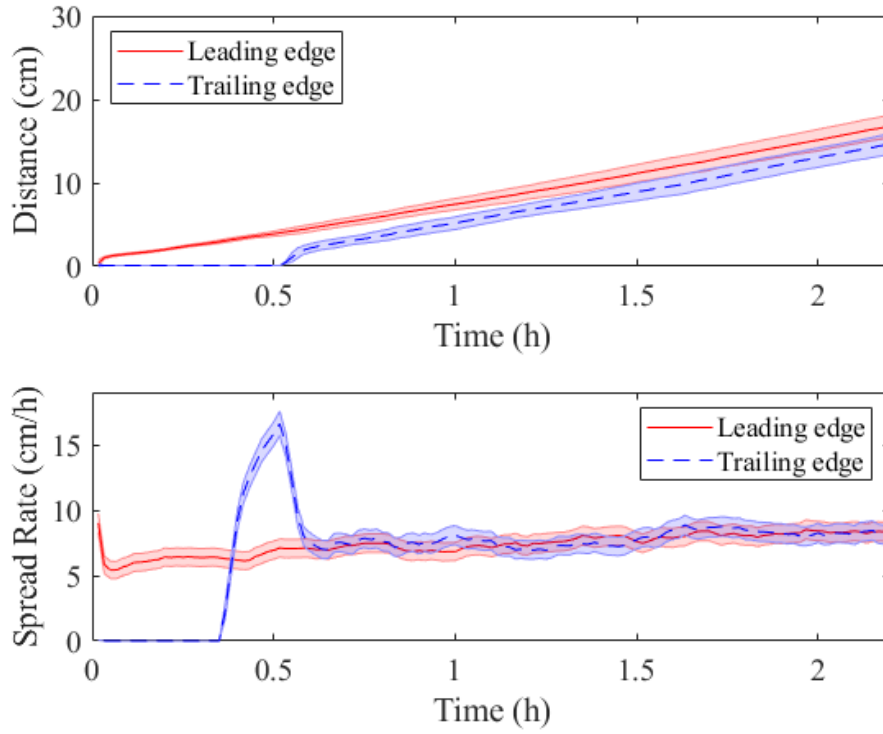


Figure 5 - Illustrating the independence of both leading and trailing edge with time. Figure a shows the distance from the centre of the leading and trailing edge with time and figure b exemplifies the consistent spread rate of the leading and trailing edge, allowing for averaged values to be used for discussion. Plots are generated from an experiment with 40 % MC and 40% IC. The clouds represent the standard deviation across all 60 transect.

3 Results and discussion

3.1 Smouldering width

The distance between the leading and trailing edges, called the smouldering width (Figure 1), was found to vary with soil conditions. Figure 6a, reveals that with increasing moisture the smouldering width shortens. Increasing the IC of the soil from 2.5 to 40% results in a systematic decrease of the smouldering width, on average by, 1.7 cm across all MC. At low MC (Figure 6b), the increase of IC bi-linearly decreases the width of the smouldering front; with the first linear trend between zero and 60% IC, followed by a steep decrease in slope from 60 to 90% IC. The widths drop to zero once spread could no longer be sustained as the sample contained too much MC, IC, or a combination of both, crossing a critical threshold [14-16].

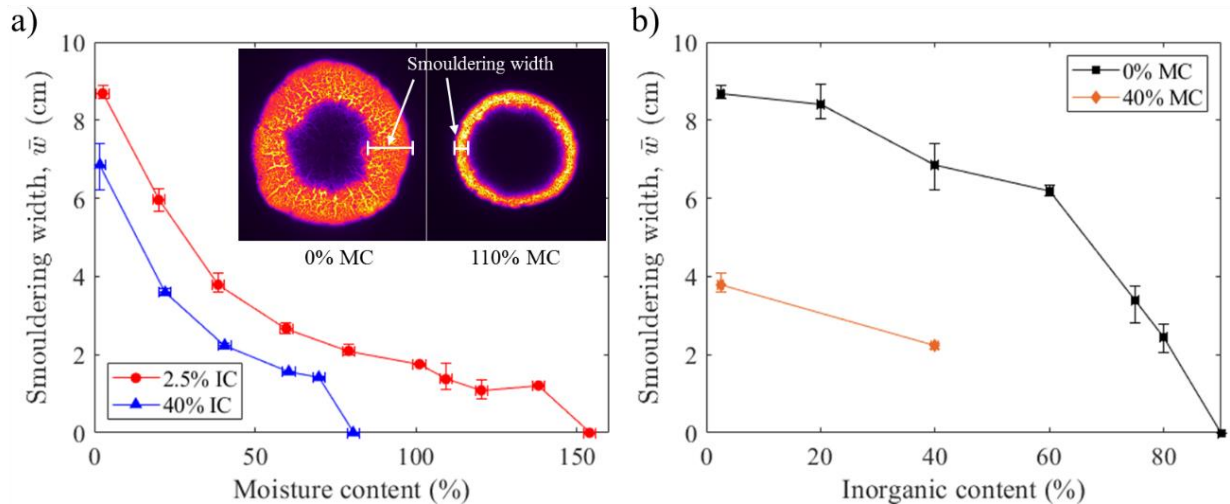


Figure 6 - Shows the change in smouldering width as affected by a) moisture content for two inorganic contents and b) inorganic content for two moisture contents.

3.2 Lateral spread rate

Lateral spread measurements are presented in Figure 7a. Apart from the behaviour of peat with both low MC and IC, a linear downward relationship was found between lateral spread rate and MC (red line; $R^2=0.94$). Increasing the IC of the soil to 40% maintains the linear relationship with moisture (blue line; $R^2=0.90$) (Figure 7a), but resulted in lower spread rates, because IC acts as a sink of sensible heat while not contributing to combustion.

Similar results were noted for the ICx series (Figure 7b) where a clear linear relationship between lateral spread rate and IC was observed (black line; $R^2=0.99$). This linear decrease in spread rate is attributed to the heat capacity of sand. Moisture can be seen to shift this trend downwards. Figure 7c, provides a visual representation of the spread rates throughout the variable space, illustrating the trade-off between IC and MC. The soil conditions at which spread rate drops to zero define a threshold of ignition, beyond which smouldering cannot be sustained. The values found here are higher than that found by Frandsen [14, 16], and on the upper end of what was computationally predicted by Huang et al. [15].

This decrease in lateral spread rate has been noted in literature [19]. Good agreement exists between current results and lateral spread rates reported for dry peat (MC <10%) [18], despite the deeper samples (10cm). This is likely because at low MCs, smouldering spreads faster along the surface, while at high MCs the overhang phenomena occurs and influences the spread rate [20]. Hu et al [22] recently reported a linear decrease in lateral spread rate with MC using the same peat as in this study. The slope is almost identical to the one reported here. However, our spread rates are 2 to 3 times greater than Hu et al [22]. Santoso et al. [19] also collated lateral spread rates from the literature and found that for MCs > 10%, spread rate averaged ~3 cm/h with a negative relationship between spread rate and MC. Notably, this comes from a range of different soils, techniques and measurements conducted at a variety of depths. The significant difference between spread rates reported here and those found in the literature may be due to the shallow design of the reactor, which minimizes the heat losses to deeper layers of soil and limits the formation of overhang. This emphasizes the importance of experiments in deep layers, and although valuable fundamental understanding can be found in the study of shallow layers, it is important to complement findings with corresponding research in deep layer setups.

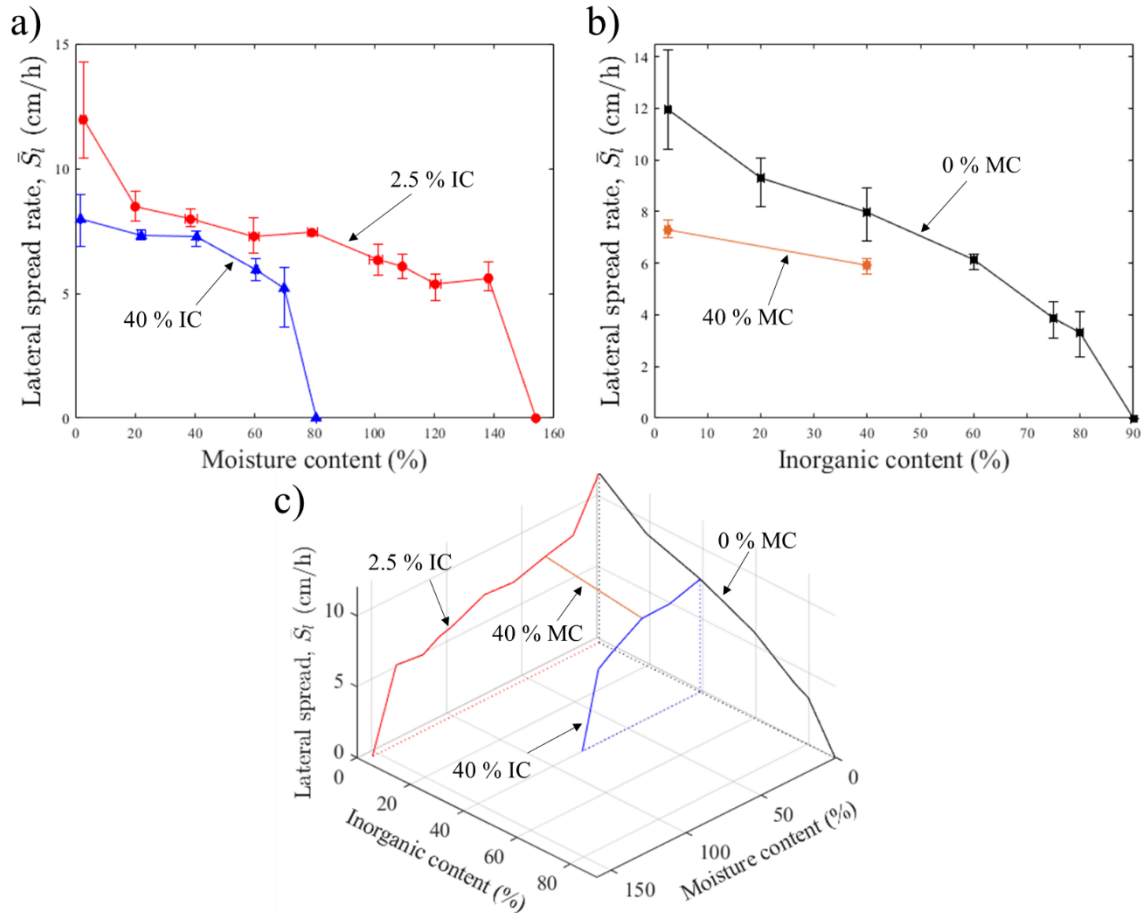


Figure 7 - The influence of soil properties on lateral spread rate: a) The effect of MC on lateral spread rate for soils with two IC values, b) the effect of IC on the lateral spread rate for two different MC values c) plot of the influence of both MC and IC on lateral spread rate. (Slopes: 2.5% IC, $-0.026 \text{ cm/h}\%_{\text{MC}}$, omitting the first data point; 40% IC, $-0.027 \text{ cm/h}\%_{\text{MC}}$; 0% MC, $-0.106 \text{ cm/h}\%_{\text{IC}}$)

3.3 In-depth spread rate

In-depth spread rates were measured and are reported here for the first time alongside lateral spread rate values for the same experiments. This is a major advantage of the shallow reactor design; providing further insight into the dynamics of smouldering. Converse to lateral spread, in-depth spread rate increases with MC, up to tripling the spread rate from 0 - 140% MC (Figure 8a). This agrees with results previously reported in the literature by Huang and Rein [28]. However, in-depth spread rates measured here are 2 to 3 times larger than Huang and Rein [23] at a depth of 5 cm. This is again likely to be due to the shallow depth of the reactor.

Here we also show the influence of IC. The increase of IC from 2.5% to 40% results in higher spread rates across all MCs apart from MC < 10%. Figure 8b shows that at low MC, in-depth spread rate is insensitive to the changes in IC except for IC > 75% where it steeply increases. Notably, at a MC of 40%, a difference in spread rate does appear with increasing IC. This suggests that in-depth spread is insensitive to IC at low MCs, but increases in sensitivity with MC. This indicates a mechanistic relationship between the moisture and the IC that promotes smouldering and requires further research to fully understand. This is particularly interesting as it may influence the fire dynamics in soils with vertical moisture profiles.

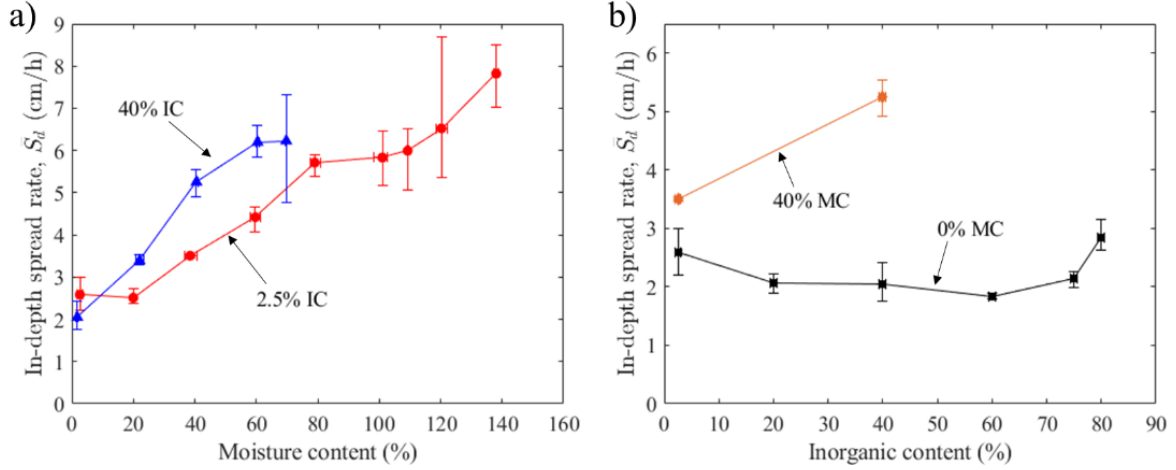


Figure 8 - Influence of soil properties on in-depth spread rate: a) shows increasing relationship between MC and in-depth spread for two different IC values, b) shows independence of in-depth spread on IC at low MCs, but changes at high MCs.

The positive effect of MC on in-depth spread rate can be explained by a decrease in organic density with MC (Figure 3). The decrease in organic density means that there is less fuel per unit depth and so less time is required to consume the full sample depth. However, this alone does not explain the difference. Examining the burning rate per unit area $\dot{m}''$, which is a measure of how quickly mass is consumed per area and is calculated by multiplying the in-depth spread rate, S_d (cm/h) by the organic density ρ_o (kg/m³) (Eq 5), it can be seen that a strong increasing linear relationship exists (Figure 9). This shows that the rate of fuel consumption increases with MC, a finding that is counter intuitive but aligns well with the conclusion drawn from Huang and Rein [23]. It suggests that the decreased organic density improves the oxygen supply, which results in an increase in char oxidation. This consistency in trend also acts as a qualitative validation of the experimental set up.

$$\dot{m}'' = \rho_o S_d \quad (5)$$

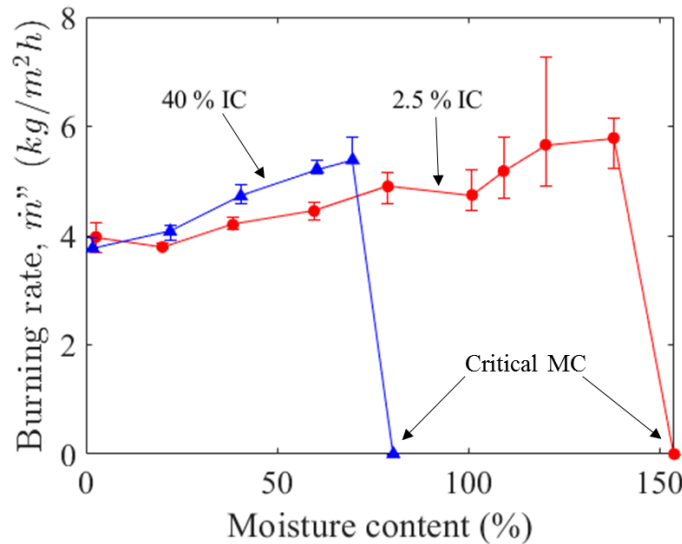


Figure 9 - Linear relationship between burning rate and MC for two values of IC. Burning rate is a measure of the rate of mass consumed per unit horizontal area, and the critical MC is the threshold beyond which smouldering cannot be sustained.

Residence time, which is defined as the duration that smouldering was present in any horizontal location, is also a metric of interest, and is used in calculating the in-depth spread rate (eq 4). As the residence time varies inversely to the in-depth spread rate and will exhibit an inverse trend to Figure 8, it can be seen that, counter intuitively, residence time decreases with

increasing MC. In other words, dryer peat will heat a region for longer than moist peat. This may have significant implication on long term soil damage [19, 30].

3.4 Global spread rate

Each of the spread rates are vector components of a single global spread with an associated direction, ϕ (Figure 1). We show, for the first time, that this global spread rate of peat fires is, at least superficially, independent of MC (Figure 10a), but changes in direction. The average global spread rate was 8.7 (omitting the behaviour of dry peat) and 8.4 cm/h for 2.5 and 40% IC, respectively which also indicates a mild influence of IC. Figure 10b shows a positive linear relationship between ϕ and MC ($R^2 > 0.99$), indicating that for wetter soils spread tends to become in-depth, while spreading more laterally in drier soils. Additionally, as with in-depth spread, the change in ϕ with MC is greater at a higher IC (40). This may have significant implication for deep soils with varying in-depth moisture profiles.

To further explore the global spread, it was calculated from reported values of lateral [20] and in-depth [23] spread rate in the literature. Prat et al. [20] studied lateral spread in a horizontal reactor, with 5 cm thick peat bed, while Huang and Rein [23] studied in-depth spread independently in a 30 cm deep column reactor. Notably, both used the same peat as that used in this experiment. The two experiments did not study the same MC values, so to make them comparable the spread rates were linearly interpolated between the two nearest MC values. The dashed black line in Figure 10a reveals a trend consistent with the experimental data presented here; a global spread that is independent of MC. The average global spread rate of the literature values was 4.0 cm/h, which is noticeably lower than that which has been calculated for the 2.5 % IC samples using the shallow reactor. It is therefore necessary to further study this independence of global spread to moisture content in deeper soil, and in the context of the overhang phenomenon.

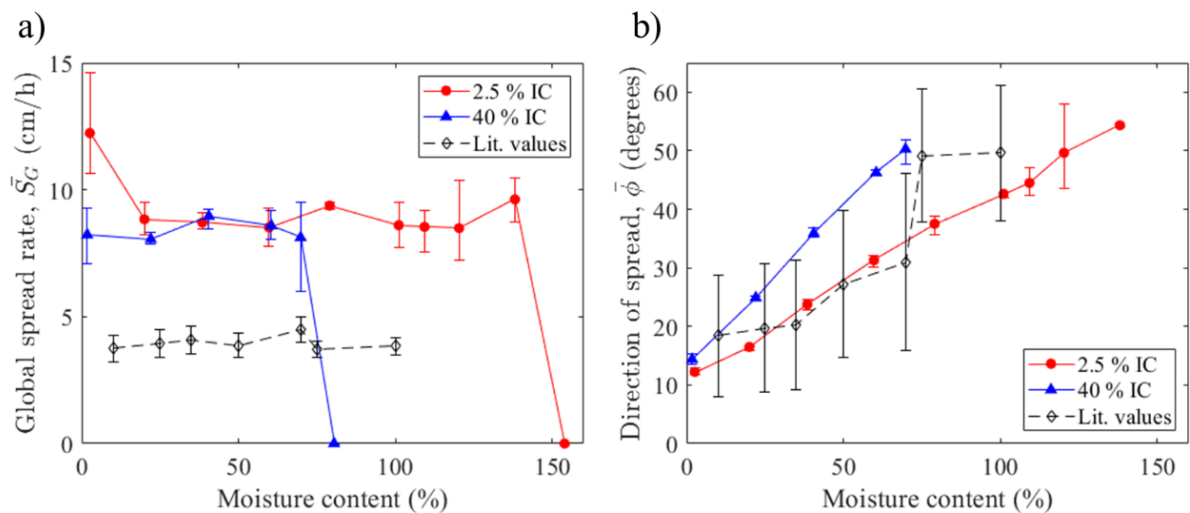


Figure 10 - Plotting a) global spread rate, which is the combination of lateral and in-depth spread, against MC reveals its independence to MC; and b) the linear change of direction of spread with MC. Error bars show the range in experimental data. Black line are results calculated, by vector addition, from literature values of lateral [18] and in-depth [23] spread rates.

3.5 Bifurcation; the partial extinction of smouldering

As MC was increased, a bifurcation of behaviour was exhibited (Figure 11, a and b) where smouldering became locally extinct (Figure 11c), resulting in an unstable and meandering smouldering front, as can be seen in the supplementary video S2. The y-axis on the right of Figure 11, a and b, provides the average proportion of transects where smouldering stopped. This was calculated by dividing the number of transects that did not exhibit pixel values above

the threshold (0.2) by the total number of transects used, which was increased to 600 so to improve the resolution of spread detection. This proportion of the smouldering perimeter that had become extinct increased with MC above the MC threshold values of 110 and 60 %, for ICs of 2.5 and 40% respectively, until smouldering could no longer be sustained and became completely extinct. This bifurcation has never been reported before, and occurs when MC is close to critical MC [14-16]. As can be seen in Figure 11, a and b, bifurcation first occurs when lateral spread becomes less than or equal to in-depth spread. This corresponds with a ϕ angel of 45°. Thus the intersection of the decreasing trend of lateral spread rate and increasing trend of in-depth spread rate, mark the critical threshold for bifurcation. It is notable that increasing the IC, which decreases the lateral spread rate and increase the in-depth spread rate, causes criticality to occur as a lower MC. This is consistent with findings in literature, which state that the critical MC is decreased through the additon of inorganic material [14].

As in-depth spread is a controlled by the burning rate of the char, which is responsible for the energy release that drives smouldering spread, and lateral spread is controlled by the endothermic processes of drying, heating, and pyrolysis, it is understandable that the intersection between these two rates define when smouldering begins to fail. As criticality is achieved when the rate of char prodction and energy consumption is slower than the rate of char consumption and energy release. Further research is needed to understand the importance of the interplay between in-depth and lateral spread rate, and how it can be applied to deeper samples of peat, where complex dynamics such as overhang can occur more prominently.

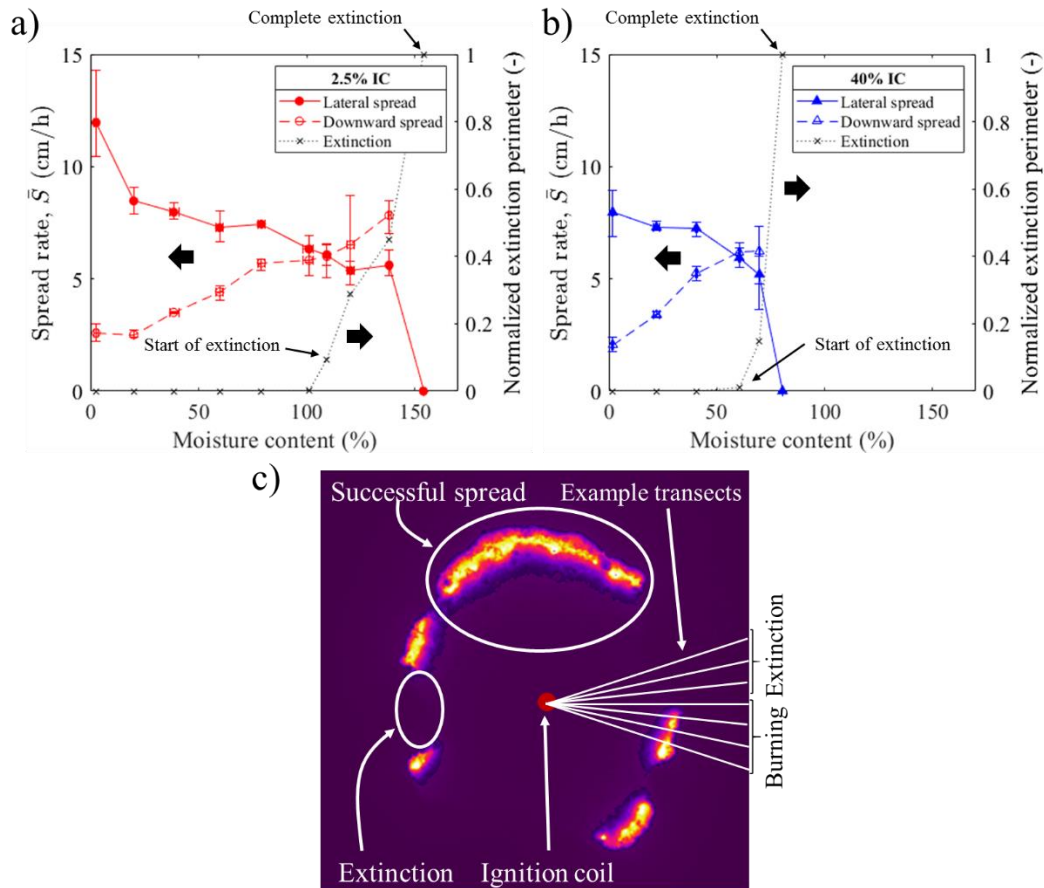


Figure 11 – a) and b) Illustrate how once in-depth spread exceeds the lateral spread rate smouldering begins to extinguish locally and exhibit a bifurcation behaviour. c) An IR image illustrating bifurcation, with regions of spread and extinction as well as illustrating the use of transects in detecting extinction and measurement of the extinction perimeter.

4 Conclusions:

A new experimental rig was developed and used to simultaneously study, for the first time, lateral and in-depth spread rates across a range of moisture contents and inorganic contents. The shallow reactor allowed for decreased experimental time and a greater number of conditions to be examined. Some of the trends found are consistent with previous experiments, which act as qualitative validation of the set-up. Both moisture and inorganic content linearly decreased lateral spread due to the additional energy required to evaporate the moisture and heat the inorganic content. Conversely, moisture content increased the in-depth spread rate by up to 300%, due to the decrease of organic density as a consequence of the swelling of peat, which decreased the total organic mass in depth as well as increasing the burning rate. Inorganic content showed little influence on lateral spread at low moisture content but was more influential at higher moisture content, which has never been studied before. The intersection of the increasing trend of in-depth spread and the decreasing trend of lateral spread, reveal a critical point at which bifurcation can be observed, and extinction becomes possible, highlighting the value of studying the fundamental dynamics of smouldering. Furthermore, for the first time it has been revealed that the global spread vector, a combination of both lateral and in-depth spread rate, is insensitive to moisture content. The direction of this spread is dependent on moisture content, spreading more downwards in wet soils. From this study, it is evident that lateral spread and in-depth spread, although distinctly different, are closely related and require further study to understand the implications and influence in deeper soils. These findings provide valuable new insights into smouldering dynamics and a better understanding of the fundamental interaction between soil conditions and burning dynamics in shallow layers, which can help inform policy makers and fire-fighting practices.

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