Fire Safety Journal xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

Self-ignition of natural fuels: Can wildfires of carbon-rich soil start by self-heating?

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ARTICLE INFO

Keywords:
Wildfires
Ignition
Soil
Smouldering

ABSTRACT

Carbon-rich soils, like histosols or gelisols, cover more than 3% of the Earth's land surface, and store roughly three times more carbon than the Earth's forests. Carbon-rich soils are reactive porous materials, prone to smouldering combustion if the inert and moisture contents are low enough. An example of soil combustion happens in peatlands, where smouldering wildfires are common in both boreal and tropical regions. This work focuses on understanding soil ignition by self-heating, which is due to spontaneous exothermic reactions in the presence of oxygen under certain thermal conditions. We investigate the effect of soil inorganic content by creating under controlled conditions soil samples with inorganic content (IC) ranging from 3% to 86% of dry weight: we use sand as a surrogate of inorganic matter and peat as a surrogate of organic matter. This range is very wide and covers all IC values of known carbon-rich soils on Earth. The experimental results show that self-heating ignition in different soil types is possible, even with the 86% inorganic content, but the tendency to ignite decreases quickly with increasing IC. We report a clear increase in ambient temperature required for ignition as the IC increases. Combining results from 39 thermostatically-controlled oven experiments, totalling 401 h of heating time, with the Frank-Kamenetskii theory of ignition, the lumped chemical kinetic and thermal parameters are determined. We then use these parameters to upscale the laboratory experiments to soil layers of different thicknesses for a range of ambient temperatures ranging from 0 °C to 40 °C. The analysis predicts the critical soil layer thicknesses in nature for self-ignition at various possible environmental temperatures. For example, at 40 °C a soil layer of 3% inorganic content can be ignited through self-heating if it is thicker than 8.8 m, but at 86% IC the layer has to be 1.8 km thick, which is impossible to find in nature. We estimate that the critical IC for a ambient temperature of 40 °C and soil thickness of 50 m is 68%. Because those are extreme values of temperature and thickness, no self-heating ignition of soil can be expected above the 68% threshold of inorganic content. This is the first in-depth experimental quantification of soil self-heating and shows that indeed it is possible that wildfires are initiated by self-heating in some soil types and conditions.

1. Introduction

Carbon-rich soils are porous reactive natural fuels found in nature, like histosols and gelisols [1]. Examples of carbon-rich soil systems are natural peatlands [2]. Peatlands store most of the terrestrial ecosystem's carbon, roughly three times more carbon than the Earth's forests. Peatlands cover about 3% of the Earth's land surface, and are primarily found in tropical and boreal regions, but store about 25% of the Earth's soil carbon [3]. Peat is an accumulation of decayed vegetation formed in anaerobic conditions [4]. As an organic porous media, carbon-rich soil is prone to smouldering ignition and combustion [5,10]. Smouldering wildland fires in soil systems, ranging from low to high inorganic contents, are a known natural hazard. Once ignited, carbon-rich soils burn the ancient carbon for months often causing the largest fires on Earth [3]. For example, in 1997 peat fires led to an extreme haze event in Southeast Asia, and released greenhouse-gas equivalent to 13–40% of the global man-made emissions [6,7]. The effect of wildfires in carbon-rich soils like peatlands can be dramatic, as seen in Fig. 1 where a smouldering soil fire burnt for weeks in Las Tablas de Daimiel National park, Spain, in 2009. Global warming can dry the soils and increase soil combustion, creating a positive feedback to the climate system [2,4].

Carbon-rich soil fires can be initiated by an external source, e.g. lightning, flaming wildfire and firebrand, or by self-heating due to its propensity to smouldering. Self-heating is the tendency of certain porous solid fuels to undergo spontaneous exothermic reactions in

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http://dx.doi.org/10.1016/j.firesaf.2017.03.052
Received 15 February 2017; Accepted 27 March 2017

Please cite this article as: Restuccia, F., Fire Safety Journal (2017), http://dx.doi.org/10.1016/j.firesaf.2017.03.052

Nomenclature

E	Effective activation energy (kJ/mol)
f	Mass action law (-)
k	Thermal conductivity (W/m-K)
IC	Inorganic content in dry weight (%)
L	Soil depth (m)
m	Mass (g)
MC	Moisture content in dry weight (%)
R	Universal gas constant (J mol^{-1} K^{-1})
T	Temperature (K or °C)

Greeks

δ	Frank-Kamenetskii parameter (-)
ρ	Density (kg/m^3)

Subscripts

a	Ambient
c	Critical
p	Peat as surrogate organic matter
s	Sand

Fig. 1. Smouldering wildfire of a carbon-rich soil system in Las Tablas de Daimiel National park [9].

oxidative atmospheres at low temperatures [9,10]. This process starts by slow exothermic oxidation at ambient temperature, but the reaction alone is insufficient to raise the material temperature. The temperature rise is determined by the imbalance between the rate of heat generation and the rate of heat losses [10]. Fire initiated by self-heating ignition is a well-known hazard for many natural materials such as coal, biomass, and shale [11–13]. Similarly, the self-heating ignition hazard for carbon-rich soils which are a typical natural biomass should not be overlooked but have not been studied in depth to date.

In the literature, there are only a handful of studies on the forced ignition of soil [14–18]. Frandsen [14,15] showed that there are two limiting factors, moisture content (MC) and inorganic content (IC)[1] of soil (i.e. minerals), for the smouldering by an external heating source (forced ignition). Both natural soils and modified soils (i.e. mixing peat with sand) with a wide range of MC and IC were studied. Fig. 2 replots his experimental results of ignition and non-ignition limits as well as the recent numerical predictions from [16]. When the soil's IC and MC are such that it is on the left side of the critical conditions, then soil can ignite with an external heat source. If it is on the right, it does not ignite with an external heat source. Moreover, MC is found to be an important factor to determine the soil conditions for ignition, and the value of critical MC is compensated by the value of IC. As the value of MC increases, critical IC for forced ignition decreases. Recently, Hadden et al. [17] and Huang et al. [18] further investigated the influence of oxygen concentration on the forced ignition of soil. However, to the best of the authors' knowledge, so far there is no research on the self-ignition of carbon-rich soil, posing a fundamental knowledge gap.

In this work, we study the self-heating ignition behaviour of modified soil samples with varying IC which covers all IC values of known carbon-rich soils on Earth using bench scale experiments, and aim to determine the limiting IC. The experimental results are then used to predict the ignition behaviour of natural carbon-rich soil systems and its dependence on ambient temperature, IC and soil layer thickness.

2. Self-heating ignition theory

The Frank-Kamenetskii theory of ignition criticality has been used extensively in the literature to investigate self-ignition characteristics of materials [10,13,19]. For a given sample size, heat generation from exothermic reactions is proportional to the volume of the sample, but volumetric heat loss is proportional to the surface area of the sample: as the size of the sample increases, the critical ambient temperature required for self-ignition decreases.

The theory can be used to predict self-ignition for larger sizes, if the mechanism of heat generation is unchanged [10,19]. The heat transfer problem in self-ignition corresponds to the transient heat conduction equation. The Frank-Kamenetskii theory of ignition assumes that the material is reactive and 1-D, and that the heat release is from a 1-step exothermic reaction which contains numerous chemical and biological elemental reactions. For organic materials there are often two main sources of heat generation that make up this global 1-step reaction, a chemical process at higher temperatures and a biological process at lower temperatures [20]. The biological process can range from temperatures under 20 °C to up to 80 °C and is usually caused by growths of psychrophilic, mesophilic and thermophilic micro-organisms [21]. The biological process will have a contributing effect at lower

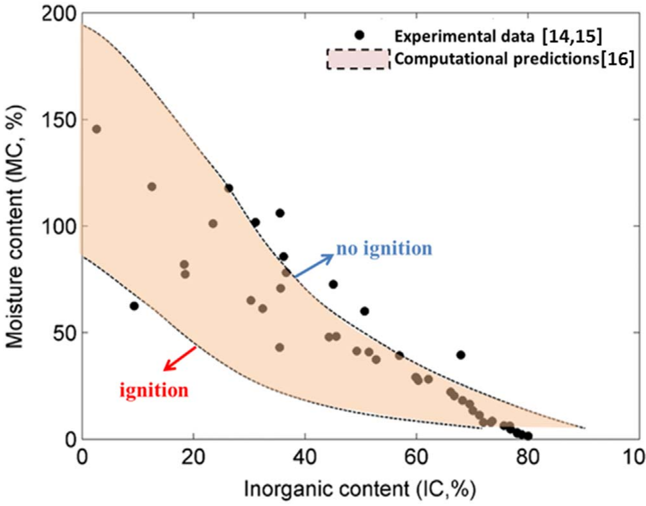

Fig. 2. Critical moisture and inorganic content for the forced ignition of peat where experimental data is from [14,15] and computational predictions are from [16]. If soil has lower IC or MC than the shaded area, it will ignite with forced ignition. If it is higher than the IC or MC of the shaded area, it will not ignite.

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[1] Moisture content (MC) is defined in dry basis as the mass of water divided by the mass of a dry soil sample, expressed as %. Inorganic content (IC < 100%) is defined in dry basis as the mass of soil inorganic matter (inert matter, like for example minerals) divided by the mass of a completely dry soil sample, expressed as %.

temperatures in raising the soil temperature. However already from 40 °C chemical oxidation will start contributing to the heat generation and as the temperature increases it becomes the dominating heat generation process [21]. This global reaction is also assumed to have a high activation energy so that a steady-state solution exists [10,19]. To solve the transient heat conduction equation, Frank-Kamenetskii theory defines a dimensionless parameter δ (Eq. (1)),

$$\delta = \frac{QEf\,L^2}{kRT_a^2}e^{-\frac{E}{RT_a}} \tag{1}$$

where E is the activation energy of the 1-step global oxidation reaction, k is the effective thermal conductivity of the sample, R the universal gas constant, T_a is the ambient temperature, L is the characteristic length of the sample (for a cube basket the side length, and for an infinite slab the thickness), Q is the heat of reaction per fuel mass, and f is the value of the mass action law which relates the concentration of fuel and oxygen at the initial time to reaction rates, and is based on initial concentrations of fuel and oxygen [19]. Expressing the reaction rate as the Arrhenius law for dependence on temperature, the transient heat conduction equation is solved and the following dependence of critical sample size and ambient temperature is obtained, Eq. (2).

$$\ln\left(\frac{\delta_c T_{a,c}^2}{L^2}\right) = \ln\left(\frac{QEf}{Rk}\right) - \frac{E}{RT_{a,c}} \tag{2}$$

where δ_c is the critical value of the dimensionless parameter in Eq. (1) for which ignition occurs, which is a function of the geometrical shape of fuel; and $T_{a,c}$ is the critical (minimum) ambient temperature for which self-ignition occurs.

A solution to Eq. (2) satisfying the boundary condition $T=T_a$ only exists when the condition $\delta \le \delta_c$ is satisfied. δ_c is a function of geometry which has been precisely calculated and can be found in the literature [9,19,22]. In our experimental work we used cubic baskets, so δ_c=2.52 [20], and for natural soil formations we assume slab geometry which has δ_c=0.878 [19].

When carrying out bench scale experiments with environmental temperatures greater than 100 °C the effect of moisture cannot be accounted for as the thermostatically controlled ovens used for measurements are at temperatures greater than the boiling point of water. Moisture effects are not studied in this work. The effect of moisture content on self-heating ignition of reactive porous media has been shown to be complex [23]. At low MC an increase in moisture content increases the reactivity of the material. At higher MC values the reactivity of the material decreases dramatically with moisture content [23]. The effect of moisture content has been studied extensively for coal, where moisture content affects the type of radical sites formed in the porous material. At low MC, moisture hinders formation of stabilized radicals where it is tightly bound within the rock, which leads to faster oxidation of the coal and therefore to a material more prone to self-heating up to approximately 50% MC [24]. At higher MC any non-tightly bound moisture, so excess moisture, takes up extra heat and slows down the release of heat from oxidation [24].

3. Experimental methods

The carbon-rich organic soil used as a surrogate in the experiments is a commercial variety, Shamrock Irish Moss peat, provided by Bord na Mona Horticulture Ltd. It was chosen for the experiments because of its low IC (≤3%) [25]. Elemental analysis of the organic matter was carried out and yielded 54% C, 39% O, 5% H, 1.2% N and traces of S. Moreover, compared to naturally sourced peat, its advantages include the availability in large quantities, constant composition, homogeneous properties, and the fact that this peat has been used in many previous studies [17,25,26]. The peat was oven-dried at 80 °C for 48 h [27] (shown in Fig. 3). Inert fine grained silica sand was used to mix with peat to vary the soil IC, (shown in Fig. 3). Both peat and sand are porous media, and their respective bulk densities are 223 ± 18 kg/m^3 and 1477 ± 3 kg/m^3.

Before each test, the sand and peat were well mixed and left for a day to ensure homogeneity. IC is calculated as the mass fraction of sand as in Eq. (3).

$$\mathrm{IC} = \frac{m_s}{m_p + m_s}100\% \tag{3}$$

where m_s is the mass of sand which is used as surrogate for IC and m_p is the mass of peat used as surrogate for the organic matter. Because sand has a higher density than peat, the density of the mixed soil increases as the IC increases (Fig. 4). The density increases nearly linearly for IC up to 50%. After this, the space taken up by the IC becomes too large for the pores to contain, and the organic content present per unit volume decreases. This can be seen in Fig. 4.

The laboratory setup to determine the minimum critical ambient temperature for self-heating $T_{a,c}$ that leads to self-ignition was constructed following a similar procedure to the British Standards EN 15188:2007. Fig. 5 shows the overall experimental setup, with the different baskets used. The soil sample was packed into cubic shaped wire mesh baskets of different sizes to study the size effect. We chose a cube shape for the baskets as it is the easiest shape with which to increase geometry size in a rectangular oven without making the larger samples approach the oven walls. The baskets were made of 0.5 mm diameter wire mesh with volumes of 131, 442, 1049, 3540 cm^3. These baskets ensure a good range of sizes for the largest possible temperature range given at the laboratory scale, between 130 °C and 200 °C for these soil samples. As the basket size increases we have lower critical ignition temperatures as the ratio of heat losses to the environment to heat generated by chemical reactions decreases [22]. Each basket filled with soil was placed in the middle of a thermostatically controlled laboratory oven with forced air circulation to prevent temperature

Fig. 3. Peat (left) and sand (right) are mixed to create the appropriate inorganic content ratios of our samples.

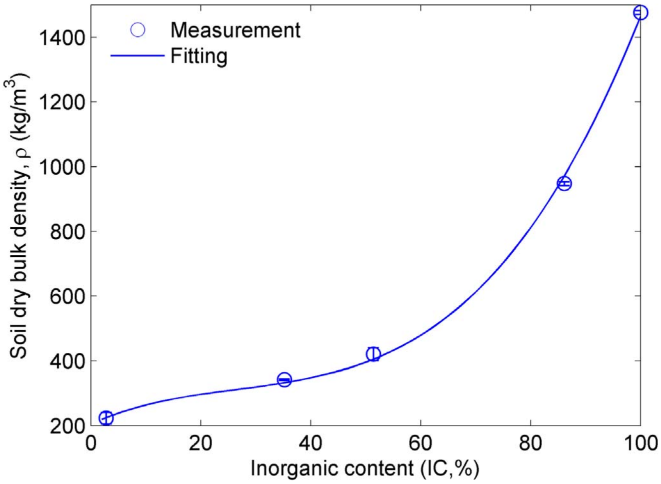

Fig. 4. Density of soil samples with increasing IC.

stratification and provide good oxygen supply. The oven was initially preheated to a given uniform ambient temperature T_a. In order to limit the influence of the forced flow, a large mesh cage was placed around the sample. The temperature inside the sample was monitored using two thermocouples placed at the centre of the sample 0.5 cm apart. Based on the standard, only one thermocouple is needed, so the second one provides redundancy. Oven temperature was also measured by a thermocouple placed several centimetres away from the basket, inside the mesh cage, in the vertical middle plane of the oven.

A summary of the experiments is presented in Table 1. In total, 39 experiments and 401 h of oven run time over the course of 8 months were carried out for different soils. The results found for the 3% IC experiments were used to estimate the ignition temperatures needed for higher ICs, reducing the number of experiments required for finding the critical ignition temperature at those given inorganic contents.

The minimum critical ambient temperature ($T_{a,c}$) is defined as the temperature for which thermal runaway leads to ignition. If the soil failed to reach ignition the experiment was repeated with a fresh sample at a higher temperature. If the soil reached ignition, then the experiment was repeated with a fresh sample at a lower temperature. The experiments were carried out until $T_{a,c}$ for ignition was located within ±5 °C for each tested soil. At least two experiments were conducted at each IC and basket size condition.

Fig. 6 shows an example of successful soil ignition. The sample before and after self-heating ignition is shown visually as well. The mass of the organic content is reduced by 94% and what remains are char and ash (IC). The temperature profile at the centre of the soil where thermal runaway is seen, along with the reference ambient temperature T_a.

Table 1
Number of experiments carried out for different soil IC and basket sizes.

IC (%)	Basket Cube Length (cm)			
	5.1	7.6	10.2	15.2
3%	4	4	2	8
35%	2	2	2	–
51%	2	3	2	–
86%	3	3	2	–

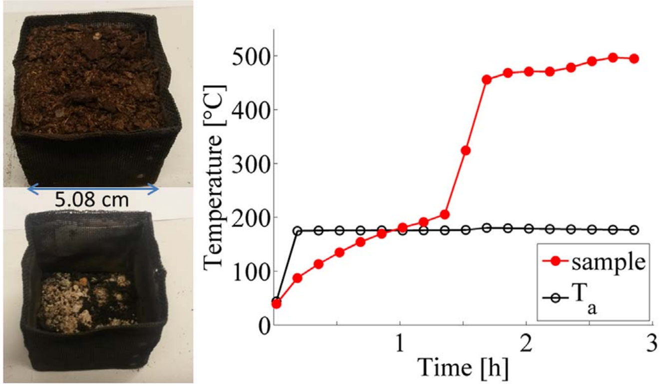

Fig. 6. Soil sample before (top left) and after (bottom left) ignition. Temperature profile in the centre of the soil sample shows clear thermal runaway at t=1.4 h, with the ambient temperature (T_a) shown for reference.

Table 2
The critical ignition temperatures found for different soil IC and basket sizes.

IC (%)	Basket Cube Length (cm)			
	5.1	7.6	10.2	15.2
3	172 ± 2 °C	161 ± 3 °C	150 ± 3 °C	139 ± 2 °C
35	173 ± 2 °C	164 ± 3 °C	152 ± 1 °C	–
51	178 ± 2 °C	164 ± 2 °C	158 ± 2 °C	–
86	197 ± 1 °C	190 ± 5 °C	179 ± 5 °C	–

4. Results

Table 2 shows the obtained critical ignition temperatures for the different basket sizes and different IC. The critical ignition data found in experiments was used to make a $\ln(\delta_c T_{a,c}^2/L^2)$ vs $1/T_{a,c}$ plot, and to calculate the best linear fit for each inorganic content value (Fig. 7). The slope of the straight line corresponds to $-E/R$, while the y-intercept is $\frac{f}{Rk}$. If the plot of $ln(\delta_c T_{a,c}^2/L^2)$ against $1/T_{a,c}$ (Eq. (2)) is a straight line, it validates the Frank-Kamenetskii theory. As seen in Table 3, $R^2 > 0.94$

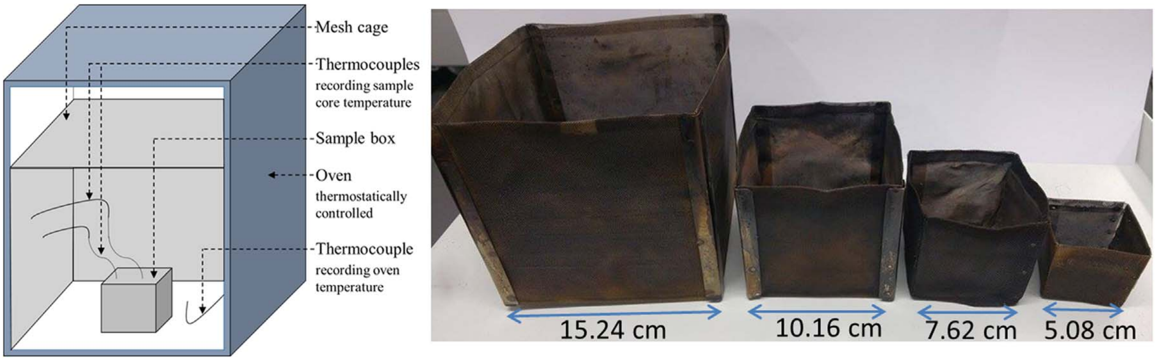

Fig. 5. Experimental setup for studying self-heating of a sample placed at the centre of the thermostatically controlled oven with thermocouples for measuring the ambient and soil temperatures (left) and meshed test baskets (right).

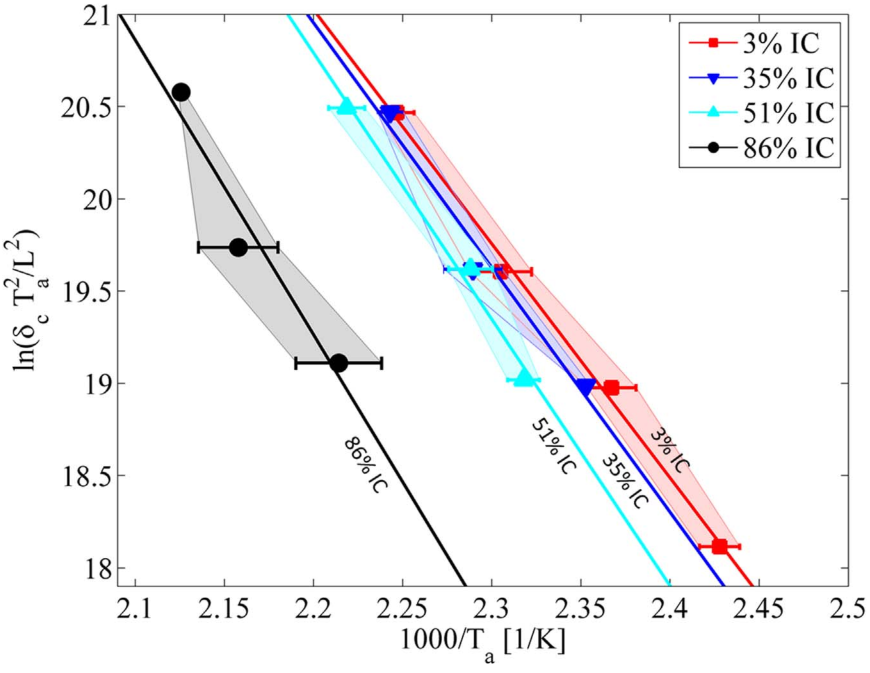

Fig. 7. Frank-Kamenetskii plot for soil with different IC ranging from 3% to 86%. Experimental error is estimated based on temperature measurements in Table 2. The linear fits have $R^2 > 0.94$ (Table 3).

Table 3
Effective activation energy E and y-axis intercepts of Fig. 7 calculated using Eq. (2) for increasing values of IC. The R^2 values of the linear fits used to calculate these is included.

IC (%)	E (kJ/mol)	$\ln(QEf/Rk)$	R^2
3	105.5 (−9.3,+17.5)	48.9 (−2.6,+4.9)	0.995
35	110.2 (−7.7,+13.1)	50.1 (−2.1,+3.7)	0.970
51	120.1 (−17.6,+34.3)	52.6 (−4.8,+9.3)	0.985
86	132.8 (−27.5,+62.8)	54.4 (−6.9,+16.2)	0.943

for all tested soil samples, confirming the validity of the Frank-Kamenetskii theory and 1-step Arrhenius reactions for the self-heating ignition of soil.

The slopes in Fig. 7 give the effective activation energies for the soil. The y-intercept of these lines allows the calculation of thermal parameters in Eq. (1). A summary of the activation energies for varying inorganic content is given in Table 3, with R^2 calculated from the linear fit for each line. The error bounds are calculated using the fits that would give the highest and the lowest possible effective activation energy from the experimental data obtained (largest possible errors).

The results found in this work help determine the effect of soil type and IC on self-heating ignition. We report a clear increase in ambient temperature required for ignition as the IC increases.

5. Upscaling for natural soil layers

The properties in Table 3 can be used in the Frank-Kamenetskii theory to upscale the laboratory results to natural soil systems. Carbon-rich soil ecosystems are typically very wide, kilometres in length, but no deeper than 50 m [28,29]. Because the width is at least an order of magnitude larger than the depth, these systems behave as semi-infinite slabs, and critical ignition temperatures can be calculated for various depths by Eq. (2) with δ_c=0.878 [19]. The upscaling of the results assumes that oxygen is present in the porous soil, as it is needed for the self-heating to take place. This means, for example, that soil would not be waterlogged and that the entire depth being considered has oxygen access.

Possible ambient temperature ranging between 0 °C and 40 °C are considered because this range includes temperatures found in the natural environment (day and night, winter and summers in boreal and tropical regions). Temperatures below 0 °C can be found in the boreal regions, where the water in the soil can freeze. Because of the complexity of the melting process, upscaling results below 0 °C would not be meaningful.

Fig. 8 shows the upscaled results for the natural soil layers. For example, at ambient temperature of 40 °C, the soil with a low IC (e.g. peat) can self-ignite with a minimum thickness (L_{min}) of 8.8 m. As soil IC increases to 86%, the minimum soil thickness for self-ignition raises to 1.8 km which would be impossible to find in nature as organic soil depth reaches a maximum of about 50 m [28]. For IC between 3% and 35% the minimum thickness for self-ignition does not change significantly. However, as IC increases above 35% the minimum thickness increases significantly. As natural soil systems have thickness from ~0.1 m to 50 m, minimum critical ignition temperatures were calculated with respect to IC in Fig. 8. A dotted line representing the 50 m thick soil layer is plotted to show intersection values for varying IC. Anything below that means self-heating is expected, above means it is not expected. For a 50 m thick soil layer, the critical ambient temperature is 14 °C for IC =3% (i.e. peat soil), but as high as 50 °C for IC =86%. At shallower thicknesses like 20 m, the minimum ambient temperature needed for ignition varies by 45 °C between the natural peat (3% IC) and the high–mineral soil (86% IC). In Fig. 8 (right) a dotted line representing 40 °C is plotted. If a given soil thickness curve does not intersect the line, we do not expect self-heating ignition to happen for that given thickness as $T_a$required would be too high to be found in natural conditions. For example, for soil systems ~1 m and ~5 m thick, self-heating ignition is not expected because even for 3% IC ambient temperatures required are greater than 40 °C. We estimate that the critical IC for a T_a of 40 °C and soil thickness of 50 m is 68%. Because those are extreme values of temperature and thickness, no self-heating ignition of soil can be expected above the 68% threshold of inorganic content.

6. Conclusions

In this work, bench-scale experiments were conducted to determine the self-ignition criteria for soil samples with different IC values. The

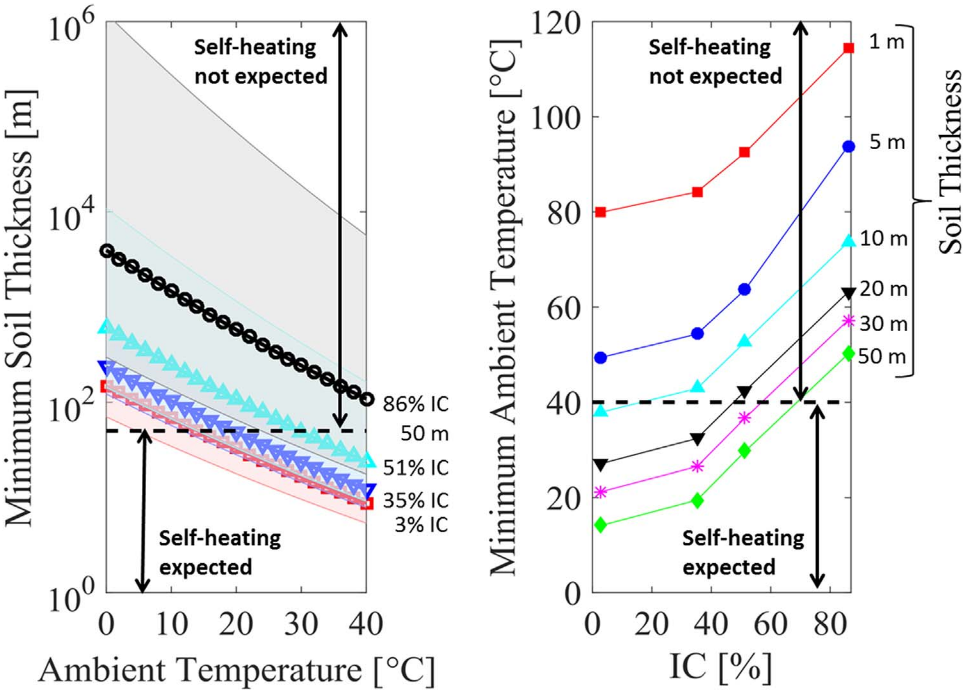

Fig. 8. Upscaled results of soil depths required for self-ignition for ambient temperature between 0 °C and 40 °C for IC between 3% and 86%. Error show the worst-case scenario in terms of experimental measurements (Table 3). On the right, critical ambient ignition temperatures for six different soil thicknesses vs IC.

experiments predict and quantify the environmental temperature conditions necessary for the onset of smouldering fires in carbon-rich soil systems such as histosols or gelisols. Experimental results show that as the IC in the soil increases, the critical ambient temperature for self-ignition increases. Using the Frank-Kamenetskii theory, it is found that the effective activation energy for the soil increases from 105 kJ/mol to 133 kJ/mol as IC increases from 3% to 86%, indicating a significant reduction in reactivity and ignitability. We report a clear increase in the ambient temperature required for ignition as the IC increases.

By upscaling the bench-scale experiments to natural ecosystem sizes, the minimum ambient temperature and soil layer thickness for self-heating ignition are predicted. For a 50 m thick soil layer, the minimum ambient temperature is estimated to be as low as 14 °C for IC =3%, but as high as 50 °C for IC =86%. The maximum IC possible for self-ignition at 40 °C for the maximum natural thickness of peat, 50 m, was estimated to be 68%. Wildfires in carbon-rich ecosystems are a hazard, and determining the ignition conditions is important. This work is the first in-depth experimental quantification of self-heating ignition of soil, showing that it is indeed possible that wildfires are initiated by self-heating of some soil types at the right conditions.

Acknowledgments

This research was funded by EPSRC (grant EP/L504786/1) and by European Research Council (ERC) Consolidator Grant HAZE (682587). The authors would like to thank Egle Rackauskaite and Franz Richter (Imperial College London) for valuable discussions. Data supporting this publication can be obtained from https://zenodo.org/communities/imperialhazelab/ under a Creative Commons Attribution license.

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