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

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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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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

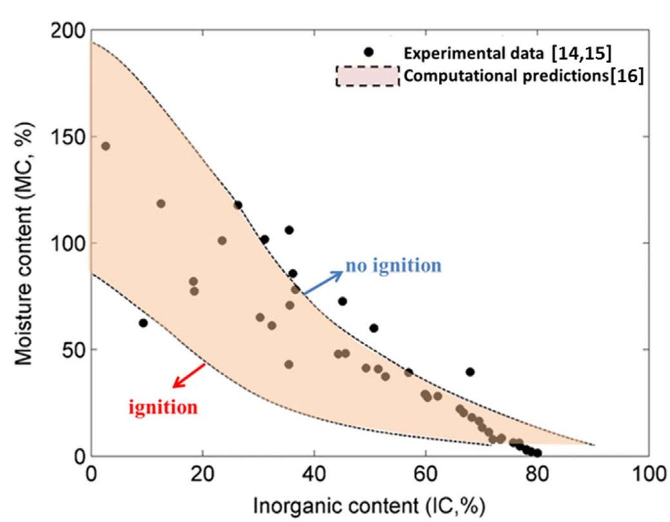

Fig. 2. Critical moisture and inorganic content for the forced ignition of peat where experimental data is from [14,15] and computational predictions are from [16]. If soil has lower IC or MC than the shaded area, it will ignite with forced ignition. If it is higher than the IC or MC of the shaded area,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

[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 %.