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Numerical investigation of downward smoldering combustion in an organic soil column

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ABSTRACT

Smoldering combustion of natural organic layers like peatlands leads to the largest fires on Earth. Smoldering wildlfires may propagate slowly for several months, consuming organic matter and threatening to release ancient carbon stored deep in the soil. It has become a topic of global interest linked to ecosystem perturbations, carbon sequestration and climate change. Although experimental studies have revealed the main factors affecting ignition and spread of natural smoldering, there is little modeling work explaining these experiments. This study aims at bridging the gap by developing a numerical model of smoldering combustion spreading downwards through a column of organic soil. Two spreading fronts are considered, drying and combustion, fed by oxygen diffusion through the top ash layer. The model predicts the transient evolution of the temperature profiles in a vertical column, and the smoldering rate for organic soils with different properties. The role of moisture content, inorganic content, bulk density and heat of smoldering combustion in the critical conditions for self-sustained propagation is investigated. The simulation results show that the critical moisture content increases linearly with heat of smoldering combustion, decreases linearly with the inorganic content and decreases with organic bulk density. These results are consistent with previous experimental observations, indicating the model is capable for guiding further experimental studies.

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1. Introduction

When a layer of organic soil ignites, it burns steadily without flame and propagates slowly into the soil [1]. Smoldering combustion of natural organic layers like peatlands leads to the largest fires on Earth and poses a positive feedback mechanism to climate change [1,2]. Smoldering wildlfires may propagate slowly for several months, consuming organic matter and threatening to release ancient carbon stored deep in the soil. In-depth spread over thick peat layers consumes biomass in the order of 100 kg/m^2 [2]. It has become a topic of global interest linked to ecosystem perturbations [3], carbon sequestration [4] and climate change [2].

In the shallow organic soil layer of the ground, the smoldering front propagates downward and laterally, consuming the fuel. The continued propagation of smoldering is controlled primarily by oxygen flow to the smoldering front and is diffusion-driven [1,2,5]. The primary controlling mechanisms of smoldering ground fires are the net fuel load (i.e. organic matter content of soil), the oxygen diffusion and availability which is dictated by the distance to the free surface and permeability of the medium to air, and the heat losses predominantly by evaporation and heat lost from the reaction zone by conduction, convection and in a lesser quantity radiation [6]. The moisture and mineral contents reduce the fuel load per total mass and also result in a lower net heat release value because of water evaporation and the heating up of the mineral content. It is known that there is a critical value for water and mineral contents above which organic soil smoldering cannot propagate [7].

Laboratory studies have revealed that the moisture and mineral contents, bulk density, together with other parameters, play important roles in smoldering of organic soils, like peat moss and duff [8–12]. The duff in eastern Ontario pine forest ceases to burn near 140% moisture content (organic mass based) [13]. Frandsen's experiments showed that duff smoldering is self-sustained if $MC + IC/4$ is less than 1.1 when the organic bulk density is fixed at 110 kg/m^3 [7]. Here the moisture content MC and inorganic content IC were expressed as mass ratios relative to the organic mass (organic mass based). Later, Frandsen applied logistic regression to define ignition probability of organic soils based on the moisture content, inorganic content and the organic bulk density [14].

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Nomenclature

T	temperature (K)
MC	the moisture content (organic mass based)
MC_p	the moisture content (dry mass based)
IC	the inorganic content (organic mass based)
$\dot{m}$	mass flux (kg/(m^2 s))
$\dot{r}_p$	consumption rate of peat (kg/(m^2 s))
Y_{O_2}	oxygen mass fraction
D	oxygen diffusion coefficient (m^2/s)
L	length (m)
x	front position (m)
K	thermal conductivity (W/(m K))
h	convective heat transfer coefficient (W/(m^2 K))
C	specific heat capacity (J/(kg K))
ΔH	heat of combustion (kJ/kg or MJ/kg)
ΔH_v	heat of water evaporation (kJ/kg or MJ/kg)
Sh	shrinkage factor
$\dot{Q}$	heat flux (kW/m^2)

Greek symbols

ρ	density (kg/m^3)
δ	boundary layer thicknesses (m)
ε	emissivity
σ	Stephen–Boltzmann constant (W/(m^2 K^4))
ϕ	void factor
θ	the volumetric water content

Subscripts

0	initial or ambient conditions
s	surface
w	water
o	organic matter
I	inorganic components
dry	dry peat
wet	wet peat
ash	ash layer
g	gas
ref	reference
c	combustion
d	drying
N	north boundary
S	south boundary
$cond$	heat conduction

Similar experimental research revealed that the moisture content of a 50% probability of self-sustained smoldering for root mat soil and muck soil is 93% and 201%, respectively [9]. Garlough et al. found that the moisture content threshold for smoldering combustion of ponderosa pine duff mounds are 57% and 102%, respectively for upper and lower duff, and bulk density is not a significant factor in either ignition or percentage combustion for the conditions examined [8]. The critical moisture content for boreal peat from Scotland peat smoldering was 125 ± 10%. [6]. Most of these experimental studies found that the moisture content is the most important factor for self-sustained smoldering, while the mineral content and organic bulk density also influence smoldering combustion processes.

The heat of smoldering combustion (HSC) is a characteristic of the process and the material, also important for sustainable limit of organic soil smoldering, which has received very little attention in the literature. Smoldering of organic soil can be self-sustained only if the heat source from combustion can overcome the heat sinks for moisture evaporation, soil pre-heating and heat losses. Heat source is related to HSC and combustion rate of organic soil, while heat sink is related to the moisture content, mineral content and bulk density. Recently, a thermodynamic fuel consumption model based on energy balance during smoldering combustion of organic soil indicates that HSC is crucial in predicting the burning depth of thick organic soil [15]. HSC is thought to be also important for self-sustained smoldering in organic soil.

These previous experimental studies have promoted the understanding on the controlling factors of self-sustained smoldering of organic soils; however, the results have not been captured in a combustion model yet. The objective of this paper is to propose a smoldering model valid for peat moss, a surrogate of organic soils. Based on this model, the characteristics of organic soil smoldering and the factors affecting self-sustained smoldering will be investigated.

2. Smoldering mechanisms

In the downward propagation of smoldering in a soil column, the rate of smoldering is typically controlled by oxygen transport and heat losses [1], as shown in Fig. 1. Smoldering combustion moves downwards to the original peat moss, leaving ash layer above. Oxygen is transferred through the ash layer to the reaction zone and the generated gases leave the reaction zone through ash layer. For simplicity, the reaction zone is assumed infinite-thinly, compared to the width and height of the column. At the front, peat moss and oxygen react to release heat and produce ash and gases. The drying process is also assumed to take place in an infinite-thin drying front. As smoldering reaction progresses, the reaction and drying fronts move downwards. The reaction front is appropriate in this configuration. For example, Aldushin et al. studied smoldering combustion in a porous medium subject to gravity-induced buoyant forces [16]. In their study, a vertical sample, open to flow at the top and bottom, is ignited at the top. This configuration is similar to the peat smoldering scenario in the present model. Aldushin et al. stated that "the reaction zone is assumed to be thin, so that the narrow reaction zone, or front approximation, is valid". The reaction front assumption is also found in many other smoldering scenarios [17–19].

In the experimental studies on ignition limit of organic soil, the smoldering is usually initiated by strong external heating sources, such as electrical heat coils [6,7,9], radiant panels [15] or electrical coils plus a slice layer of dry peat [8,14]. When the external heating source is removed, a thin ash layer has formed and the temperature of sample near the igniter also rises. At the same time, the smoldering and drying fronts are established, which will then move downwards for self-sustained smoldering combustion. Fig. 1 illustrates the process after the ignition heat source is removed. At the initial state, shown in Fig. 1(A), the sample is composed of a thin ash layer on top and exposed to the open atmosphere, a dry peat layer under it, and a thick wet peat layer down to the bottom. Reaction front spreads downwards and is located between the ash layer and dry peat layer, while the drying front is between the dry peat layer and wet peat layer. The initial temperature profile after ignition is shown is Fig. 1(B). It is assumed that the temperature increases from the free surface temperature T_{s0} to initial reaction front temperature T_{c0}, then decreases to drying temperature T_w in dry peat layer and continues decreasing to ambient temperature T_0 in some depth of wet peat layer.

When smoldering combustion continues, the ash layer at the top becomes thicker and the height of the sample shrinks as shown

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