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Carbon Emissions from Smouldering Peat in Shallow and Strong Fronts

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ABSTRACT

A series of experiments of shallow and strong smouldering fronts in boreal peat have been conducted under laboratory conditions to study the CO and CO₂ emissions. Peat samples of 100 mm by 100 mm in cross section and 50 mm in depth were smouldered in the cone calorimeter apparatus. Two laboratory variables, moisture content and the external heat flux are varied over a wide range of values to establish different burning rates and front thicknesses. This provides a novel framework to study smouldering dynamics by varying the controlling mechanisms and providing burning conditions that otherwise cannot be obtained. Measurements of the burning rate and gas flow, yield and ratio for CO and CO₂ are reported at steady state burning conditions. Average mass flow rates per area of smouldering front are reported here for the first time to be $0.27 \pm 0.09 \text{ g s}^{-1} \text{ m}^{-2}$ for CO and $0.65 \pm 0.24 \text{ g s}^{-1} \text{ m}^{-2}$ for CO₂. This CO₂ mass flux is about 3,000 times larger than the natural decomposition flux from peatlands. The CO yield in dry base is $17 \pm 3\% \text{ g g}^{-1}$ and the CO₂ yield $42 \pm 13\% \text{ g g}^{-1}$. The CO and CO₂ total yield is of $59 \pm 15\% \text{ g g}^{-1}$, and the CO to CO₂ ratio was measured on average 0.43 ± 0.12 . The results indicate that peat with high moisture content smoulders producing larger CO₂ yield but the same CO yield compared to dryer peat. This suggests that smouldering of biomass at lower moisture contents develops wider pyrolysis fronts that release a larger fraction of other carbon-containing gas species.

Keywords: biomass burning; carbon monoxide; carbon dioxide; emission factor; smouldering

I. INTRODUCTION

Smouldering fires can consume more than half of the biomass burned during temperate, boreal and tropical wildfires [1, 2]. Thus, it contributes significantly to atmospheric emissions from wildfires.

Smouldering is a flameless form of combustion, deriving its heat from heterogeneous reactions occurring on the surface of a solid fuel when heated in the presence of oxygen [3]. The fundamental difference between

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smouldering and flaming combustion is that in smouldering, oxidation of the reactant species occurs on the surface of the solid rather than in the gas phase. The characteristic temperature, spread rate and heat released during smouldering are low compared to those in the flaming combustion of a solid. Smouldering fires in forest biomass propagate on average at around of $10\text{-}30\text{ mm}\cdot\text{h}^{-1}$ and the peak temperature is around $550\text{-}650\text{ }^{\circ}\text{C}$ [4].

Smouldering fires of peatlands and other organic-soil systems represent a large perturbation of the global atmospheric chemistry. When active, the burning of ground and subsurface biomass layers can last for long periods of time and emit large quantities of combustion products causing the deterioration of the air quality [5, 6]. Such fires are difficult to extinguish despite extensive rains or firefighting attempts. The fire removes layers of soil and the prolonged heating kills roots, seeds and plant stems. By propagating in the subsurface, it offers the means for flaming combustion to re-establish during wildfires in unexpected locations (*e.g.* across a fire break) and at unexpected times (*e.g.* long after burn out of the flame front). The ignition, depth, duration, and extent of smouldering fires are governed primarily by the diffusion of heat and oxygen through the porous fuel layers from/to the propagation front [7, 3]. The peat properties affecting these two mechanisms are in turn, the moisture and inert contents, botanical composition, bulk density, matrix permeability, and the presence of cracks and deep channels.

Peat is an accumulation of partially decayed vegetation matter. Peatlands are the most widespread of all wetland types in the world. They cover over $4\cdot 10^6\text{ km}^2$ (3% of the Earth's land surface). They are important ecosystems for a wide range of wildlife habitats supporting biological diversity, hydrological integrity and carbon storage. These ecosystems hold one third of the world's soil carbon and 10% of global freshwater resources. Their total carbon pool exceeds that of the world's forests and is comparable to that of the atmosphere [8].

Peatlands play an important role in the global carbon balance and recent environmental changes, such as climate change and human activities including drainage, peat harvesting and air pollution have raised questions regarding the long term stability of these carbon sinks. After the 2002 study of the Borneo episodes [5], smouldering biomass fires have started to be seen as an emerging threat, posing a global risk with social, economic and environmental consequences in both the short and the long terms.

The largest peat fires registered to date took place in Indonesia during the *El Niño* dry season of 1997 (previously occurred in 1982, 1991 and 1994, and later repeated in 1998, 2002, 2004 and 2006) and lasted for several months and destroyed over 10^4 km^2 of peat swamp with a loss of peat layers between 0.2 and 1.5 m deep. According to Page *et al.* [5] the peat fires accounted for 20% of the total burn area but produced 94% of total emissions. The smoky haze covered large parts of South East Asia for weeks, disrupting shipping and aviation and causing very large economic losses, long term damage to the environment and health care problems. It has been estimated that the 1997 fires released between 0.8 to 2.6 Gton of carbon emissions into the atmosphere, equivalent to 13-40% of the global fossil fuel emissions of that year [5].

Research in smouldering fires is at present modest and little is known [9, 5, 10, 4]. More experimental and theoretical studies are needed, especially to explore the issues of ignition, propagation dynamics, emissions and extinction mechanisms. The aim of this paper is to examine the carbon emissions from smouldering peat.

2. EMISSIONS AND STRUCTURE OF THE SMOULDERING FRONT

Biomass smouldering fires can burn in shallow or deep fronts [10]. Each has different dynamics. Shallow fronts, the objective of this study, burn near the free surface and are open to the atmosphere, thus having large supplies

of oxygen available but being exposed to convective heat losses. Deep subsurface fires burn many meters below the ground, and thus have a limited supply of oxygen but are insulated from heat losses to the atmosphere.

Shallow smouldering fronts in the organic layers of the ground propagate laterally and downwards. The front structure is similar to that of the forward-smouldering configuration, where the drying and the pyrolysis fronts move ahead of the oxidization front where the heat is released. When the top surface of the fuel is exposed to ambient air and an imposed heat flux, heat and oxygen have to diffuse to the lower layers which remain colder and in oxygen-poor atmospheres below a depth of a few centimeters. The structure of a smouldering front is formed of four different sub-fronts. The spread rates, widths and overlapping of these sub-fronts depend on the particular thermal and chemical conditions. This structure for a shallow front propagating downward through porous biomass and its general evolution in time is illustrated in Figure 1. It is composed of the following sub-fronts:

- Preheating of the undisturbed peat: heat from the upper layer is conducted downwards preheating the peat up to temperatures where water evaporation takes place. This front does not emit gases in any significant quantity.
- Evaporation: this endothermic reaction occurs within a range of temperatures around 100 °C, emitting water vapour. In this front the mass loss depends on the moisture content (*e.g.* 50% of the total weight for a moisture of 100% in dry base).
- Pyrolysis: at temperatures of above 200 °C [11] and in the absence of oxygen, pyrolysis of peat dominates the mass loss. Subsequent heating above this temperature increases the pyrolysis rate. Carbonaceous char is formed as a product. In this front the mass loss of peat ranges from 5-10% of the dry mass [11] and emits volatile organic species (*e.g.* CH₄, C₃H₈, CH₃OH), polyaromatic hydrocarbons, trace levels of CO and CO₂, and water vapour.
- Oxidation: this front is at the top of the sample and the closest to the atmospheric air. It involves the exothermic oxidation of the dry organic content left by the pyrolysis front. Peat oxidation, as seen in thermogravimetric analysis at low heating rates [11], occurs at temperatures over 350 °C but the actual temperature range would be lower for the higher heating rates expected in biomass smouldering. The oxidation reaction is the main source of CO and CO₂, and produces a fine layer of ashes (the mineral content). CO₂ is formed where the oxygen supply is large (*i.e.* closer to the top free surface) and CO where it is small (*i.e.* deeper into the sample layers). Most of the organic content in the peat will be lost in this front, ranging between 50 to 70% in dry base [12, 11] depending on the composition. This front could overlap with the pyrolysis front depending on the oxygen availability.

The combustion reaction in smouldering is characteristically incomplete. It emits partially combusted gases at a higher yield than flaming fires, *e.g.* volatile organic compounds, CO and polyaromatic hydrocarbons. The field studies by Bertschi *et al.* [1] of natural biomass fires in the tropical savanna show that the smouldering phase releases on average 130% more CO and 670% more hydrocarbons, but 15% less CO₂ and no NO_x compared to the flaming phase.

Field studies can provide atmospheric gas concentrations during real fire, but laboratory studies are required to measure the emission factors and capture their dependence on different burning conditions. These emission factors are essential input data to models of pollution transport in atmospheric chemistry simulations (*e.g.* [13]).

The available literature on emissions from smouldering peat is scarce. Muraleedharan *et al.* [14] reports the emissions from the heating of two small samples of around 50 mg in sealed beakers. Christian *et al.* [15] reports the average emission from a single block of peat 25 cm in size that smouldered in open air. Both studies measured that 95-96% of the total gas emissions are CO₂ and CO species (when excluding water vapour). Other species present with yields above 1% are CH₄ and C₃H₈ in one study [14], and CH₄ and NH₃ in the other [15]. A review of these results is provided in section 5 as a comparison to the results reported in this paper.

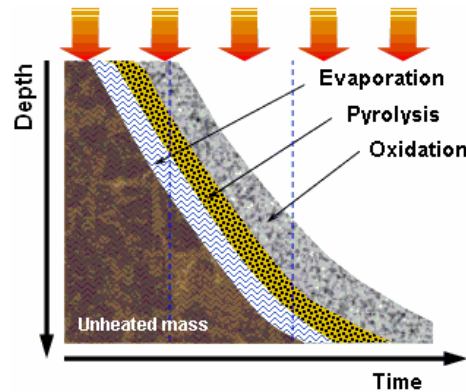


Figure 1: Depth vs. time sketch of a downward smouldering front showing the evolution of the front structure. Vertical lines marked the beginning and end of the steady-state regime

3. EXPERIMENTS

The transient evolution of CO and CO₂ emissions during the smouldering combustion of peat samples has been measured experimentally using the cone calorimeter apparatus [16]. The fuel sample is radiated at the top exposed surface (configuration similar to that in Figure 1). The mass loss rate is measured and the exhaust gases are analyzed for mass flow and composition.

The cone calorimeter is an apparatus commonly used in fire engineering to study the burning behaviour of condensed fuels [16]. It is used here to study smouldering combustion of biomass. It allows a shallow and horizontal smouldering front to propagate downwards through a sample several centimeters thick. The test procedure is carried out in accordance of the ISO 5660, which outlines the standard operating procedures and practices, but without using the sparking ignition device since flaming combustion is not of interest here. The top surface of the sample is exposed to a uniform radiant heat flux large enough to ignite a smouldering reaction and establish stable propagating-fronts. In this study, the external heat flux ranged from 30 to 70 kW·m⁻². The mass loss of the sample is measured with a balance. The released gases are channeled towards the exhaust tube where volumetric flow rate is measured by a Pitot tube. The CO and CO₂ concentrations are measured using an infra red system.

Natural peat fires ignite and self-propagate only at moisture contents below the critical value. The critical moisture for the boreal peat of these experiments is 125% in dry base [4]. Depending on composition and thermal properties, the critical moisture for different peat is in the range 100 to 130% in dry base [9]. With the relative high external heat flux used in these experiments, a strong smouldering front is initiated on the top of each sample and maintained during the experiments, even for samples with high moisture contents. The external heat flux enhances the spread rate and widens the burning conditions, assisting the propagation of the drying,

pyrolysis and oxidation fronts. Burning at high moisture contents with strong external heat fluxes is not observed in natural fires but provides a novel framework to understand the reaction dynamics. The combination of different moisture contents and heat fluxes results in variations of the controlling mechanisms and allows the establishment of stable smouldering fronts in a range of burning rates and front thicknesses that cannot be obtained otherwise in small-scale samples. Moreover, small-scale experiments of smouldering propagation with no external heat flux are significantly influenced by the edge effects. The effect of the size of the samples is always a concern in small-scale experiments because smouldering is controlled by heat losses (together with supply of oxygen [3]) and thus the presence of the walls affects the propagation. A strong external heat flux provides uniform heating and overcomes the effect of heat losses.

The moisture content of the peat samples is determined by taking a small sub-sample and calculating the content in dry base ϕ_w using Equation (1).

$$\phi_w = \frac{m_o - m_d}{m_d} \quad (1)$$

Where the mass of the sub-sample, m_o , is recorded and then placed in an oven at 80 °C, then removed 48 h and weighed again, providing the dry mass, m_d . All moisture values in this paper are expressed as % of the dry mass, which results in most values greater than 100%.

The boreal peat used, collected from Edinburgh, Scotland, was old, moderately decomposed, and of herbaceous composition. The measured bulk density of the dry mass was 430 kg·m⁻³ and the mineral content was 8 ±2% in dry base [4]. After being dug from layers 0.1 to 0.5 m deep, the blocks were stored indoors and left to dry naturally during the course of the study. Experiments were performed over a period of several months. During this time, the samples dried considerably giving the desired wide range of moisture contents, from 600% initially to 80% at the end. They were turned regularly to induce homogenization. The sample size for the tests was 100 mm by 100 mm in cross section and 50 mm in depth (typical dimensions for the cone calorimeter's samples). Because the size of the samples is fixed, the wide range of moisture content tested resulted in samples with different initial mass between 250 and 500 g and bulk densities between 500 and 1000 kg·m⁻³. When cutting samples from the blocks, care was taken to ensure that they were of homogenous moisture and structure. The sides and bottom of the cut sample are wrapped in foil so that during the experiment only the top surface is exposed to ambient oxygen.

Efforts were made in the preparation protocol to keep the sample size, packing conditions and homogeneity invariable for all tests. However any peat sample has an inherent inhomogeneity in composition, cracks and gas permeability that induces scatter in the measurements. The identified and quantified sources of experimental uncertainties are: the radiant heater heat flux ±5% (calibrated); load cell ±2% (calibrated); moisture content ±5% (measured); sample surface area and cracks ±10% (estimated); bulk density ±3% (estimated); and steady-state mass flow values ±5-15% (measured). These errors are combined for each measurement, resulting on average in a total uncertainty of ±18-31% for CO₂ mass flow; ±17-30% for CO mass flow rate; and ±17.6% for the mass burning rate.

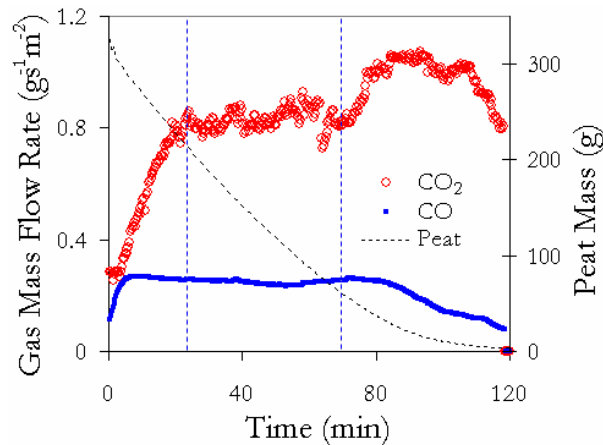


Figure 2. Example of measured burning rate and CO and CO₂ flows during a cone calorimeter test (sample moisture content of 260 % and heat flux of 50 kW·m⁻²). Vertical lines marked the beginning and end of the steady-state regime

Figure 2 shows the evolution of the burning rate and the CO and CO₂ mass flows during a particular experiment. They can be used to illustrate a general time history of the process showing three different regimes. All experiments show similar evolution and equivalent time scales. The external heat flux is turned on at time zero and very rapidly (less than 1 min) CO and CO₂ are being produced at significant quantities, thus indicating that a smouldering front is ignited on the top surface of the sample. The smouldering front, assisted by the radiant heat flux, propagates downwards through the peat. The gas mass flows show an initial transient response (first regime) of 7 min for the CO and of 21 min for the CO₂, after which the front is fully developed and steady-state conditions are reached (second regime). During the pseudo steady-state regime, lasting 55 min in the experiment in Figure 2, approximate constant values are maintained with some degree of fluctuations. The third phase is reached when the thermal front approaches the end of the sample 75 min after ignition and is characterized by the influence of the lower boundary. The smouldering goes through a decay of the burning rate, the CO yield decreases and the CO₂ yield increases. The decay lasts for about 45 min for the presented experiment.

It is deemed that the steady-state regime reached in these experiments is more representative of free propagation in field conditions (not influenced by the boundaries and scale effects). Thus, the analysis of the experimental results focuses on the values reached during the steady-state. Note that most values reported in the literature are for average emission over the entire test, and thus take into account the initial and decay transient responses which are influenced by the boundaries and depend on the size of the sample.

4. RESULTS & DISCUSSION

Changes in the burning dynamics imposed by the different moisture contents and the external heat fluxes have an impact on the gas emissions. The different emissions resulting from these dynamics are investigated in these experiments.

Figure 3a shows the steady-state mass flow rates of CO and CO₂ vs. moisture content for all the heat fluxes tested. The trend has a negative gradient showing that the higher the moisture content, the lower the mass flow

of carbon emissions. Figure 3b shows the flow rates vs. heat flux for the samples with moisture between 350 and 550%². The trend has positive gradient with the heat flux. Based on all the experiments, the average and standard deviation of all measurements for the emission rate of CO is $\dot{m}_{g,CO}'' = 0.27 \pm 0.09 \text{ gs}^{-1} \text{ m}^{-2}$ of smouldering front, and for CO₂ is $\dot{m}_{g,CO_2}'' = 0.65 \pm 0.24 \text{ gs}^{-1} \text{ m}^{-2}$.

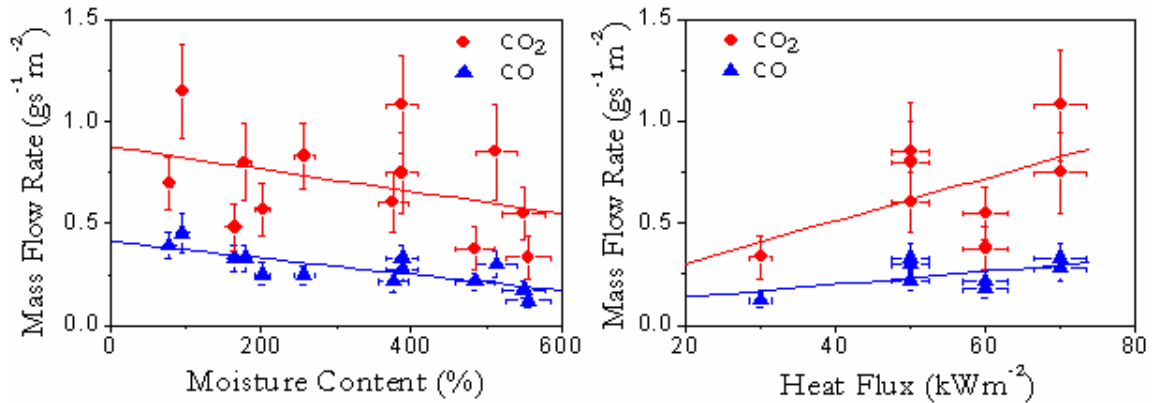


Figure 3: Measured CO and CO₂ mass flow rates at steady-state; a) vs. moisture content; and b) vs. heat flux for moisture content in the range 350 to 550%.

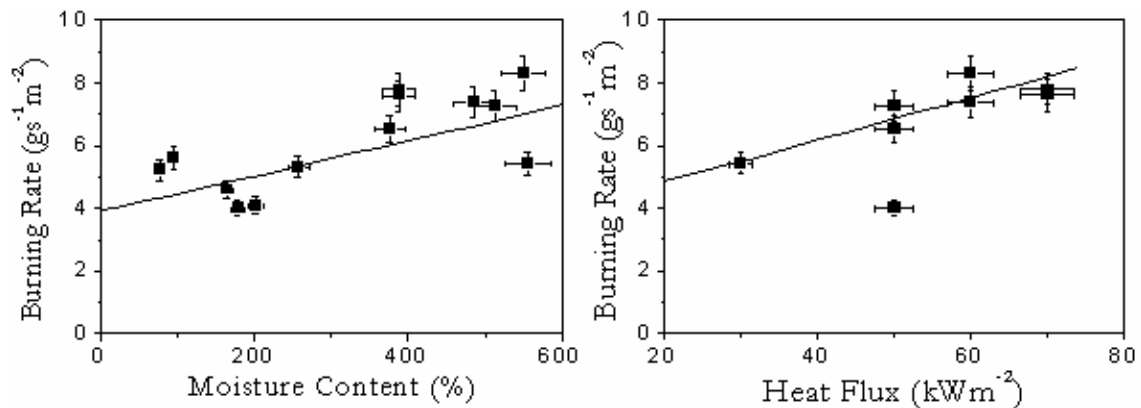


Figure 4: Measured steady-state burning rate of peat; a) vs. moisture content; and b) vs. heat flux for moisture content in the range 350 to 550 %.

The burning rate \dot{m}_b'' (*i.e.* mass loss rate) of peat is an important variable needed to characterize the combustion regime and explain the emissions rate. Figure 4a shows the steady-state peat mass loss vs. moisture content for all the heat fluxes tested. The trend has a positive gradient showing that the higher the moisture content, the higher the mass loss. This can be explained by the larger mass of water that is lost by evaporation as the front progresses. Figure 4b shows the mass loss vs. heat flux for the samples with moisture contents between 350 and 550%. The trend has a strong correlation with positive gradient showing that the higher the heat flux, the higher the mass loss rate. This seems obvious since the larger the heat flux on the sample the larger the water

² Figure 3a includes all experiments but 3b shows only the results from a selected range of moistures only to show the weaker dependence on heat flux

evaporation, pyrolysis and oxidation rates. Based on all the experiments, the average and standard deviation of all measurements for the burning rate $\dot{m}_b'' = 6.1 \pm 1.4 \text{ g s}^{-1} \text{ per m}^2$ of smouldering front.

Peat can embed very large quantities of water resulting in moisture contents in excess of 600% in dry base (85% of the total weight is water). When referring to the combustion yield of species i γ_i , it is important to define it as a function of the dry mass containing the organic fraction and not the total weight that includes the water. Here, the yield is expressed in mass released per mass loss of peat (*i.e.* % g g^{-1}), also called emission factor in atmospheric sciences [13]. It is calculated using Equation (2).

$$\gamma_i = \frac{\dot{m}_{g,i}''}{\left(\frac{\dot{m}_b''}{\varphi_w + 1} \right)} \quad (2)$$

Where $\dot{m}_{g,i}''$ is the measurement of the species mass flow rate, \dot{m}_b'' the peat burning rate and φ_w the moisture content in dry base.

Factoring in all the experiments, the average and standard deviations for γ_{CO} is $17 \pm 3.3\% \text{ g g}^{-1}$, and for γ_{CO_2} is $42 \pm 13.4\% \text{ g g}^{-1}$. Figure 5a shows the steady-state CO and CO₂ yields vs. moisture contents for all the heat fluxes tested. The trend for γ_{CO} shows that it is independent of the moisture content. For γ_{CO_2} , the trend has a small but positive gradient indicating that for higher moistures, the CO₂ yield is larger. The observation that γ_{CO_2} increases slightly with moisture whereas γ_{CO} remains constant indicates that as water content increases, the burning condition are such that more carbon content of the peat is being oxidized into CO₂. A possible explanation for this is presented at the end of the section. Figure 5b shows the yields vs. heat flux for the samples with moisture content between 350 and 550%. The near zero gradient of the trendline implies that the yields of CO and CO₂ are independent of the heat flux within a narrow range of moisture contents. This observation is also supported by the data in Figure 5a, where samples with similar moisture contents but different heat fluxes are adjacent to each other. Summing the two yields, the average and standard deviation for the yield of total CO and CO₂ emissions is $59 \pm 15.8\% \text{ g g}^{-1}$.

These values can be compared with the only data available in the literature. Muraleedharan *et al.* [14] reported γ_{CO} between 3-7.5% g g^{-1} , and γ_{CO_2} between 30-36% g g^{-1} , providing a total CO and CO₂ emission in the range 33-43% g g^{-1} . The experiments of Muraleedharan *et al.* did not reproduce smouldering conditions but study general thermooxidative emissions from heated peat in sealed beakers. This explains the consistently lower yields reported in [14]. Christian *et al.*³ [15] reported a γ_{CO} of 9.5% g g^{-1} , and a γ_{CO_2} of 77% g g^{-1} and a total CO and CO₂ of 87% g g^{-1} .

³ After correcting their values for the mineral content and mass conservation

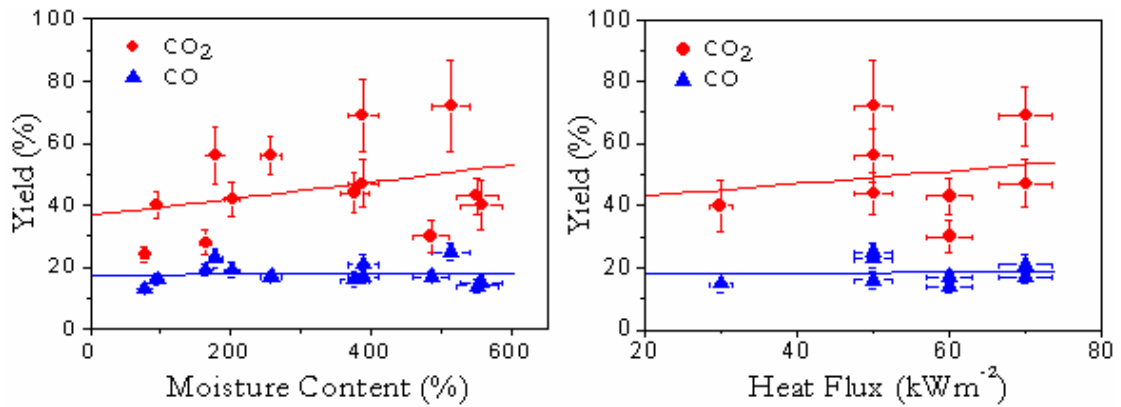


Figure 5: Measured CO and CO₂ steady-state yields in dry base; a) vs. moisture content; and b) vs. heat flux for moisture contents in the range 350 to 550%.

Figure 6a shows the CO to CO₂ ratio with varying moisture contents. The ratio is between 0.3 and 0.7, with average 0.43 and standard deviation 0.12. The trend is a decrease of the ratio with higher moisture content. Figure 6b shows the CO to CO₂ ratio dependence with heat flux, the trend line has a near zero gradient showing that there is weak dependence. Comparing with the values for tropical peat, the ratio is reported between 0.1 and 0.2 [14], or 0.12 [15].

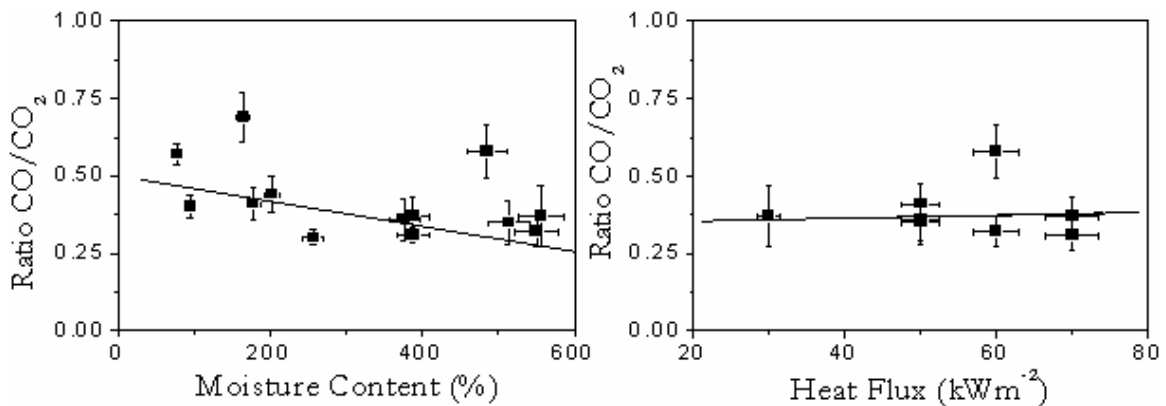


Figure 6: Measured CO/CO₂ ratio, a) vs. moisture content; and b) vs. heat flux for moisture contents in the range 350 to 550 %.

The trend of the CO/CO₂ ratio, together with the increasing CO₂ yield with moisture content observed in Figure 5, could be explained in terms of the smouldering dynamics. Biomass with lower moisture contents results in higher rates of heat transfer from the burning front to deeper layers of the soil. But oxygen diffusion from the free surface into the deeper soil is independent of moisture. Therefore, as the moisture content decreases, the thickness of the thermal front increases but the oxidation front thickness stays constant. Thus, lower moistures content could lead to wider pyrolysis fronts, allowing a larger fraction of the organic content at deeper layers to be released without being oxidized. This mechanism explains the observed results and would imply that deeper smouldering fronts produce more gas species typical of pyrolysis decomposition, e.g. volatile organic compounds and polyaromatic hydrocarbons.

5. CONCLUSION AND FINAL REMARKS

Measurements of the carbon emissions from shallow and strong smouldering fronts in boreal peat have been conducted. Flow rates from the two most important carbon gases, CO and CO₂, have been measured under a wide range of smouldering burning rates and front thicknesses resulting from different moisture contents and external heat fluxes. Burning at high moisture contents with strong external heat fluxes is not observed in natural fires but provides a novel framework to understand the smouldering dynamics by varying the controlling mechanisms.

Smouldering peat was found to release large flows of carbon gases, with average mass flow rates per m² of front of 0.27 ± 0.09 for CO and 0.65 ± 0.24 g·s⁻¹ for CO₂. This CO₂ mass flux is equivalent to approximately 3,000 times the normal flux from peatlands due to natural decomposition at ambient conditions (0.31 g·h⁻¹·m⁻² for sphagnum peat [17]). On average, the measured CO yield in dry base is $17 \pm 3.3\%$ g·g⁻¹, and the CO₂ yield $42 \pm 13.4\%$ g·g⁻¹. The total CO and CO₂ carbon yield is of $59 \pm 15.8\%$ g·g⁻¹, and the CO to CO₂ ratio was measured in the range between 0.3 and 0.6, with average and standard deviation of 0.43 ± 0.12 .

The experiments have been designed to minimize the scale effect by the use of the external heat flux and reporting measurements in the steady-state regime. The measurements under a wide range of burning conditions can be extrapolated to shallow natural fires. Extrapolation of the burning rates to the condition of no-external heat-flux (unaided smouldering) gives a peat mass loss rate of 4.5 g·s⁻¹·per m² of smouldering front. Extrapolation of emissions to the range of moistures were natural peat fire take place (50 to 130% in dry base) give flow rates of 0.4 g·s⁻¹·m⁻² of CO, 0.9 g·s⁻¹·m⁻² of CO₂; CO yield of 14% g·g⁻¹, CO₂ yield of 32% g·g⁻¹, and a CO/CO₂ ratio of 0.45. This is the first time that emission mass flows per unit area of smouldering front are reported.

The observed trends of the mass flow rates are explained well by the burning rate and the dynamics of the smouldering front. Whereas the external heat flux does not affect the emission yields, the moisture content affects the yield and the structure of the front. The results indicate that peat at low moisture smoulders with wider pyrolysis front, releasing a larger fraction of non-fully oxidised volatile carbon-containing species. This allows concluding that narrow burning fronts favor lower CO/CO₂ ratios and wider fronts favor larger ratios.

Based on these results, it is expected that in deep smouldering fires, where the lower oxygen availability and heat losses result in wider thermal fronts, the ratio CO/CO₂ will be larger than for shallow fires burning close to the free surface. However, the findings of this study pertain to shallow burning fronts, and behaviour at other conditions and configurations typical of smouldering fires, especially fire fronts propagating many meters deep into the subsurface, need to be investigated further.

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