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Forest floor chemical transformations in a boreal forest fire and their correlations with temperature and heating duration

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ABSTRACT

Boreal soils account for ~30% of the global soil organic carbon (C) stock. Wildfires are an important perturbation of this C pool, particularly affecting the top organic soil layer, which constitutes the forest floor. Alterations to the forest floor by fire are relevant to the soil C balance and have profound implications for soil properties. However, relationships between forest floor transformations and actual wildfire characteristics have not been established to date due to the logistical challenges of obtaining the necessary fire behaviour data, together with associated pre- and post-fire sample material. We used a high-intensity experimental wildfire to address this research gap, which enabled us to determine forest floor chemical transformations in a Canadian boreal forest in relation to temperature–time profiles for 18 sampling points during the fire. Forest floor samples taken pre- and post-fire were characterized using elemental and $\delta^{13}C$ analysis, differential scanning calorimetry and ^{13}C nuclear magnetic resonance.

During this typical boreal crown fire average maximum temperature (T_{max}) at the forest floor was 745 °C ($550 < T_{max} < 976$ °C) with the average heating duration (t) >300 °C being 176 s (65 < t < 364 s). Significant correlations were detected between the chemical characteristics of the pyrogenic (charred) forest floor layer and the temperature–time profiles at the corresponding sampling points. Higher T_{max} and associated prolonged heating durations correlated with greater C enrichments, increased thermal recalcitrance and degree of aromaticity of the pyrogenic organic matter. These changes were particularly pronounced for T_{max} > 600–700 °C, which is higher than the range of 300–500 °C for aromaticity development previously reported from laboratory experiments. One reason for this discrepancy could be the generally much longer heating durations used in laboratory studies, and we therefore advise caution when extrapolating findings from laboratory studies to wildfire conditions.

Almost half of the initial total C stock in the forest floor (20 Mg C ha^{-1}) was affected by fire, with ~24% of this fire-affected C transformed to pyrogenic organic matter. This pyrogenic material possessed variable, yet distinct, chemical characteristics when compared to unburnt forest floor, including higher recalcitrance and associated resistance to biological degradation. As some boreal regions already show a rise in fire severity and area burned linked to climate change, our findings suggest a potential accompanying increase in the more stable organic carbon stock, with important implications for the functioning and turnover of organic matter in boreal soils.

1. Introduction

Fire is one of the most frequent and recurrent perturbations in a wide range of environments, with profound effects on ecosystem properties and functions including the carbon (C) cycle (Reichstein et al., 2013). Fire not only alters C stocks by releasing C stored in the dead and living vegetation to the atmosphere, but also changes the quantity and composition of the soil organic matter (SOM) pool. In the boreal region, fire is one of the dominant drivers of the C balance (Bond-Lamberty et al., 2007), with, on average, over 12 Mha burnt annually and associated emissions of ~208 Tg C $year^{-1}$ (period 2001–2010, Randerson et al., 2012). In recent decades, boreal ecosystems have undergone profound changes in response to climatic change, including an increase in wildfire activity (Kelly et al., 2013). This upward trend is expected to be further enhanced by the end of this century (Flannigan et al., 2013; Héon et al., 2014). In boreal regions, the top organic soil layer, the forest floor, is the fuel component most affected by fire, accounting for up to 85% of the total fuel burnt (Amiro et al., 2001; de Groot et al., 2009). Given that around 30% of the global soil organic C stock is held in the boreal regions (Scharlemann et al., 2014), a full understanding of fire effects on boreal soils is of global importance. However, the relationships between fire characteristics and alterations of the soil organic C stock in the boreal ecosystems,

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and beyond, are still not well understood (Kane et al., 2010; Turetsky et al., 2011).

Alterations of the quantity and composition of SOM by fire are many and very diverse (González-Pérez et al., 2004). They are not only relevant to the C budget but also affect many ecosystem properties and functions, such as microbial dynamics, nutrient cycles and vegetation succession (Holden et al., 2015; Schmidt et al., 2011; Turetsky et al., 2011). Quantitatively, fire can lead to a substantial depletion of the SOM stock by, for example, combustion of organic horizons (Kane et al., 2007) or loss of mineral soil by enhanced post-fire erosion (Pingree et al., 2012), but it can also result in an increase of SOM content by incorporation of dead and charred biomass from vegetation and litter (Santín et al., 2008). Fire effects on SOM composition range from negligible to the loss of labile components and enrichment of pyrogenic recalcitrant forms (González-Pérez et al., 2004). An increase of labile compounds could also occur by inputs of dead, but uncharred, vegetation (Alexis et al., 2007).

In order to elucidate SOM transformations by fire, many studies have compared SOM quantity and characteristics of wildfire-affected soils with those of unburnt soils in similar areas, either soon (Mastrolonardo et al., 2014) or sometime after burning (Dymov and Gabov, 2015; Santín et al., 2008). This approach, however, leaves substantial uncertainties regarding actual fire characteristics and the representativeness of unburnt samples as substitutes for pre-fire soil conditions (Bormann et al., 2008). Prescribed fires (i.e. controlled burns for fuel management and/or ecological purposes) have also been used to examine the transformations of SOM, litter and vegetation by fire (Alexis et al., 2007, 2010), as the scheduling of the fire allows pre-fire and post-fire sampling and in-fire monitoring. Unfortunately, most prescribed fires are carried out at lower fire intensities and higher fuel moisture contents than is typical for wildfires, and/or at sites with modified fuel conditions, and are, therefore, not fully representative of wildfire conditions (Santín et al., 2015a). Other studies have explored relationships between transformations of organic matter and inferred soil burn severity as a proxy for fire conditions (e.g. Merino et al., 2014, 2015; Vega et al., 2013). None of these approaches, however, allows direct characterization of the relationships between actual fire parameters (i.e. temperature, heating duration, oxygen availability) and SOM transformations.

The current understanding of the relationships between fire parameters and SOM changes is largely based on laboratory experiments (e.g. Badía-Villas et al., 2014; Verdes and Salgado, 2011), which are not necessarily representative of field conditions, due to, for example, different heating durations and oxygen availability (Alexis et al., 2010; Atanassova and Doerr, 2010; Spokas, 2010). To date, the relationships between SOM transformations and specific fire parameters have not been directly examined in a wildfire context. This study addresses this research gap by utilizing a high-intensity experimental boreal forest fire to elucidate specific relationships between transformations of the organic top soil layer (the forest floor) and temperature–time profiles. Forest floor samples taken before and after fire were analysed by elemental and $\delta^{13}C$ analysis, differential scanning calorimetry (DSC) and ^{13}C nuclear magnetic resonance (NMR). Temperatures were continuously monitored during the fire at 18 sampling points using thermocouples placed at the forest floor surface and at the forest floor/mineral soil interface. Examining these relationships does not only help to understand real wildfire conditions and the processes occurring under these, but it can also provide insights into potential effects of the already increasing fire occurrence and severity in the boreal regions driven by the changing climate.

2. Material and methods

2.1. Study site and the FireSmart experimental forest fire

An experimental forest fire aimed at simulating wildfire conditions was conducted as part of the Canadian Boreal Community FireSmart Project at Fort Providence, Northwest Territories, Canada (61°34′55″N, 117°11′55″W). This boreal region has a dry, subhumid continental climate with low annual precipitation (300 mm) and a wildfire season lasting from May to September. The terrain is flat with an elevation of 160 m.a.s.l. (Alexander et al. 2004). The experimental plot (1.7 ha) was a mature stand of jack pine (*Pinus banksiana*) originating from a stand-replacing fire in 1931, with a tree density (live and dead) of 7600 stems ha^{-1} and average tree height of 14 m. The understorey was very sparse (<0.1 stems m^{-2}) with a few jack pine and black spruce (*Picea mariana*) saplings and shrubs. The soils in the experimental plot are stony sandy loams derived from fluvio-glacial deposits with a distinct organic surface layer, the forest floor (hereafter abbreviated as FF). This organic soil layer, the FF, had an average thickness of 6.5 cm and was composed of mosses, lichens, needles, fermented litter and humidified organic material (Santín et al., 2015b). In this study woody debris <0.5 cm diameter were also considered as part of the FF.

The fire was started at 16 h on 23 June 2012 with a line ignition initiated along the upwind east edge of the plot using a Terra torch (Fig. 1). The ambient temperature was 28 °C and relative humidity was 22% with winds of 10–12 km h^{-1}. The last rain (0.5 mm), occurred 6 days previously with a total precipitation over the preceding month of 4.3 mm (more information in Santín et al., 2015b).

2.2. Temperature monitoring and forest floor sampling

Before the fire, three parallel transects of 18 m length were established 7.5 m apart in the direction of the prevailing wind (E–W) (Fig. 1). These were instrumented at a spacing of 2 m with thermocouples connected to data loggers (Lascar, Easylog) that recorded temperatures at the FF surface and the FF/mineral soil interface every second (1 Hz) (Fig. 2a&b). In total, 27 points (9 per transect) were monitored. In our study area, the FF developed under jack pine does not present well differentiated layers and, for simplicity, was sampled as a single FF layer (Preston et al., 2006). The FF was sampled along two parallel lines between the three sampling transects with 20 × 20 cm sampling squares (n = 10). The total depth of the FF was measured at each corner of the 20 × 20 cm square and the entire layer was carefully collected. At the centre of these same points, samples of the underlying mineral soil were taken using a 5 × 5 cm soil corer (n = 10).

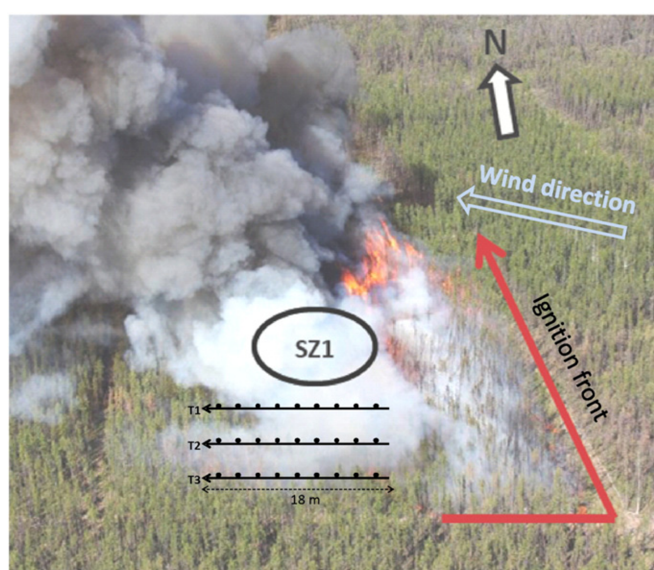

Fig. 1. Aerial view of the forest plot (shortly after ignition) burnt by the FireSmart experimental 'wildfire' (June 2012) with location of the sampling transects (T1-T3) and ignition front. The circle SZ1 is marking the location of a survival zone designed for fire-fighting safety research. Sample numbers were continuous starting at the East end of T1 (sample n.1) and finishing at the West end of T3 (sample n.27).