Science of the Total Environment 627 (2018) 622–632

Contents lists available at ScienceDirect

Science of the Total Environment

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

Inferring changes in soil organic matter in post-wildfire soil burn severity levels in a temperate climate

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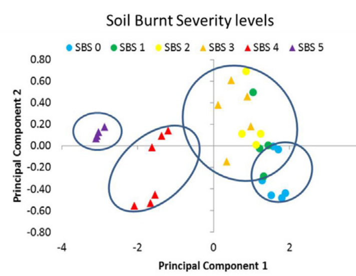
HIGHLIGHTS

- Calorimetry as a useful analysis for SOM with high spatial heterogeneity
- Relationship of OM changes with temperatures differ in organic and mineral soils.
- The different SBS are characterized by different SOM qualities.
- SBS and calorimetry as a strategy for planning soil rehabilitation tasks

GRAPHICAL ABSTRACT

Experimental burning of soil monoliths in a combustion wind tunnel to simulate different fire conditions and different Soil Burnt severities



Soil organic matter content and thermal recalcitrance (both measured by calorimetry) discriminated the Soil Burnt Severity levels.

ARTICLE INFO

Article history:
Received 13 September 2017
Received in revised form 17 January 2018
Accepted 19 January 2018
Available online xxxx

Editor: Charlotte Poschenrieder

Keywords:
Forest fire
Soil burn severity
SOM quality
Thermal analysis
^{13}C NMR spectroscopy

ABSTRACT

Simple, rapid and reliable methods of assessing soil burn severity (SBS) are required in order to prioritize post-fire emergency stabilization actions. SBS proxies based on visual identification and changes in soil organic matter (SOM) content and quality can be related to other soil properties in order to determine the extent to which soil is perturbed following fire. This task is addressed in the present study by an approach involving the use of differential scanning calorimetry-thermogravimetric analysis (DSC-TGA) to determine changes in SOM generated in soils subjected to different levels of SBS.

Intact topsoil monoliths comprising the organic horizons and the surface mineral soil (alumic-humic umbrisols) were collected from a representative *P. pinaster* stand in NW Spain. The monoliths were experimentally burned in a combustion wind tunnel to simulate different fire conditions (fuel bed comprising forest pine litter and wood; air flow, 0.6 m s^{-1}). Changes in OM properties in the soil organic layer and mineral soils samples (0–2 cm) at the different temperatures and SBS levels were identified.

For both duff and mineral soil, the data revealed a temperature-induced increase in aromatic compounds and a concomitant decrease of carbohydrates and alkyl products. However, for a given temperature, the degree of carbonization/aromatization was lower in the mineral soil than in the duff, possibly due to the different composition of the OM and to the different combustion conditions. The low degree of aromatization of the organic matter suggests that this soil component could undergo subsequent biological degradation. SOM content and thermal

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https://doi.org/10.1016/j.scitotenv.2018.01.189

recalcitrance (measured as T50) discriminated the SBS levels. Use of visual identification of SBS levels in combination with DSC-TGA enables rapid evaluation of the spatial variability of the effects of fire on SOM properties. This information is useful to predict soil degradation process and implement emergency soil stabilization techniques.

1. Introduction

Wildfire causes severe disturbance in many ecosystems worldwide (Scott et al., 2014, Belcher, 2013). Soil heating during wildfire alters various properties of the soil that determine its state of conservation, leading to e.g. increased erosion, sediment transfer to surface waters and nutrient depletion (Neary et al., 2005; Certini, 2005; Moody et al., 2013). The changes in soil organic matter (SOM) content and quality that occur during wildfire are particularly important because of the direct and indirect effects that they have on many important soil properties and also carbon cycling and balance (e.g. González-Pérez et al., 2004; Almendros and González-Vila, 2012; De la Rosa et al., 2012). Identification and prediction of the main changes associated with SOM can therefore provide a better understanding of the risks of soil degradation with a view to implementing effective post-fire mitigation measures.

Soil heating and fire conditions (i.e. maximum temperatures, type of combustion and duration, oxygen availability) are the main factors involved in the profound changes that can occur in soil properties as a result of wildfire (Santín et al., 2016; Keiluweit et al., 2010). Changes in key hydrological properties such as water repellency and aggregate stability have been identified in relation to fire severity (e.g. Doerr and Moody, 2004; Mataix-Solera et al., 2011) and attributed to thermo-induced alterations in SOM (Neris et al., 2013; Badía-Villas et al., 2014). These studies have revealed that the crucial processes determining the extent to which wildfire degrades soil involve changes in SOM composition rather than a decrease in SOM content. The main changes in SOM generally include loss of the most labile pools of organic matter (OM) (microbial C and carbohydrates C functional groups) and alkyl compounds, along with relative gains in aromatic compounds (pyrogenic carbon) (Knicker et al., 2008). Thus, the labile organic compounds in SOM play an important role in stabilizing soil aggregates (Gregorich et al., 1996; Kavdır et al., 2005), whereas changes in extractable lipids seem to be related to different types of alteration, such as changes in water repellency (Lozano et al., 2013). The wide variability in these degradative processes may explain the large differences in the erosion rates within a burnt area, corresponding to different levels of soil burn severity (Fernández and Vega, 2016a; Parsons et al., 2010).

The changes in the SOM may also involve the formation of pyrogenic organic compounds, which are more resistant to microbial decomposition than fresh plant material and can therefore act as an efficient C sink (e.g. Singh et al., 2014). However, the pyrogenic biomass contains different C forms, ranging from partly charred plant material to soot (Schmidt and Noack, 2000), in which the degree of carbonization depends on the heating conditions and the initial composition of the fuel (González-Pérez et al., 2004; Rumpel et al., 2007; Hilscher et al., 2009; Soucémarianadin et al., 2013; Merino et al., 2015). The composition/stability of the charred material determines the degree of biological mineralization and abiological degradation (Doerr et al., 2018) and may substantially alter the source-sink function of these ecosystems (Santín et al., 2016).

Studies examining the relationships between soil key variables and processes and temperature reached during combustion are very useful for identifying the main mechanisms of soil degradation during fire. However, development of a simple, comprehensive method of identifying the extent of the damage (soil burn severity) continues to be a challenge due to the complex, variable changes that take place in the soil. The resulting burnt area encompasses patches of land affected by different levels of fire severity and characterized by different soil properties and degradative processes. These areas require different conservation approaches (Vega et al., 2013a). However, there is an urgent need for an operational tool that can discriminate different levels of impact in burned areas, thus providing a solid basis for prioritizing post-fire mitigation treatments.

Measurement of soil temperature during wildfire is difficult for reasons related to safety and logistics. Additionally, thermologgers only record point-specific measurements that do not reflect the high degree of variability in temperature and combustion conditions found in a wildfire (Alexis et al., 2010; Santín et al., 2016). Use of a SBS index based on the visual recognition of changes in the organic and surface mineral soil has been proposed as a proxy for identifying the level of fire-induced soil perturbation (for reviews, see Neary et al., 2005; Jain et al., 2012; Keeley, 2009; Morgan et al., 2014). We have developed a classification index for characterizing the level of SBS in OM-rich soils in NW Spain (Vega et al., 2013a). The index has proved operationally useful for post-fire emergency stabilization tasks (Vega et al., 2013b), showing good relationships with post-fire alterations in relevant soil properties (Vega et al., 2013a; Merino et al., 2014, 2015) and erosion rates (Vega et al., 2014; Fernández and Vega, 2014; Vega et al., 2015; Fernández and Vega, 2016a, 2016b, 2016c). The index can be obtained within a short time, thus enabling identification of the most perturbed areas in which application of urgent conservation strategies are necessary (Regional Forest Service of Galicia, Spain).

Given the determining role of the changes in SOM composition in post-fire soil degradation processes and C balance, special attention should be paid to this aspect and to those changes related to the temperature reached during the fire and SBS. Analytical techniques such as SOM fractionation by chemical procedures, solid-state ^{13}C NMR spectrometry and pyrolysis–gas chromatography–mass spectrometry (Py–GC/MS) are used to characterize the structure and composition of SOM in burned soils (Almendros and González-Vila, 2012; De la Rosa et al., 2012). However, the decision-making process associated with emergency soil rehabilitation in burnt areas requires rapid assessment of the damage to SOM in a large number of samples to enable evaluation of the wide spatial heterogeneity of the burnt area. Hence, faster and simpler methods of thermal analysis such as differential scanning calorimetry (DSC) and themogravimetric analysis (TGA) could be used in preference to lengthy analytical procedures, such as those mentioned above. Thermal parameters obtained from thermal analysis have been found to be related to the degree of aromatization (NMR analysis)/carbonization (H/C and O/C ratios) of charred OM (Merino et al., 2014, 2015). In addition, several studies have shown that thermal stability may play an important role in microbial activity in the soil (Harvey et al., 2012; Leifeld and von Lützow, 2014; Siewert et al., 2012; Campo and Merino, 2016).

The above-mentioned studies have shown that SBS can be used to predict soil degradation process and therefore implement emergency stabilization techniques. The purpose of this study is to develop a methodology for evaluating the spatial changes in SOM properties which can be used to infer degradative processes and the post-fire resilience of the soil. The specific aims of the present study were i) to explore the use of thermal analysis for the rapid identification of SOM content and quality, and ii) to define the relationship between the degradation of SOM quality and the SBS level calculated using the index developed by Vega et al. (2013) for OM-rich soils. The findings obtained with this approach expands those of previous research in similar soils (Vega et al., 2013a; Merino et al., 2014, 2015; Campo and Merino, 2016) by simultaneously