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Influence of wildfire severity on soil physical degradation in two pine forest stands of NW Spain

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ABSTRACT

This study examined the effect of wildfire on the physical degradation of two forest soils in NW Spain and compared this against changes produced by controlled laboratory heating experiments in which unburned soils from neighbouring sites were exposed to five different heating regimes. The physical soil degradation was considered with respect to organic carbon content, dry aggregate size distribution, water aggregate stability, water repellency, and hydraulic conductivity. The results of this analysis show that the changes in the physical properties of the wildfire-affected soils were similar to the changes observed in the heating experiments. However, the wildfire had contrasting effects in terms of soil physical degradation at the two study sites, which can be attributed to differences in soil heating regimes and fire severity. At one study site, the wildfire did not produce marked changes in organic carbon content or in aggregation, except for a slight fragmentation of macro-aggregates into micro-aggregates. Also, soil water repellency remained very strong after the wildfire, resulting in low hydraulic conductivity. Based on the laboratory experiments, the soil at this site was not exposed to temperatures above 220 °C. The wildfire at the other study site resulted in more pronounced degradation of the soil, as shown in the reduction of organic carbon content by almost 50%, resulting in reduced stability of the aggregates. The wildfire also reduced soil water repellency considerably, but hydraulic conductivity did not increase noticeably. In this case the soil could be exposed to temperatures between 220 and 380 °C.

1. Introduction

Wildfires are one of the most important agents of hydrological and geomorphological disturbance in Mediterranean and semiarid ecosystems (Cerdà and Mataix-Solera, 2009; Shakesby and Doerr, 2006). The substantial increase in wildfire activity in recent decades in southern Europe has led to increases in fire related damage and landscape degradation (Ferreira et al., 2009; Shakesby, 2011). Although wildfire is a natural phenomenon, since the 1970s, the abandonment of agricultural lands and the increase in human population and activities have resulted in a dramatic increase in number and size of fires, and severe soil degradation due to increased fire frequency (Collins et al., 2013; Ferreira et al., 2009; Moreno et al., 2014; Tàbara et al., 2003).

Fire effects on soils in the Iberian Peninsula have been the focus of numerous studies, and various aspects of these have been evaluated in a series of reviews including Sala and Rubio (1994), Cerdà and Mataix-Solera (2009), Ferreira et al. (2009) and Mataix-Solera et al. (2011).

The principal direct effect of fire on soil physical properties is related to the combustion of organic matter (Mataix-Solera et al., 2011). Organic matter is essential for the formation and stabilization of soil aggregates, particularly in the surface horizons (Amézketa, 1999; Benito et al., 2014; Cerdà, 2000; Gelaw et al., 2013; Mataix-Solera et al., 2011). In turn, soil aggregates play a crucial role in hydrological behaviour of soils, with structural degradation reducing total pore space and, thus, infiltration capacity and thereby enhancing overland flow generation and the associated loss of soil (fertility) (Cerdà, 1998; Machado et al., 2015; Martins et al., 2013; Prats et al., 2013). Fire can also influence a soil's hydrological behaviour by inducing or enhancing soil water repellency, for example by the formation of a hydrophobic layer at or parallel to the soil surface (DeBano, 2000; Keizer et al., 2008; Shakesby et al., 2007; Varela et al., 2005). This quantity and type of organic compounds consumed or produced by the soil heating is dependent upon a number of factors, amongst which fire severity is critical (Bodí et al., 2011; Doerr et al., 2009; Rodríguez-Alleres et al., 2012).

In general, the negative effects of fire on soil properties are associated with medium or high severity fires, with low severity fires being primarily beneficial in terms of increasing soil fertility (Certini, 2005). Assessing the severity of a wildfire is challenging in terms of how to make a quantitative characterisation of the heating regime in terms of temperatures attained and their duration. Therefore, various studies have utilized controlled heating experiments in the laboratory to examine the influence of temperature on soil properties (Badía et al., 2014;

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Campo et al., 2014; Doerr et al., 2004; García-Corona et al., 2004; Giovannini et al., 1990; Thomaz and Fachin, 2014; Varela et al., 2010b; Zavala et al., 2010).

The aim of this study is twofold: (i) to assess the effects of wildfire on selected indicators of the physical degradation status of two Maritime Pine forest stands, by comparing recently burnt and neighbouring unburned soils; and (ii) to determine the effects of controlled heating experiments at (25, 170, 220, 380, and 460 °C) on these same parameters from the same unburned soils, and use these results to infer differences in the severity of the two wildfires. In case of consistent field and laboratory results for one or more of the selected indicators, the present methodology could be used as tool for quantifying soil heating regime by wildfires. This is especially the case for Maritime Pine forest stands (which are widespread in the western part of the Mediterranean Basin) and, possibly, for other fire-prone Mediterranean ecosystems where organic matter plays a key role in soil hydrology and erodibility.

2. Materials and methods

2.1. Study area and field sample collection

The study area is located in Galicia (NW Spain), in the temperate-humid Atlantic European zone. Galicia's oceanic climate is characterised by high precipitation with a strongly seasonal pattern. Mean annual rainfall is 1180 mm and 63% of the rain occurs in the autumn–winter periods, with only 13% occurring in the summer (Cortizas and Alberti, 1999). The temperature regime is typical of temperate areas, and the mean annual temperature ranges from 8 °C to 15 °C.

Two forest sites (site 1: 42°28′36″N, 8°53′09″W, site 2: 42°42′11″N, 8°13′19″W) were identified which were both affected by wildfire on the same date (31th August of 1999), with each wildfire affecting an area of approximately 2 ha. Simultaneously, two long unburnt sites situated in close proximity to the burned sites were selected as a control. The four sites (two unburned and two burnt) were primarily vegetated with Maritime Pine (*Pinus pinaster* Ait.) and shared the same soil type (Leptic Regosols according to WRB, 2014) and underlying geological material (granite rocks). Both unburned soils are highly acidic sandy loam, with a pH of 4.16 in location 1 and 3.91 in location 2. The areas adjacent to the burnt sites were nearly entirely covered in a dense canopy of natural vegetation. A thick litter layer formed by needles and residues from pines and shrub was observed at the unburned control sites, but was absent at the burnt sites. According to simple field indicators (Moreno and Oechel, 1989; Parsons et al., 2010; Shakesby and Doerr, 2006), location 1 appears to have had a low fire severity, since the consumption of tree canopies and shrub cover was partial and ashes were predominantly black. By contrast, at location 2 the combustion of the litter layer was total, shrub vegetation less than 4 mm was consumed by fire, and black and white ashes prevailed indicating that the fire severity was moderate.

Field sample collection took place during the first month after the wildfire and before the occurrence of significant rainfall. At each of the four study sites, three soil samples were collected from the topsoil horizon (0–5 cm). To this end, the litter or ash layer was removed prior to sampling. The samples were air-dried and, subsequently, sieved with a mesh size of 10 mm.

2.2. Heating experiments

The heating tests were conducted in triplicate on the fraction smaller than 10 mm of unburned samples. This test utilized a muffle furnace equipped with a timer, heating rate control, and a thermocouple for measuring the temperature of the samples themselves. The different heating temperatures (25, 170, 220, 380 and 460 °C) represent the soil's most typical thermal reactions, as determined by differential thermal analysis (Giovannini et al., 1988; Soto et al., 1991). The fraction less than 10 mm was filled into capsules of porcelain of 15.5 cm in diameter by 3 cm high. 1 cm of soil with a known weight was placed in each capsule, forming a thin layer to avoid possible formation of a temperature gradient between the surfaces of contact with the capsule or air and the interior of the mass of soil, in order to achieve homogeneous conditions in the whole burnt sample. A heating rate of 3 °C min^{-1} was used to prevent sudden combustion when reaching the soil ignition temperature (Fernández et al., 1997). Samples were then held at a constant temperature for 30 min (Soto et al., 1991). Once the soil samples were heated to the different temperatures (3×5 n = 15), the laboratory analysis was conducted as described in Section 2.3.

2.3. Laboratory and data analysis

Aggregate size distribution was determined by mechanically sieving the smaller-than-10 mm fractions through sieves of 5, 2, 1, 0.25, and 0.05 mm mesh size, and then weighting the resulting sub-fractions. Aggregate size distribution was then expressed as the dry mean weight diameter (MWD) following Kemper and Rosenau (1986). Aggregate stability was measured using the 'Water Drop Impact' (WDI) test of Low (1954), which simulates the impact of water drops on aggregates. Twenty-five aggregates of 4 to 5 mm in diameter from each soil sample were selected and then subjected individually to the impact of up to 200 water drops of 0.1 g released from a height of 1 m. Aggregate stability was then expressed as the percentage of aggregates surviving the impact of 200 water drops. Water repellency severity was determined using the 'Molarity of an Ethanol Droplet' (MED) test (e.g. Doerr et al., 1998; King, 1981). This was done using air-dried samples, and involved applying droplets of increasing ethanol concentrations until infiltration of the droplets occurs within 10 s. The concentrations used in this study are shown in Table 1, together with the corresponding ethanol classes and repellency severity ratings.

Saturated hydraulic conductivity (Ks) was determined using a constant-head laboratory permeameter, with cylinders 10 cm high and 7.5 cm in diameter, in which the soil fraction smaller than 2 mm was repacked. Total organic carbon content was measured using the Sauerlandt method as modified by Guitián and Carballas (1976).

The differences between unburned and burnt soils were assessed using a T-Test. The laboratory heating results were analysed using parametric statistics, i.e. one-way ANOVA and Pearson's product–moment correlation coefficient. Namely, the Kolmogorov–Smirnov and Levene Tests indicated that the conditions of normality and homoscedasticity could be assumed. The software package SPSS 17.0 was used for the various statistical analyses, and testing was done against a significance level α of 0.01 and/or 0.05.

3. Results

3.1. Effects of fire on soil properties

The carbon content of soils examined in this study is strongly influenced by the climatic characteristics of the area (as described in Section 2.1), which favour the presence of high carbon contents in unburnt soils, as shown in Table 2.

However these soils show weak soil aggregation, with the most abundant size fraction of aggregates being between 1 – 0.25 mm. Both soils are strongly hydrophobic, but with high hydraulic conductivity due to their coarse texture.

Fire had distinct effects on topsoil properties in the two study locations (Table 2). In the case of location 1, organic carbon content, aggregate stability, and water repellency do not show statistical differences for the neighbouring burnt and unburned site. By contrast, in location 2 these variables had noticeably higher values at the unburned site than at the adjacent burnt site. In this location, the carbon content decreased by 44% after the passage of fire, and the soil water repellency