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Effects of prescribed burning on soil organic C, aggregate stability and water repellency in a subalpine shrubland: Variations among sieve fractions and depths

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A B S T R A C T

Soil organic matter, aggregation and water repellency are relevant interrelated soil properties that can be affected by fire. The aim of this work was to analyse the effects of shrub prescribed burning for pasture reclamation on the soil aggregate stability, organic carbon and water repellency of different soil depths and aggregate sizes in a subalpine environment. Soil samples were collected from an area treated by an autumnal low-intensity prescribed fire in the Central Pyrenees (NE-Spain) at 0–1, 1–2, 2–3 and 3–5 cm depths just before and ~1 h, 6 months and 12 months after burning. Samples were separated as whole soil (< 10 mm) and 6 sieve fractions, < 0.25, 0.25–0.5, 0.5–1, 1–2, 2–4 and 4–10 mm. We analysed soil organic C (SOC), aggregate stability (AS) and soil water repellency (SWR). In the unburned samples, SOC and SWR were higher in the < 0.25 to 2 mm sieve fractions than the 2 to 10 mm sieve fractions. Fire severely and significantly decreased the SOC content in the whole soil and the < 0.25 mm fraction at 0–1 cm depth and in the 0.25–0.5 mm fraction at 0–2 cm depth. SWR was reduced by burning mainly at 0–1 cm depth for the whole soil and the < 0.25 to 2 mm sieve fractions. Nevertheless, the AS of the 0.25–0.5 mm aggregates increased after fire, while the rest of the sieve fractions remained virtually unaffected. One year after the prescribed burning, SOC slightly increased and SWR recovered in the fire-affected fractions, while the AS for all aggregate sizes and depths showed a considerable decrease. The results suggest that the direct effects of burning are still present one year after burning, and the post-fire situation may pose an increased risk of soil loss. Furthermore, our results indicate that fine soil fractions are more likely to be affected by fire than coarser soil fractions and highly influence the whole soil behaviour.

1. Introduction

Livestock grazing has played a primary role in the traditional management of pasturelands in the Central Pyrenees (NE-Spain) (Nadal-Romero et al., 2016). Nevertheless, as a consequence of socio-economic changes (i.e., rural exodus and reduction of stocking densities), this activity has considerably decreased in the past few decades (Komac et al., 2013). Currently, pasturelands cover a surface of approximately 600,000 ha in the Central Pyrenees (Caballero et al., 2010). The mesophytic Pyrenean pastures are composed of subclimax species that require the grazing of shrubs to survive (Halada et al., 2011). As a consequence of grazing reduction, the Pyrenees have suffered shrub encroachment processes, dominated by the thorny cushion dwarf (*Echinospartum horridum* (Vahl) Rothm), among others (Komac et al., 2013; Nuche et al., 2018). This species forms large and dense mono-specific covers (Komac et al., 2011) that pose a threat to biodiversity and increase flammability risks (Caballero et al., 2010). Prescribed burning, defined as the planned use of fire to achieve precise and clearly defined objectives (Fernandes et al., 2013), serves as a practical and economical procedure for maintaining grazing lands and stopping shrub succession (Goldammer and Montiel, 2010). However, fire, depending on its severity, can affect most of the soil physical, chemical and biological properties (Certini, 2005). The intensity and duration of fires are highly influenced by the environmental conditions; for this reason, prescribed burnings are carried out under favourable conditions of soil and fuel moisture, temperature and topography (Molina, 2009) to limit their impact on the soil (Vega et al., 2005). Nevertheless, contrasting effects of prescribed burning on soil properties have been reported in the literature (Alcañiz et al., 2018).

Soil organic matter (SOM), aggregation and water repellency (SWR) are relevant interrelated soil properties (Zheng et al., 2016) that can be affected by fire (Mataix-Solera et al., 2011). SOM plays a primary role

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in soil quality, influencing relevant properties such as soil aggregation and its stability since it can act as a binding agent during aggregate formation (Tisdall and Oades, 1982). SOM is also known to be linked to the occurrence of SWR, which is a natural property of soils that reduces infiltration and enhances surface runoff and erosion (Doerr et al., 2000; Zavala et al., 2014). SWR can be determined by SOM, among many other factors (Jordán et al., 2013 and references therein), as it contains organic hydrophobic substances that coat mineral particles or are present in the interstitial spaces of soil. However, the SOM amount is not always the most determinant factor in the development of SWR; its composition and distribution among the different soil aggregate sizes are also important (Jiménez-Morillo et al., 2016a). Additionally, hydrophobic substances can coat soil aggregates, increasing their stability (Mataix-Solera et al., 2011).

Fire can induce changes in SOM, since its combustion is initiated when temperatures of 200–250 °C are reached (Badía and Martí, 2003; Certini, 2005; Santín and Doerr, 2016). Several studies have reported that prescribed burning has no effects on SOM (Alexis et al., 2007; Goberna et al., 2012; Fultz et al., 2016), while others have observed increases in SOM content (Úbeda et al., 2005; Alcañiz et al., 2016) due to the incorporation of partly charred plant material or litter (González-Pérez et al., 2004). However, previous works investigating *Echinospartum horridum* prescribed fires in the Central Pyrenees have indicated a severe decrease in SOM immediately after burning (Armas-Herrera et al., 2016; Girona-García et al., 2018).

Although fire effects on soil aggregation have been widely studied, contrasting results have been reported, as reviewed by Mataix-Solera et al. (2011), and there are still uncertainties about how this property is affected by heat (Jiménez-Pinilla et al., 2016a). Low-intensity fires may have a neutral effect on soil aggregation or even increase it due to the stability of SOM and inorganic binding agents in temperature ranges below 200 °C. However, sudden heating can produce disaggregation even at low temperatures due to the forces exerted by escaping water steam (Albalasmeh et al., 2013 and references therein). On the other hand, high-intensity fires may produce remarkable changes in soil aggregation, as it can be degraded due to SOM combustion or increased as a consequence of particle fusion and the recrystallisation of clay minerals (Mataix-Solera et al., 2011 and references therein). These effects may vary depending on the fire severity and main aggregate stabilising agent, so the analysis of related parameters, i.e., SOM, soil aggregate size distribution, and water repellency, are required in order to understand how this property is affected by fire. Furthermore, there is a gap in knowledge on how prescribed burnings applied for vegetation management purposes affect aggregate stability (Alcañiz et al., 2018).

SWR is a soil property that can be affected by fire in different ways, induced or enhanced as a consequence of the partial combustion of SOM (Mataix-Solera et al., 2011) as well as removed by the oxidation or translocation of hydrophobic organic substances (Jordán et al., 2010).

Numerous studies have been carried out in Mediterranean environments involving the aforementioned soil properties after wildfires and prescribed and experimental burnings. However, to the author's knowledge, no studies of this type have been conducted for prescribed burnings in subalpine environments.

The objective of this work was to study the effects of the prescribed burning of shrubs for pasture management in a subalpine environment on interrelated soil properties, such as SOC content, aggregate stability and SWR, among different aggregate sizes and topsoil depths during a one-year period. In this way, we also aimed to detect which soil aggregate sizes are more prone to be affected by fire and how those changes influenced the whole soil behaviour.

2. Material and methods

2.1. Study area and prescribed burning description

The study site is located in Buisán, Central Pyrenees (NE-Spain; 42°36′04.4″ N 0°00′43.3″ E), at 1760 m a.s.l. The average slope ranges from 12 to 30% and faces south. The mean annual temperature is 5.7 °C, and the mean annual precipitation 1270 mm. Due to fire exclusion after 1980 and the decay of grazing activity, the *Echinospartum horridum* population in this region has widely increased, considerably decreasing the grassland cover (Komac et al., 2011, 2013).

Table 1
Physical and chemical properties of the Eutric Cambisol at the study site.

Horizon	Ah_1 (0-5 cm)	Ah_2 (5-15 cm)	Bw_1 (15-25 cm)	Bw_2 (25-40 cm)	C (40-65 cm)
pH (H_2O, 1:2.5)	6.7	6.4	6.7	6.6	6.5
pH (KCl, 1:2,5)	5.9	5.6	5.6	5.4	5.2
$EC_{1:5}$ (μS/cm)	115	80.5	50.5	36.4	32.3
CEC (cmol(+)/kg)	33.1	24.2	19.9	17.9	14.3
OM (g/kg)	173	89.3	53.2	39.1	27.7
C/N	12.9	10.1	9.1	8.1	7.6
Clay (g/kg)	228	318	310	370	370
Silt (g/kg)	661	602	612	550	554
Sand (g(kg)	111	80	80	80	76
Textural class (USDA)	Silty loam	Silty clay loam	Silty clay loam	Silty clay loam	Silty clay loam
FC (g/kg)	546	409	337	325	302
PWP (g/kg)	394	252	202	189	174
AWC (g/kg)	152	157	135	136	128

EC: electrical conductivity; CEC: cation Exchange capacity; OM: organic matter; FC: water content at field capacity; PWP: water content at permanent wilting point; AWC: available water holding capacity.

Soils are characterised by neutral pH values, high soil organic matter content, fine textures and variable carbonate content and are classified as an association of Eutric Cambisols and Calcaric Cambisols (IUSS Working Group WRB, 2014). The characteristics of a representative soil profile are shown in Table 1.

The prescribed burning was performed in November, 2015 by qualified firefighters of the EPRIF (Wildfire Prevention Team) of Huesca and BRIF (Reinforcement Brigades against Wildfires) of Daroca units when the environmental conditions met the established prescription parameters. It had not rained for 10 days prior to the burning, and the air relative humidity was 35–70%, with a maximum temperature of 15 °C and a wind speed $<$ 8 km/h. The delimited burning area (3.8 ha) presented a rectangular shape, and approximately 75% of its total surface was covered by *E. horridum* shrubs. The estimated aerial biomass was ~9.2 kg/m^2, and the amount of litter was ~1.6 kg/m^2. Fire was applied on *E. horridum* shrubs following the point source ignition technique from N to S, forming a fire line that spread from E to W at a rate of 0.64 ha/h. The average flame length and height were 1.5 and 1 m, respectively. Burning eliminated all the *E. horridum* shrubs in the area, leaving only burned trunks, ashes and partially charred litter.

An approximation of the temperatures reached during the prescribed burning (Table 2) was obtained via Type-K thermocouples placed at the mineral soil surface and at 1, 2 and 3 cm depths in one of the sampling sites. The recorded data show a maximum temperature of 438 °C at the soil surface, whereas the temperature remained almost unchanged below 1 cm depth. Data analysis also indicates that the uppermost soil layer was exposed to a temperature range of 100–400 °C for 12 min.

2.2. Soil sampling

We chose three representative sampling points covered by *E. horridum* shrubs separated by 5 m. At each point, soil was carefully scrapped from the topsoil Ah horizon at 0–1, 1–2, 2–3 and 3–5 cm depths in an approximate surface area of 0.25 m^2 (Fig. 1) in the early morning to obtain unburned (U) control samples. Prior to sampling, the shrubs and organic layers were removed. Hours later, prescribed burning was conducted, and as soon as possible, points adjacent to the