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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HIGHLIGHTS

- Prescribed fire is used to reduce shrub encroachment and recover subalpine pastures
- Its effects on SOC, AS and SWR were analysed in the whole soil and sieve fractions
- Fire reduced SOC and SWR in the whole soil and finer fractions, mainly at 0-1 cm
- One year after fire, SWR increased and AS decreased compared to the unburned soil
- The whole soil behaviour was mainly influenced by changes in its finer fractions

ABSTRACT

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 hour, 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.

Keywords: pasture management, topsoil, shrub encroachment, mountain soils, prescribed fire

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 monospecific 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 & 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 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 & 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 ºC are reached (Badía & Martí, 2003; Certini, 2005; Santín & 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 ºC. 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).

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.**

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

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 ºC 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 ºC for 12 minutes.

Table 2 Temperature recorded via type-K thermocouples placed at soil surface and at 1, 2 and 3 cm depth. Data analysis comprises the elapsed time since temperature increase was detected until it stabilised during cooling stage

Variables	Surface	1 cm	2 cm	3 cm
Maximum temperature (°C)	438	31.1	18.5	18.5
Initial temperature (°C)	13.1	9.77	9.60	8.93
Final temperature (°C)	27.5	22.2	17.6	18.2
Duration (min)				
<60 °C	2.50	30.0	30.0	30.0
60 - 100 °C	15.0	0.00	0.00	0.00
100 - 200 °C	6.00	0.00	0.00	0.00
200 - 300 °C	4.00	0.00	0.00	0.00
300 - 400 °C	2.00	0.00	0.00	0.00
> 400 °C	0.50	0.00	0.00	0.00

2.2. Soil sampling

We chose three representative sampling points covered by *E. horridum* shrubs separated by 5 metres. 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 U points were sampled after ashes and charred plant remains were removed to study the immediate effects of fire (B0). Additionally, in order to assess short-term changes in the studied soil properties, the burned soils were sampled 6 months (B6) and one year (B12) after the prescribed burning. All samples were preserved in sealed containers in order to maintain the original soil structure. It should be noted that, for most of the period between the collection of B0 and B6 samples, the study site was covered by snow, and livestock (cows and goats) grazed the study site between 8 and 12 months after burning.

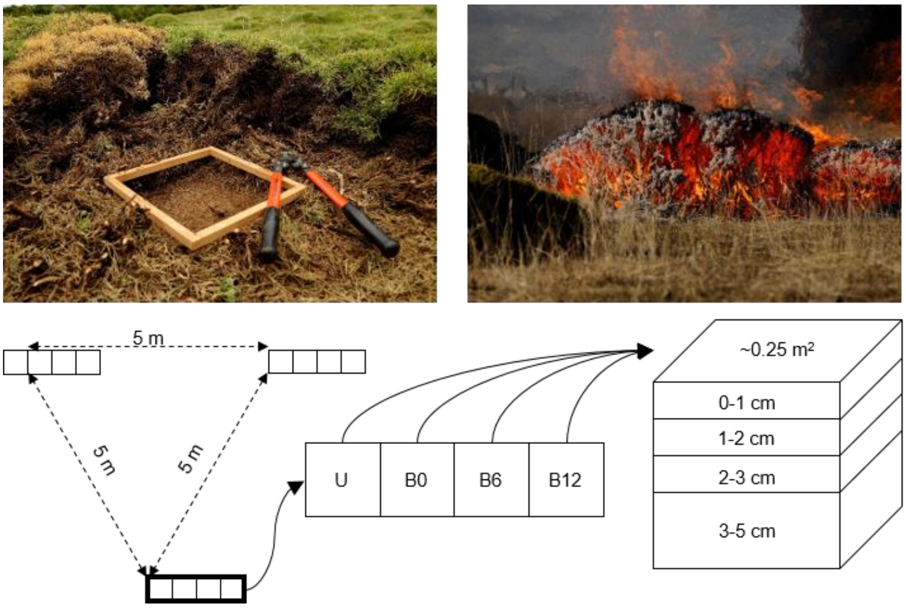

Fig. 1 Design of sampling plots and burning of *Echinospartum horridum*. Unburned (U), immediately after (B0), 6 months (B6) and one year (B12) after burning sampling

2.3. Samples preparation and analysis

Soil samples were air-dried at room temperature until constant weight. A small portion was taken from all samples (n = 48) in order to analyse the whole soil (<10 mm). The remaining samples were separated in 6 different aggregate sizes (<0.25, 0.25-0.5, 0.5-1, 1-2, 2-4 and 4-10 mm) by manually shaking a nested column of sieves, avoiding aggregate destruction, to obtain 288 fractional samples (4 sampling times x 3 sampling points x 4 soil depths x 6 aggregate sizes). Afterwards, stones were removed when they were present in the sieve fractions. Then, each aggregate size was weighed separately to obtain the mean weight diameter (MWD, Van Bavel, 1949) and preserved to analyse the following properties.

The soil organic carbon (SOC) content was obtained for ground samples through the chromic acid wet oxidation method (Walkley-Black, 1934) for the whole soil (<10 mm) and each sieve fraction (0.25-0.5, 0.5-1, 1-2, 2-4 and 4-10 mm).

Soil aggregate stability (AS) was determined by the wet sieving method detailed by Kemper & Koch (1966) and revised by Schinner et al. (1996). This treatment emulates the forces exerted on soil by runoff or immersion conditions. Approximately 4 g of each sieve fraction (0.25-0.5, 0.5-1, 1-2, 2-4 and 4-10 mm) were placed in duplicate on 38 mm diameter sieves with 0.25 mm mesh size and then submerged and subjected to sieving action for 5 minutes. Afterwards, the remaining aggregates were carefully removed from the sieves, oven-dried at 105 ºC and weighted in order to obtain the weight of the stable aggregates and large-sized sand (>0.25 mm). Then, each sample was submerged in 50 mL of 0.1 M sodium pyrophosphate decahydrate ($Na_4P_2O_7 \cdot 10H_2O$) for 2 hours to disperse the stable aggregates. Eventually, the samples were washed using distilled water, oven-dried at 105 ºC and weighted, obtaining the weight of sand. The percentage of soil AS was determined using expression [1]

$$AS\ (\%) = \frac{100\ (weight\ of\ stable\ aggregates\ and\ sand) - (weight\ of\ sand)}{(weight\ of\ sample) - (weight\ of\ sand)} \quad [1]$$

AS could not be measured in the <0.25 mm sieve fraction, as we used a sieve with 0.25 mm apertures. The AS values obtained for the 1-2 mm aggregate size were considered representative of the whole soil, as suggested by the method.

The persistence of soil water repellency (SWR) was assessed through the water drop penetration time test (WDPT) consisting of applying droplets of distilled water on the soil surface and measuring the time until its complete infiltration (Wessel, 1988). The analysis was conducted under laboratory conditions with controlled temperature (20-25 °C) and relative humidity (50 %) in order to reduce sources of variability. Drops of distilled water (~0.05 mL/drop) were applied to the whole soil samples and each sieve fraction, and the complete penetration time into the soil was measured (8 drops per sample; n = 2688).

Given the wide array of values obtained via the WDPT, SWR was categorised into the 5 classes defined by Bisdom et al. (1993): wettable (<5 s), slightly water repellent (5-60 s), strongly water repellent (60-600 s), severely water repellent (600-3600 s) and extremely water repellent (>3600 s).

2.4. Statistical analysis

To identify the differences in the studied soil properties related to burning and post-fire elapsed time, as well as soil depth and aggregate size, one-way ANOVA tests were used, since the interaction between time and depth was significant in most cases. The sampling time (U, B0, B6, B12) was considered a fixed factor to analyse the effect of fire and time, and the data were split by soil depth (0-1, 1-2, 2-3 and 3-5 cm) for each soil fraction (<0.25, 0.25-0.5, 0.5-1, 1-2, 2-4, 4-10 and <10 mm). Additionally, changes in soil properties with depth were checked using soil depth (0-1, 1-2, 2-3, 3-5 cm) as a fixed factor, for which the data were split by sampling time (U, B0, B6, B12) for each soil fraction (<0.25, 0.25-0.5, 0.5-1, 1-2, 2-4, 4-10 and <10 mm). The correlations among variables for all sampling time and soil depth categories were also studied. These analyses were performed using StatView for Windows version 5.0.1 (SAS Institute Inc. Cary, North Carolina, USA). The homogeneous groups for the studied variables among the soil fractions within every soil depth and sampling time category were obtained using Statistica 8.0 (Stat Soft Inc. Tulsa, Oklahoma, USA). Data presented in the text are reported as the mean ± standard deviation of the mean unless otherwise stated.

3. Results and discussion

3.1. Soil Organic Carbon

The highest soil organic carbon (SOC) content, 182 ± 62 g/kg, was detected in the <0.25 mm aggregates of the unburned (U) samples at 0-1 cm depth (**Fig. 2**). At 0-1 and 1-2 cm depths, the U SOC values showed a decreasing trend with increasing aggregate size, whereas in deeper soil layers, this trend was not so marked. In this way, SOC of all aggregate sizes consistently decreased with depth. A similar behaviour was observed for SOC content of the U whole soil (<10 mm), which also decreased with depth from 161 ± 40 g/kg at 0-1 cm depth to 55.4 ± 5.1 g/kg at 3-5 cm depth. Compared to U, burning (B0) markedly decreased SOC content in the <0.25 mm fraction at 0-1 cm depth (81.8 ± 39.3 g/kg) and in the 0.25-0.5 mm fraction at 0-1 and 1-2 cm depth (64.7 ± 13.2 and 53.7 ± 15.3 g/kg, respectively). However, the rest of the studied soil sieve fractions and depths were not significantly affected by fire. The whole soil (<10 mm) had a similar response to fire as the <0.25 and 0.25-0.5 fractions, showing a significant decrease in SOC from 161 ± 40 (U) to 72.5 ± 23.2 g/kg (B0) at 0-1 cm depth. These results suggest that the SOC contents in the U and B0 whole soil are linked to those of the finer fractions, which appear to be more sensitive to fire than the coarser fractions. This result is supported by the variance analysis, which indicates that the SOC values in the finer sieve fractions are highly influenced by fire (**Table 3**).

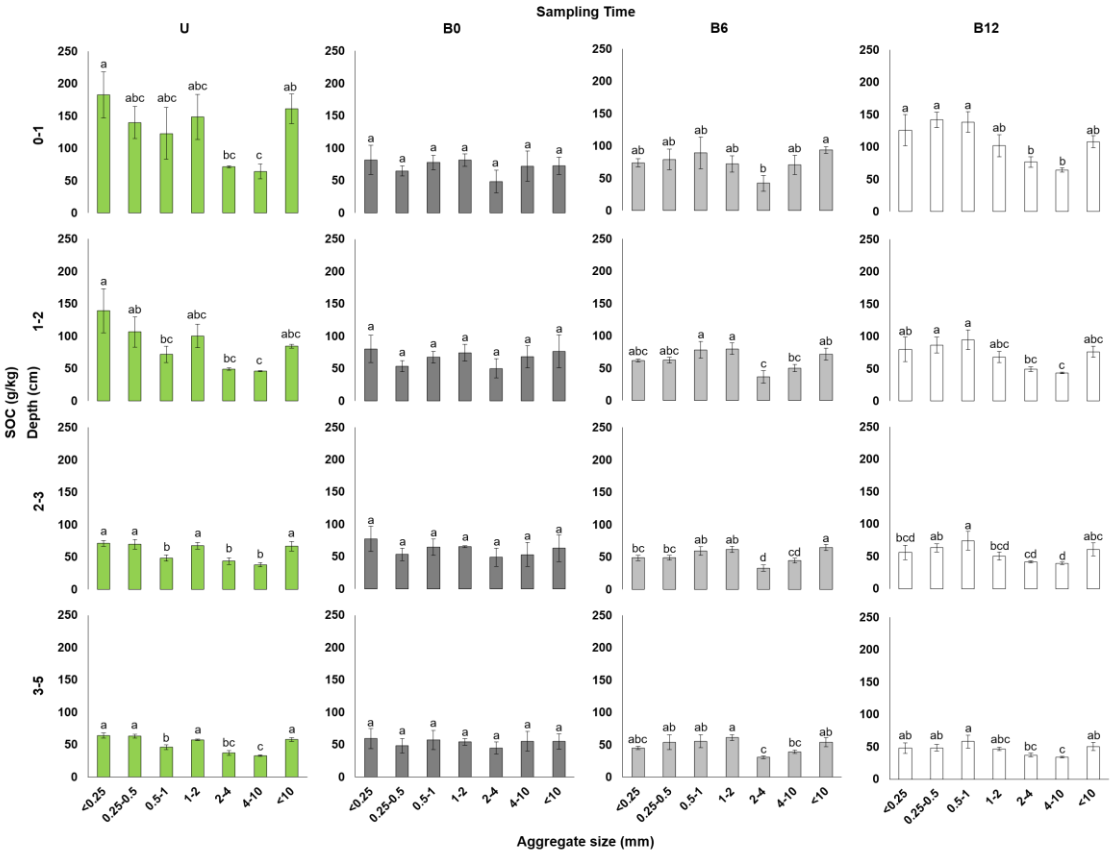

Fig. 2 Soil Organic Carbon (SOC) content of unburned samples (U), immediate post-fire samples (B0), 6 months (B6) and one year (B12) post-fire samples for each sieve fraction (<0.25, 0.25-0.5, 0.5-1, 1-2, 2-4 and 4-10 mm) and whole soil (<10 mm) per sampling depth (0-1, 1-2, 2-3, 3-5 cm). Letters indicate homogeneous groups at p< 0.05 among sieve fractions and whole soil for each soil depth and sampling time. Mean ± SE

Table 3 Variance analysis of Soil Organic Carbon (SOC), Aggregate Stability (AS) and Soil Water Repellency (SWR) for all studied depths (D) and treatments (T; burning and elapsed time since burning) in each sieve fraction (<0.25, 0.25-0.5, 0.5-1, 1-2, 2-4, 4-10 mm) and whole soil (<10 mm)

Fraction (mm)		<0.25		0.25-0.5		0.5-1		1-2		2-4		4-10		<10	
		F	p	F	p	F	p	F	p	F	p	F	p	F	p
SOC	*T*	6.998	**0.0009**	9.753	**0.0001**	2.149	0.1135	4.118	**0.0144**	2.663	0.0653	2.065	0.1245	3.208	**0.0361**
	D	9.590	**0.0001**	15.40	**<0.0001**	8.843	**0.0002**	10.51	**<0.0001**	3.443	**0.0286**	4.907	**0.0064**	15.16	**<0.0001**
	T x D	1.614	0.1533	1.983	0.0749	0.818	0.6036	1.590	0.1618	0.352	0.9489	0.114	0.9991	2.073	0.0628
AS	*T*	-	-	30.47	**<0.0001**	87.15	**<0.0001**	71.97	**<0.0001**	68.13	**<0.0001**	70.61	**<0.0001**	71.97	**<0.0001**
	D	-	-	2.362	0.0954	3.552	**0.0251**	0.987	0.4113	1.433	0.2513	1.468	0.2423	0.987	0.4113
	T x D	-	-	1.479	0.2098	0.634	0.7595	0.905	0.5323	0.186	0.9942	0.997	0.4631	0.905	0.5323
SWR	*T*	9.371	**0.0002**	14.31	**<0.0001**	2.578	0.0709	5.097	**0.0054**	0.270	0.8467	0.064	0.9786	13.763	**<0.0001**
	D	7.424	**0.0008**	24.17	**<0.0001**	5.051	**0.0056**	6.562	**0.0014**	6.228	**0.0019**	3.748	**0.0205**	30.493	**<0.0001**
	T x D	3.844	**0.0029**	7.286	**<0.0001**	0.897	0.5392	2.800	**0.0152**	0.272	0.9778	0.300	0.9694	5.221	**0.0002**

Six months after fire (B6), the detected fire effects on SOC were still present and it decreased in the <0.25 mm fraction at 1-2 cm depth compared to U. One year after fire (B12), the SOC values of the <0.25 mm fraction showed a slight increase at 0-2 cm depth compared to those of B0 and B6. The statistical analysis showed that the SOC state of B12 was between that of B0-B6 and U, which suggests signs of recovery of the fire-affected fractions. For the 0.25-0.5 mm fraction at 0-1 cm depth, the B12 SOC values were similar to those of U, indicating a recovery for this aggregate size and depth; in addition, at 1-2 cm depth, SOC also showed a slight increase for the <0.25 mm fraction. No further changes related to fire or elapsed time were observed for the rest of the studied aggregate sizes and depths. The SOC increase detected in B12 for the smaller sieve fractions could be explained by the late incorporation of ashes and partially charred plant remains that become fine organic particles that are mixed with the soil after fire

(González-Pérez et al., 2004). Nevertheless, these slight variations were not observed in the whole soil, which remained virtually unchanged compared to B0 during the studied period.

The SOC distribution among the U sieve fractions agrees with the results of Jiménez-Morillo et al. (2016a), which indicated that the SOC content was higher in the finer fractions than the coarser fractions of unburned soils under four different vegetation species (*Quercus suber*, *Pteridium aquilinum*, *Pinus pinea* and *Halimium halimifolium*) in the Doñana National Park (SE-Spain). However, Jiménez-Morillo et al. (2016b), in a different study carried out on soils under *Quercus suber*, detected higher C contents in the 0.5 to 2 mm sieve fractions than in the finer <0.5 mm sieve fractions. Nevertheless, the SOC values obtained in the sieve fractions after burning contrasted with those previously reported in the literature. Jiménez-Morillo et al. (2016b) observed that, after a wildfire, sieve fractions (<0.05 to 2 mm) generally showed higher C contents than unburned sieve fractions, which could be related to the incorporation of different sizes of charred materials (Skjemstad et al., 1996; Nocentini et al., 2010). Our results also contrast with those of Jordán et al. (2011), who suggested that the destruction of organic matter during fires affects mainly the coarse aggregates, as combustion can be more intense in this size range due to the oxygen present in macropores.

Our whole soil results contrast with the traditionally reported neutral or positive effects of prescribed burning on SOC, as reviewed by Alcañiz et al. (2018). However, these reductions in the SOC content after the prescribed burning of *E. horridum* were also detected by Armas-Herrera et al. (2016) and Girona-García et al. (2018). Immediately after fire, Armas-Herrera et al. (2016) reported an average SOC decrease of 43 % at 0-3 cm depth, while Girona-García et al. (2018) reported a SOC reduction of 54 % at 0-1 cm depth. A reduction in the SOC content is a common effect of fire, since SOM combustion is initiated when temperatures reach a range of 200-250 °C (Badía & Martí, 2003; Certini, 2005; Santín & Doerr, 2016). Temperature analysis showed that, in at least one of the studied points, the uppermost soil layer was exposed to temperatures between 200-400 ºC for 6 minutes. In addition to this approximation, the slow spread of fire (0.64 ha/h) suggests high fire residence times. Additionally, *E. horridum* shrubs (**Fig. 1**) form low and dense patches (Komac et al., 2011) with a homogeneous spatial distribution of fuel loads, which supports higher temperatures and longer fire residence times (Santana et al., 2011). In this way, the fuel loads and fire residence times observed in our study are higher than those of previous studies on burned shrublands and forest understories (Vadilonga et al., 2008; Santana et al., 2011; Fernández et al., 2013; Vega et al., 2005, 2014). The differences in our results compared to those of the literature reporting neutral or positive effects of prescribed burning on SOC may also be related to soil sampling. A dilution effect could be produced when too much soil thickness is sampled, since the effects of fire may be confined to the uppermost layer. Furthermore, when sampling is not carried out soon enough, ash and charred material could mix into the soil, increasing its SOC content (Badía-Villas et al., 2014, 2017).

3.2. Soil Aggregate Stability and Mean Weight Diameter

Soil aggregate stability (AS) was very high in all the studied U samples (> 76 %), and it increased concomitantly with aggregate size (**Fig. 3**). No variations in AS were observed among aggregate sizes for the different soil depths, except for the 0.25-0.5 mm fraction, which showed an increase from 76.0 ± 4.6 % at 0-1 cm depth to 89.1 ± 1.4 % at 3-5 cm depth. Immediately after the prescribed burning (B0), AS only showed changes in the 0.25-0.5 mm aggregate size at 0-1 cm depth, increasing from 76.0 ± 4.6 (U) to 85.1 ± 3.8 % and diluting the previously mentioned depth gradient. Six months after burning (B6), the AS values in all aggregate sizes and depths remained virtually unchanged from those of B0. Nevertheless, one year after fire (B12), the AS of all aggregate sizes and depths showed an average reduction of 16.92 %. The mean weight diameter (MWD) in the U samples was 3.57 ± 0.43 mm at 0-1 cm depth and increased to 4.82 ± 0.41 mm at 3-5 cm depth, as represented in **Fig. 4**. In B0, no significant changes in MWD were observed in any of the studied depths compared to U, although the aforementioned gradient disappeared. In B6, the MWD values increased at 1-2 and 3-5 cm depth compared to U and B0. However, those differences are not detectable in the corresponding B12 samples.

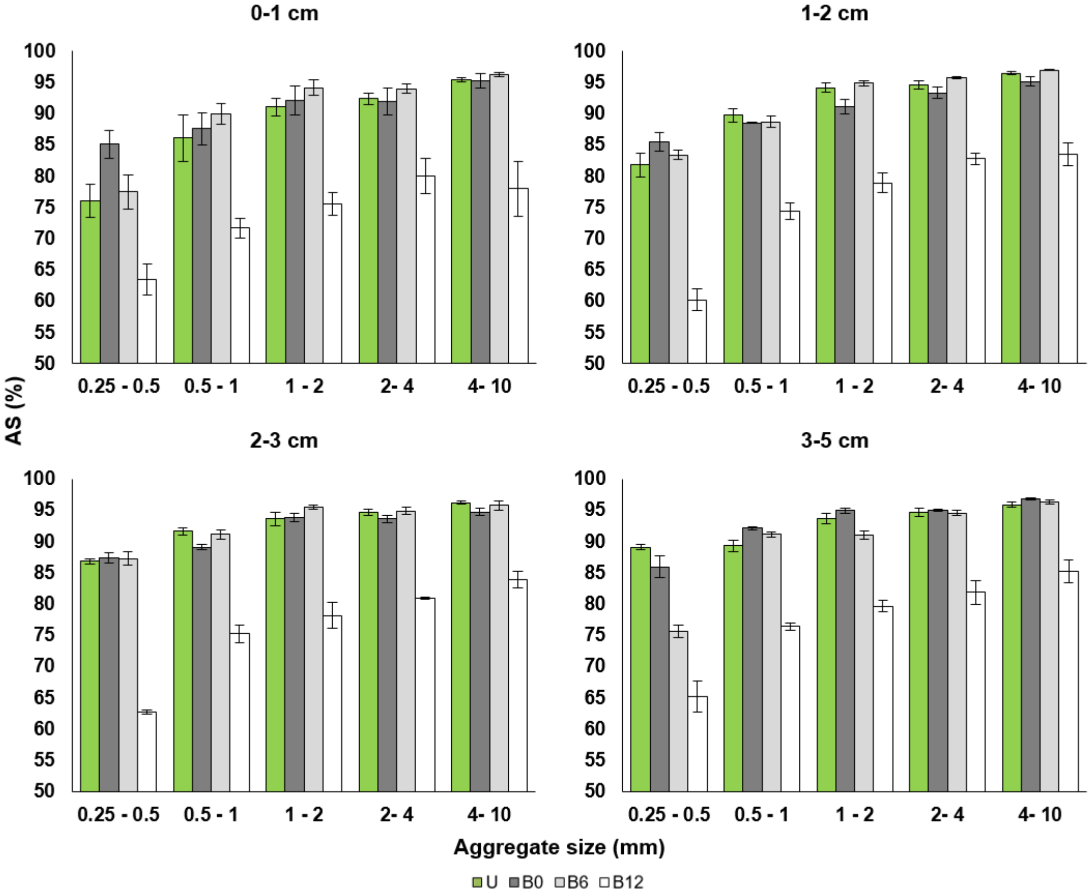

Fig. 3 Aggregate Stability (AS) of unburned samples (U), immediate post-fire samples (B0), 6 months (B6) and one year (B12) post-fire samples for each aggregate size (<0.25, 0.25-0.5, 0.5-1, 1-2, 2-4 and 4-10 mm) and sampling depth (0-1, 1-2, 2-3, 3-5 cm). Mean ± SE

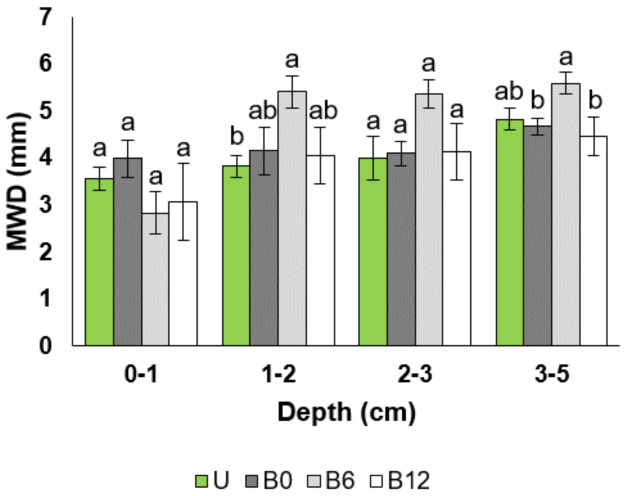

Fig. 4 Mean Weight Diameter (MWD) of unburned samples (U), immediate post-fire samples (B0), 6 months (B6) and one year (B12) post-fire samples at different sampling depths. Mean ± SE. Letters indicate significant differences ($p < 0.05$) among sampling times for each soil depth.

These results agree with previous studies indicating that soil aggregation can remain practically unaffected (Arcenegui et al., 2008; Jordan et al., 2011) or increase (Giovannini & Lucchesi, 1997) after fires when the temperatures in the soil remain below 220 °C. The AS of the 0.25-0.5 mm aggregate size increased after burning, despite its reduction in the SOC content, which could be explained by mineralogical modifications, as observed by Jiménez-Pinilla et al. (2016a), who detected an increase in AS by heating at 300 °C that was related to the compaction of structural units. On the other hand, Giovannini & Lucchesi (1997) reported that AS could remain unaltered after SOM combustion at temperatures of 150 °C due to transformations of the cementing iron oxides. Giovannini et al. (1990) explained the increase in soil aggregation after heating by the dehydration of soil gels at temperatures over 170 °C. Additionally, this slight increase does not seem to be related to aggregate coating by hydrophobic organic substances that increase its resistance to water slaking (Terefe et al., 2008) since SWR also decreased in B0 for this sieve fraction, as explained in section 3.3, and both properties are negatively correlated (**Table 4**). The high AS observed in both the unburned and burned samples during the study period indicate that SOM may not be the main cementing agent, since AS does not change when the SOC content is reduced by fire. This contrasts with the results of Boix-Fayos et al. (2001), who reported that the macroaggregate stability of SE-Spain soils depends on organic matter when its content is higher than 5 or 6 %. The high clay content and the presence of carbonates suggest that the aggregation in our soil might be mainly driven by inorganic binding agents that act as a permanent cement (Tisdall & Oades, 1982). Additionally, calcium carbonate is not usually affected by low-intensity fires, as it might resist temperatures up to 1000 °C (Rabenhorst, 1988). The AS reduction in B12 samples could be linked to trampling by cattle, which is known to alter soil structure (Drewry et al., 2008) and cause its compaction at ranges of 5 to 20 cm depth (Nawaz et al., 2013). This is supported by the fact that cattle grazed the plots from 2 months after B6 until B12. Despite the decrease in the B12 AS values compared to those of previous samples, the change was possibly not great enough to significantly affect the MWD, although it tended to decrease at 1-5 cm depth compared to B6.

Table 4 Regression analysis of Soil Organic Carbon (SOC), Soil Water Repellency (SWR) and Aggregate Stability (AS) among the soil sieve fractions (<0.25, 0.25-0.5, 0.5-1, 1-2, 2-4 and 4-10 mm) for each sampling time: unburned (U), immediate post-fire (B0), 6 months (B6) and one year (B12) post-fire

Time	U		B0		B6		B12	
	r	p	r	p	r	p	r	p
SOC x SWR	+0.649	**<0.0001**	+0.228	0.0566	+0.613	**<0.0001**	+0.798	**<0.0001**
SWR x AS	–0.605	**<0.0001**	–0.894	**0.0004**	–0.253	0.0607	–0.440	**0.0008**
AS x SOC	–0.568	**<0.0001**	–0.243	0.0617	–0.335	**0.0123**	–0.598	**<0.0001**

3.3. Soil Water Repellency

The occurrence of each class of SWR for each soil depth, aggregate size and sampling time is shown in **Fig. 5**. The finer fractions (<0.25 to 2 mm) of the U samples at 0-1 cm depth showed high natural SWR ranging from strongly to extremely water repellent, while the coarser fractions (2 to 10 mm) were mainly wettable or only slightly water repellent.

In the unburned soil, SWR showed a decreasing trend with both increasing depth and aggregate size, and at 3-5 cm depth, only a low occurrence of strong water repellency was observed in the 0.5 to 2 mm fractions, whereas slightly water repellent or wettable were the most representative classes for <0.25-0.5 mm and 0.5 to 10 mm, respectively. The SWR of the whole soil (<10 mm) showed strong water repellency that gradually decreased with depth and was wettable at 3-5 cm. Fire decreased the SWR at 0-1 and 1-2 cm depths in the finer fractions (<0.25 to 2 mm), while the coarser fractions remained virtually unchanged, as observed in the B0 samples. At 0-1 cm depth in B0, unlike in U, no extreme SWR was observed, and the occurrence of severe SWR was reduced to less than 10 % in the 0.25-0.5 and 1-2 mm aggregate sizes. In this way, the predominant classes of SWR in B0 for the finer fractions were strongly and slightly water repellent. At 0-2 cm depth, the wettability of the finer fractions also increased with burning, as the severe SWR observed in U was not observed in B0, and a higher occurrence of the wettable class samples was detected in B0 than U. The same pattern was observed for the whole soil (<10 mm), in which fire reduced SWR to slightly water repellent at 0-1 cm depth. At B6, an opposite trend was observed between 0-1 cm and 1 to 5 cm depths. While SWR at 0-1 cm depth increased in B6 compared to B0 for the finer fractions, in the deeper soil layers, it continuously decreased to only slightly water repellent and wettable classes. One year after the prescribed burning (B12), SWR increased for all the studied soil depths in the finer fractions (<0.25 to 2 mm) compared to B6. B12 SWR increased mainly in the <1 mm fractions at 0-1 and 1-2 cm depths, showing an even higher occurrence of severe and extreme water repellency classes in these samples than the corresponding U samples. These results are reflected in the SWR occurrence of the whole soil (<10 mm), which recovered from the fire and even exceeded the pre-fire SWR occurrence, showing strong and severe water repellency classes at 0-1 cm depth. According to these results, the occurrence of SWR in the whole soil seems to be highly related to changes in the SWR of the fine fractions (<0.25 to 2 mm).

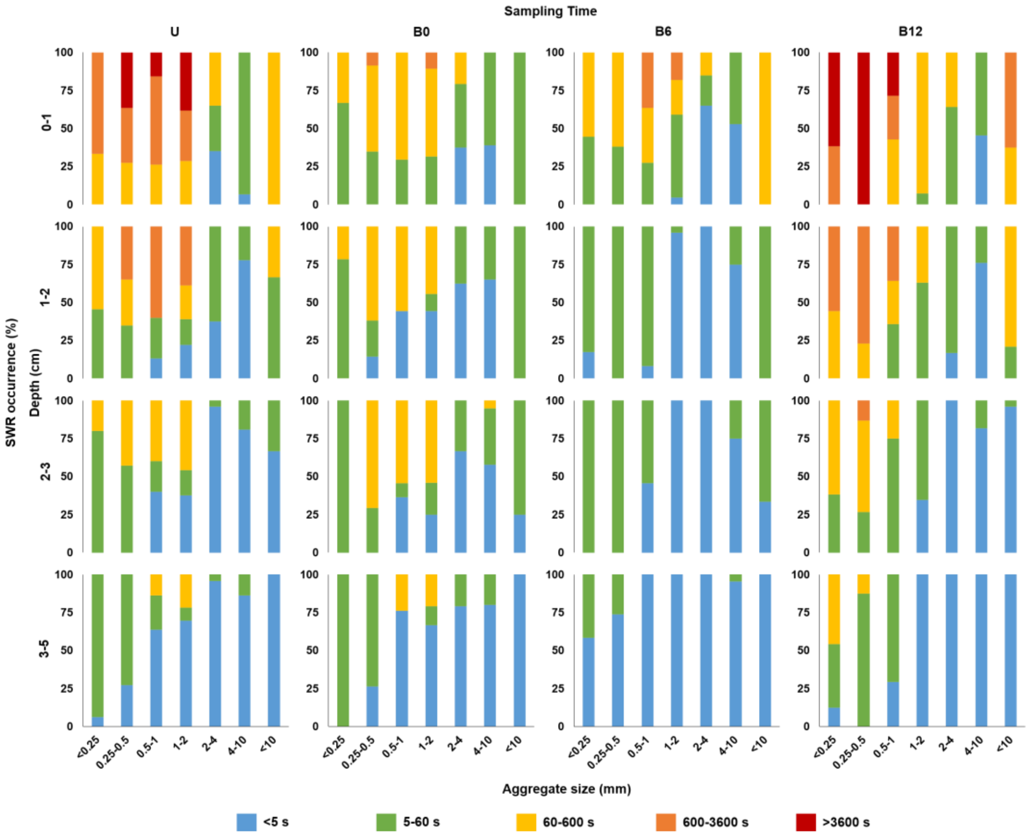

Fig. 5 Occurrence (%) of Soil Water Repellency (SWR) according to the Water Drop Penetration Time (WDPT) test in the unburned (U), immediate post-fire (B0), 6 months (B6) and one year (B12) post-fire samples for each aggregate size (<0.25, 0.25-0.5, 0.5-1, 1-2, 2-4 and 4-10 mm) and whole soil (<10 mm) per sampling depth (0-1, 1-2, 2-3, 3-5 cm). SWR classes defined by Bisdom et al. 1993

The detected SWR distribution among aggregate sizes was also found by Arcenegui et al. (2008) in Mediterranean pinewood soils, indicating that the <0.25 and 0.25-0.5 sieve fractions were the most water repellent; however, unlike the present study, SWR increased after fire. The higher occurrence of SWR in the finer sieve fractions was also observed by Jordán et al. (2011) in Mexican volcanic soils that had been unburned for a long time. Nevertheless, they detected no differences between the burned and unburned soils affected by low-severity wildfires, whereas sites affected by higher severity fires showed lower degrees of SWR. González-Pelayo et al. (2015) identified a trend to increasing SWR in the <0.25 mm sieve fraction beneath unburned shrubs (*Arbutus unedo* > *Pistacia lentiscus* ≈ *Quercus coccifera* > bare soil) in Central Portugal, although its persistence was lower than that of our findings for soil under *E. horridum*; furthermore, they observed a slight increase in SWR after prescribed burning.

We found significant differences in the SOC content among samples from different WDPT classes, showing increases in the SOC content with increasing SWR persistence (**Fig. 6**). However, the SOC content does not fully explain the variability in SWR in all the sieve fractions of U, B0 and B6 according to the regression analysis (**Table 4**). This suggests that SOM quality and its fire-induced changes could be a possible contributing factor in SWR variations (Jiménez-Morillo et al., 2016a). Zheng et al. (2016) also indicated that, in some cases, the distribution of SOM among the different aggregate sizes might be the driving factor of SWR occurrence rather than its content. In this way, the greater SOM concentrations in the smaller aggregates may explain their strong contribution to SWR (Jiménez-Morillo 2016a) and could be a result of the presence of fine, hydrophobic interstitial SOM that accumulates in the finer sieve fractions (Mataix-Solera & Doerr, 2004). The drastic reduction in SWR observed for B0 might be related to the destruction of these hydrophobic SOM, since the SOC content decreased concomitantly. The recovery of SWR in B12 could be related to the incorporation of ashes into the soil, since they play an important role in SWR evolution following fire (Jiménez-Pinilla et al., 2016b) and a significant positive correlation between SOC and SWR was detected ($r = 0.798$; $p = <0.0001$). This SWR increase in B12 could also be attributed to the sampling being carried out after a low-rainfall season, as SWR can be more pronounced following dry periods, as reported by Doerr et al. (2000).

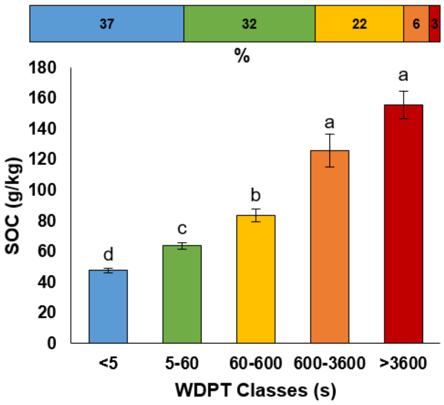

Fig. 6 Soil Organic Carbon (SOC) content of all the sieve samples (n= 288) distributed in each Water Drop Penetration Time (WDPT) class. Mean ± SE. Numbers in the upper bar indicate the percentage of the total samples included in each class. Letters indicate significant differences in SOC content among WDPT classes at $p < 0.05$

Traditionally, high SWR occurrence has been related to coarse soil textures (Giovannini & Lucchesi, 1983). González-Peñaloza et al. (2013) suggested that a limited amount of SOM may cause higher SWR in coarse-textured than fine-textured soils due to the low specific surface of larger particles. However, our studied soil showed a 22 % clay content and high natural SWR and SOC contents. This may occur if the hydrophobic organic materials causing SWR are small enough, increasing the hydrophobicity in the finer rather than the coarser fractions (de Jonge et al., 1999).

3.4. Post-fire implications of prescribed burning

Results indicate that one year after burning, the direct effects induced on SOC were still present, while SWR recovered to higher values than those of U samples. On the other hand, AS, which remained almost unaltered during the study period, was dramatically reduced in B12.

The detected SOC reduction and the biomass carbon losses have negative effects on C sequestration that could extend over the long term. Knowledge about the effects that land management practices, such as prescribed burning, can exert on mountain soils is of vital importance, since these soils store large amounts of C (Saenger et al., 2015). Therefore, further research is needed on this topic in order to assess the sustainability of burning practices in mountain environments from the point of view of C sequestration.

Prior to burning, soils showed high SWR but were covered by dense patches of *E. horridum*, which is a species that physically protects soil and improves water and nutrient retention (Montserrat et al., 1984). Burning reduced SWR, but one year after burning, it recovered to even higher levels than the pre-burning SWR in an environment where vegetation had been removed, exposing the soil to raindrop splash and increasing overland flow (DeBano, 1981). Indeed, Girona-García et al. (2018) indicated for the same study site that the recovered vegetation observed 8-12 months after fire only represented a small surface of the burned plots. However, it is difficult to isolate the effect of SWR on erosion processes since it is highly dependent on the continuity of the hydrophobic layer (Shakesby et al., 2000). Moreover, only the *E. horridum* shrubs were burned, while the pre-existing grasses remained unaltered; this, together with the occurrence of different fire severities, created a mosaic of patches (Cawson et al., 2012). Thus, further research is needed in order to detect the influence of SWR on the general overland flow, since it may vary due to the high spatial variations in infiltration (Doerr et al., 2000).

The maintenance of soil structure is of vital importance for plant growth because it determines the air and water flows. AS remained virtually unaffected by fire, although it suffered a non-fire-related significant decrease one year after the prescribed burning. The reduction in aggregate stability and therefore its destruction in extreme cases enhances soil sealing, which, combined with the development of SWR, reduces water infiltration and increases soil erodibility (Mataix-Solera et al., 2011; Cawson et al., 2016).

Fine soil fractions are of great importance in nutrient exchange processes. The occurrence of SWR in small aggregates could lead to a reduction in nutrient exchange between the soil and plants, given the reduced wettability of the soil (Mataix-Solera & Doerr, 2004). This could negatively affect the recovery of the pastures, which is the objective of the studied prescribed burning.

4. Conclusions

Fire severely decreased the SOC content in the <0.25 mm fraction at 0-1 cm depth and in the 0.25-0.5 mm at 0-2 cm depth. This translated to a 45 % SOC reduction at 0-1 cm depth in the whole soil that did not recover during the studied period. SWR was reduced by burning mainly at 0-1 cm depth for the <0.25 to 2 mm sieve fractions and the whole soil. One year after the prescribed burning, SWR recovered in these fractions, reaching even higher values than those of the unburned soil. The AS of the 0.25-0.5 mm aggregates increased after fire, but one year later, it suffered a striking decrease in all aggregate sizes and depths, probably related to cattle trampling. These findings suggest that the direct effects of prescribed burning were still present one year after burning, and further research is needed in order to assess the increased soil loss risks of the post-fire situation. Based on our results, we can also conclude that fine fractions (<2 mm) are more prone to be affected by fire, and they determine the behaviour of the whole soil to a greater extent than coarser fractions.

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