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Short-term effects of prescribed fires with different severity on rainsplash erosion and physico-chemical properties of surface soil in Mediterranean forests

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ABSTRACT

Prescribed burning with different severity may induce erosion and change many physico-chemical properties of forest soils. Few studies have compared the effects of prescribed fires with different severity on rainsplash erosion and soil properties under natural rainfalls. Therefore, there is the need to better understand these variables of forest soils burned by prescribed fires with low and high severity under natural conditions. Rainsplash erosion, and covers and physico-chemical properties of surface soil have been evaluated in the short term (15 months) in micro-plots of a burned pine forest of Central-Eastern Spain in comparison to unburned areas. The results of the investigation have shown that the high-severity fires gave higher rainsplash erosion (by 160% and 95%, respectively) compared to the unburned plots and areas affected by prescribed fires with low severity. The high-severity prescribed fires changed some soil properties (e.g., pH, electrical conductivity, total nitrogen and phosphorus), while no significant changes were observed in others (e.g., organic carbon and cations). Also low-severity prescribed fires played a significant disturbance on soils (e.g., on electrical conductivity, organic carbon, and total nitrogen), although this disturbance was negligible for some soil properties (e.g., pH and cations) in comparison to unburned soils. The multivariate analysis using the Principal Component Analysis coupled to Analytical Hierarchical Cluster Analysis has demonstrated that fire is able to discriminate unburned and burned soils, especially about organic carbon and nitrogen dynamics. However, this discrimination is not always sharp compared to the unburned sites. This smooth difference was mainly due to the limited soil changes after fire, despite the very high differences in soil temperatures during burning. Overall, this study supports a better understanding of hydrological processes and changes in soil chemistry due to fire with different severity, towards a more effective planning of pre- and post-fire management in fire-affected areas.

KEYWORDS: prescribed fire; fire-severity; soil loss; soil covers; organic matter; nutrients.

1. INTRODUCTION

The hydrological and physico-chemical changes in soils due to fire depend on several factors, such as the fire intensity and severity, amount, type, and water content of fuel, air humidity, wind speed, topography of the site (Certini, 2005). Among these factors, the magnitude of these soil changes is strictly linked to the fire intensity (i.e., the energy release by fire) and severity (i.e., the entity of changes in the burned ecosystem) (Certini, 2005; Zavala et al., 2014). The latter fire characteristic is considered as a key descriptor of the magnitude of the soil changes after fire (Fernández et al., 2020; Fernández and Vega, 2016). More specifically, for low-severity prescribed fires (the planned use of generally low-intensity fire to reduce future wildfire risk in forests), soil heating is low and the impact on soil properties is limited, including erosion (e.g., Cawson et al., 2012; Morris et al., 2014). However, the prescribed fires may have low and high severity, which can variably alter soil hydrological properties. Sometime, their use has been questioned due to some uncertainties over effectiveness and consequences (Altangerel and Kull, 2013). In the soils burned by high-severity prescribed fires, such as fires used to burn piles of logging slash, the burning temperatures are very high, and the fire-induced changes in soil properties are strong and often irreversible (Certini, 2005; Zavala et al., 2014; Zema, 2021). However, the post-fire physico-chemical and biological processes in soils are very complex, due to the large variability of the influential factors (e.g., ash amount, level of vegetation removal, site morphology, weather and post-fire management) (Pereira et al., 2018; Robichaud et al., 2020; Salis et al., 2019). This variability can lead to unexpected responses of soil to fire. In other words, even low-severity prescribed fires can significantly change soil properties (e.g., Carra et al., 2021; Cawson et al., 2016; Hueso-González et al., 2018). In more detail, soil's physical and biological properties are more severely affected by prescribed fires than are its chemical properties (with the electrical conductivity and soil water repellency being the most sensitive soil properties) (Cawson et al., 2016; Hueso-González et al., 2018), and these effects also depend on the time elapsed from the fire application. Conversely, the effects of high-severity prescribed fires are more known, and therefore their impacts can be better anticipated (e.g., Mataix-Solera et al., 2011).

These potentially contrasting results in runoff rates and erosion, and soil properties of burned areas in forests suggest the need of more research about the fire effects on soil hydrology and properties, with particular attention to the fire severity (Cawson et al., 2013). In particular, rainsplash erosion is considered an essential process driving the overall soil loss from burned or disturbed forest hillslopes. Due to the kinetic energy of the rainfall, soil particles are displaced by the raindrop impact, and fall at a distance from their original position. Rainsplash is the first stage of erosion, which detaches a large share of soil particles that can be entrained by overland flow and transported downstream. Insight about this process is very important for land managers, in order to choose the most effective anti-erosive practice (for instance, mulching or erosion barriers). Post-fire surface runoff and soil erosion rates have been largely investigated across the Mediterranean ecosystems under a variety of pedological, climatic and management conditions. This problem is also felt in other environments, especially where soils are highly erodible and rainfall shows high erosivity associated with low soil cover (Russell-Smith et al., 2006). Much attention has also been paid to rainsplash erosion in forests burned by wildfire (e.g., Fernández-Raga et al., 2021; Lucas-Borja et al., 2022; Zavala et al., 2009). In more detail, Fernández-Raga et al. (2021) found high splash erosion in severely-burned drylands of NW Spain, and ascribed this soil loss mainly to the presence of bare soil and the low vegetation recovery rate. Lucas-Borja et al. (2022) reported that rainsplash erosion in semi-arid lands covered by *Macrochloa tenacissima* was much lower compared to the burned areas with the same species and bare soils. Zavala et al. (2009) demonstrated that undisturbed ash and charred litter reduced post-wildfire rainsplash erosion. However, the majority of the published studies have focused on wildfire (Fernández-Raga et al., 2017).

The effects of prescribed fires on surface runoff and erosion have been explored in many environmental contexts, and under variable time (from event to year scales) and spatial (from micro-plot to catchment scale) domains (e.g., Carrà et al., 2021; Ferreira et al., 2015; Jordán et al., 2016). However, the majority of the studies about the erosive effects of the prescribed fires have measured the global erosion rates rather than focusing on the different erosion forms (rainsplash, sheet, and rill erosion). As such, it is difficult to disentangle the contribution of each individual process that contributes the total erosion.

In contrast to those investigations, few studies have explored the magnitude of rainsplash erosion after prescribed fire. To summarise, de Dios Benavides-Solorio and MacDonald (2005) and Pierson et al. (2009) evaluated the prescribed-fire effects on rill and interrill (rainsplash and sheetwash) erosion in pine forest and mountainous sagebrush landscape of Colorado and Idaho, respectively, using simulated rainfalls. Again in the USA (Great Basin Region), Williams et al. (2020) used small-plot (0.5 m^2) rainfall simulations, and overland flow experiments (9 m^2) to quantify the effects of prescribed fire on rainsplash, sheetflow, and concentrated flow erosion processes at two woodlands 9-yr after burning. In Mediterranean areas, Jordán et al. (2016) studied the effect of wettable and water-repellent ash on the intensity of splash erosion in a shrubland burned by a low-severity prescribed fire. Carrà et al. (2021) evaluated rainsplash erosion after a prescribed fire and soil mulching, using a rainfall simulator, in three forests of Southern Italy. From this short state-of-the-art, it is evident that: (i) the published studies generally used simulated rainfalls that do not take into account the natural variability of precipitation as well as the repeated occurrence of rainfalls on the same site; (ii) the comparison of the effects of prescribed fires with low and high severity was never carried out; (iii) the changes in soil properties resulting from the fire application and rainsplash erosion are rarely available (except in the study by Jordán et al., 2016). It is therefore evident that the the knowledge about the rainsplash erosion and modifications in soil properties due to fire is still not sufficient to easily establish forest management practices that mitigate post-fire hydrological risks (Moody et al., 2013; Shakesby, 2011).

To fill these research gaps, this study aims to assess short-term rainsplash erosion and physico-chemical changes of surface soils after prescribed fires of different severities and natural precipitation in Mediterranean forests. This study is the first investigation comparing the rainsplash erosion rates in pine forests of Western Europe burned by prescribed fires with different severity. In these areas, the soils are particularly prone to erosion, given their specific climatic and geomorphological characteristics (soils that are shallow and poor in organic matter, rainstorms that are frequent and very intense).

The two research questions this study addresses are: (i) how much erosion by rainsplash is higher in soils burned by high-severity prescribed fires compared to unburned areas or sites subjected to low-severity fires?; and (ii) which and to what extent physico-chemical properties of the burned soils change after high-severity and low-severity prescribed fires? The replies to these questions should demonstrate whether prescribed fires of different severity are able to noticeably and significantly alter the rainsplash erosion rates as well as other important soil properties.

The results of this study can help to support a better understanding of this key erosional process and the related changes in soil chemistry due to fire, towards to a more informed planning of prescribed fire and post-fire management.

2. MATERIAL AND METHODS

2.1. Study area

The study area (La Moraleja forest) is located in the southern part of the Albacete province (Castilla La Mancha region, Central Eastern Spain) at a mean altitude of 1130 m a.s.l. (Figure 1a). According to the Köppen-Geiger classification, the climate area can be classified as Csa (Mediterranean climate with warm summers (Kottek et al., 2006). The average annual temperature is 14.1 °C, and the total precipitation is 406 mm per year, according to the National Meteorological Agency of Spain (AEMET) records collected at the Hellín weather station (period of 2000–2020). The soils of the study area are classified as cambisols, with a cambic horizon characterized by clay minerals and iron oxides (Chesworth et al., 2008). In geological terms, the area lies among Beti-Iberian Mountain chains with calcareous formations alternating with marly intercalations that date back to the quaternary, according to the map prepared by the National Geographic Institute of Spain in 2006. The current vegetation is mainly composed of *Pinus pinaster* A. at the tree level, whereas *Juniperus oxycedrus* L. is the main shrub species. The understory vegetation is mainly composed of *Macrochloa tenacissima* (L.), *Quercus coccifera* L., *Pistacia lentiscus* L., and *Salvia rosmarinus* L. In general, the tree density in the area approximately ranges from 500 to 600 trees per ha, with diameters of 15 to 25 cm and height of 8 to 15 m. The forest area has not received active management since the early 2000s. In addition, no perturbations, such us forest fires or extreme storms, have been recorded in the study area.

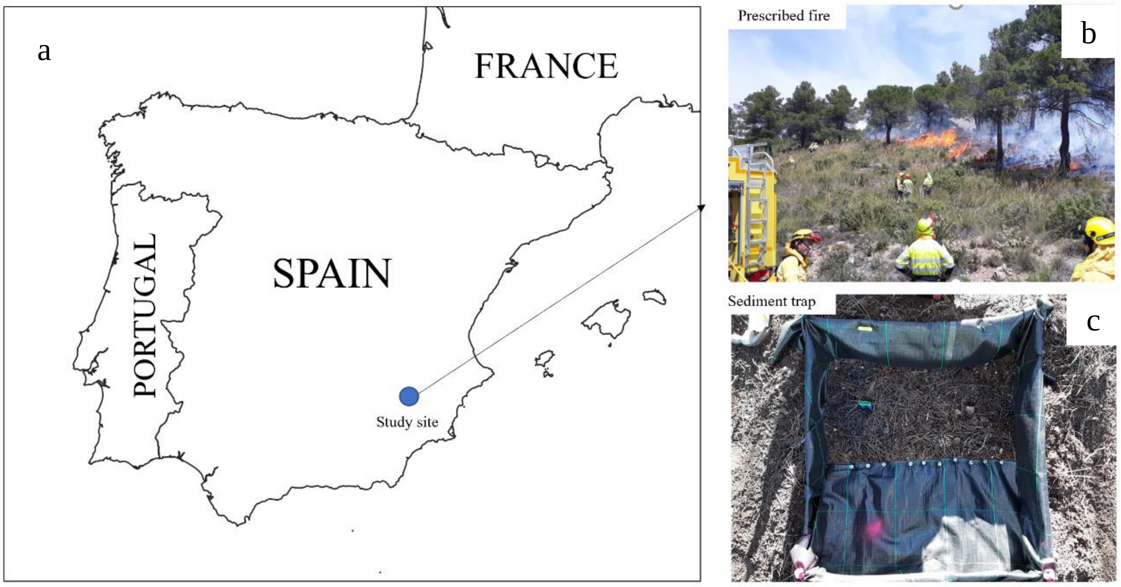


Figure 1 - Geographical location (a) of the study area (La Moraleja forest, Province of Albacete, Castilla La Mancha region, Spain); prescribed fire application (b); sediment trap to monitor rainsplash erosion (c).

2.2. Prescribed fire operations

Prescribed burning was carried out in part of the study area by the Regional Forest Service on 16 October 2019 (Figure 1b). The safety measures were observed by applying the prescribed fire along fire lines separated by 1 m in the opposite direction to dominant winds, to minimize the flame length and height (avoiding that the fire catches up more energy), to reduce the consumed organic matter, and to lower the fire temperatures (Hidalgo et al., 2000). The fire started at 12:30 CET (mean air temperature of 12.3 °C, mean relative humidity of 47% and wind speed of 2.6 km/h with SE direction). The burned area in the site covered 6 ha (coordinates 38º31’12.20”N; -2º11’28.30”E).

2.3. Plot preparation and experimental design

Ten plots of about 2-m2 each were installed inside the burned area prior to burning. Before prescribed fire application, the forest fuel and litter quantity were measured in each plot (Table 1). Moreover and in order to generate high and low severity fire, forest fuel was manually accumulated on each plot (Table 1). The forest fuel was composed mainly of Pinus pinaster A. branches, needles, cones, *Juniperus oxycedrus* L. and *Quercus coccifera* L.

species. A higher fire intensity and severity were expected in plots with greater forest fuel quantity. Finally, five plots were named as low-severity prescribed fire, and five other plots were named as high-severity fire. All plots (e.g. low and high severity prescribed plots) were randomly distributed inside the burned area. The distance between plots was always greater than 300 meters, in order to avoid pseudo-replication. The plots were selected on hillslopes with similar profile slope (between 20 and 25%) and aspect (north), to ensure comparability among the plots.

Table 1 – Main characteristics of the prescribed fire under three soil conditions (no fire, high-severity prescribed fire and low-severity prescribed fire prescribed fire). Soil temperatures were recorded at a 2 cm depth. Mean fuel and litter load were measured at each plot prior to prescribed fire.

Soil condition	**Temperature (°C)**		**Litter (kg/m^2)**		**Fuel (kg/m^3)**	
	Max	*Min*	*Max*	*Min*	*Max*	*Min*
High-severity prescribed fire	685	66.5	1.96	1.24	5.37	1.63
Low-severity prescribed fire	265	35.9	1.01	0.26	1.13	0.15
No fire	-	-	0.89	0.10	1.51	0.2

After the prescribed fire, the burn severity at each plot was classified according to Parson et al. (2010). Following Keeley (2009), the term "burn severity" has caused some confusion, because it is often used interchangeably with fire severity. In this study, two soil conditions for the burn severity of the prescribed fire will be identified: (i) "low-severity prescribed fire"; and (ii) "high-severity prescribed fire". Parson et al. (2010) have proposed some visual indicators to identify the burn severity of soils affected by prescribed fires. In more detail, in the soil treated by the "low-severity prescribed fire", surface organic layers are not completely consumed and are still recognisable, and the ground surface appears brown or black (lightly charred), while the tree canopies appear green. In contrast, a "high-severity prescribed fire" consumes all or nearly all of the pre-fire ground cover and surface organic matter (litter, duff, and fine roots), and charring may be visible on larger roots; the prevailing colour of the site is often "black", due to extensive charring, white or gray ash indicates that considerable ground cover or fuels were consumed. Soil is often gray, orange, or reddish at the ground surface where large fuels were concentrated and consumed.

Soil temperatures during the burn were measured at the soil surface and at a depth of 2 cm (Table 1), using three thermocouples with dataloggers in each plot. The residence time of heat on the ground barely exceeded one hour in the low-severity prescribed fire plots, and five hours in high-severity prescribed fire plots.

Five plots with similar characteristics were selected in a neighbouring unburned area (coordinates 38º31'35.62" N; -2º11'25.60" E). This area was not treated with prescribed fire and was used as an experimental control (hereafter indicated as "no fire").

Therefore, the experimental design consisted of three soil conditions ("no fire", "low-severity prescribed fire", and "high-severity prescribed fire"), each one with five plots as e replications, totalling 15 plots.

2.4. Data collection

2.4.1. Measurement of rainsplash erosion

Immediately after the prescribed fire application, a 50 cm x 50 cm sediment trap was installed at each 2-m^2 plot, one trap per plot (Figure 1c). The sediment trap was delimited by a geotextile fabric fixed to posts and trenched around the outside, to prevent external inputs of runoff or erosion. The bottom part of the sediment trap was protected with geotextile fabric fixed to the soil, to enable periodic sediment collection after each rain event. Therefore, a net area of 0.12 m^2 (30 x 40 cm^2) was exposed to rain drop impact. At each trap, the sediment collected is the soil lost by rainsplash detachment, and this sediment is usually entrapped by the overland flow in its downstream path. However, due to the very small size of the sediment trap, it is unlikely that the overland flow begins, and therefore the installed device is able to measure only the sediment lost by rainsplash erosion, and not by sheet flow. Moreover, no visual indications of other erosion forms were identified in the sediment traps after each rainfall event (e.g., initiating rills, tracks of laminar flow, etc.), and this confirms the fact that this device was able to estimate only rainsplash erosion.

The eroded soil stored in each sediment trap was periodically collected, oven-dried and weighed in the laboratory. Following the methodology used by (Keizer et al., 2018), the following soil covers were measured in the area contributing to each sediment trap: moss, needles, living vegetation (shrub and herbaceous layers), stoniness, dead wood (dead forms of organic material, principally dead plant parts), bare soil and ash (black and white). These covers were measured one day after the prescribed fire application and after each rainfall event (excluding the first date). A weather station (WatchDog 2000 Series model) was placed in the study area to measure the total daily precipitation, rainfall intensity and air temperature during the study period. The soil loss was divided by the precipitation for the period of sediment accumulation (hereafter "unit rainsplash erosion").

2.4.2. Measurement of the physico-chemical properties of soil

In each plot, outside the sediment trap and according to previous studies (Lucas-Borja et al., 2020b), three composite soil samples were collected two days after the prescribed fire and the main physico-chemical properties of the soil sample were analysed. Before sample collection, litter and stones were removed from a 15 × 15 cm square on the soil surface. A ruler (precision of 1 mm) and trowel with markings (precision of 1 cm) were inserted into the soil to remove the top 2-3 cm of soil within the square for each sample. The following physico-chemical properties were analysed: clay, silt and sand contents (determined by the international Robinson pipette method, Gee and Or, 2002), pH, electrical conductivity (EC) (both in deionized water, 1:2.5 and 1:5 w/w, respectively, at 20 °C), organic carbon (SOC, by the potassium dichromate oxidation method, Nelson and Sommers, 1996), total nitrogen (TN, Bremner, 1982), available phosphorus (P, Olsen, 1982), sodium (Na^+), potassium (K^+), and cation exchange capacity (CEC, Roig et al., 1980). The soil texture was calculated based on the measured soil contents of clay, silt and sand, using the Soil Texture Calculator, prepared by the USDA-Soil Survey Staff in 2014.

2.5. Statistical analysis

The statistical analysis was carried out using the XLSTAT release 2019 software. A one-way ANOVA was applied for statistical processing of data about soil loss and physico-chemical properties. In the first case, an ANOVA with repeated measures (one per each monitored precipitation event) was applied to soil loss as dependent or response variable. In the other case, the ANOVA was applied to the three sample measurements of each soil property (dependent or response variable). In both cases, the independent variable (ANOVA factor) was the soil condition with three levels ("no fire", "low-severity prescribed fire", and "high-severity prescribed fire"). The pairwise comparison by Tukey's test (at $p < 0.05$) was also used to evaluate the statistical significance of the differences among the soil conditions in each response variable. In order to satisfy the assumptions of equality of variance and normal distribution, the data were square root-transformed when necessary. A Principal Components Analysis (PCA) was used to identify representative derivative variables (Principal Components, PCs) from the original dataset of soil properties (Lee Rodgers and Nicewander, 1988). In this study, PCA was carried out by standardizing the original variables (expressed by different measuring units) and using Pearson's method to compute the correlation matrix. The first two PCs, explaining at least 70% of the original variance, were retained. Finally, the observations were grouped in clusters using Agglomerative Hierarchical Cluster Analysis (AHCA), a distribution-free ordination technique to group samples with similar characteristics by considering an original group of variables. Euclidean distance was used as the similarity-dissimilarity measure.

3. RESULTS

3.1. Prescribed fire effects on rainsplash erosion

This study has analysed the short-term rainsplash erosion in the period (about one year) when the prescribed fire exerts significant effects on those physical characteristics of the soil that generate erosion (e.g., lack of vegetation, changes in soil aggregate stability, soil water repellency). Throughout the monitoring period, a total rainfall of 397 mm was measured, but only eight precipitation events observed at the study site, ranging from 3 mm of rain (15 June and 14 October 2020) to 23 mm (16 March 2021), caused rainsplash erosion (Figure 2).

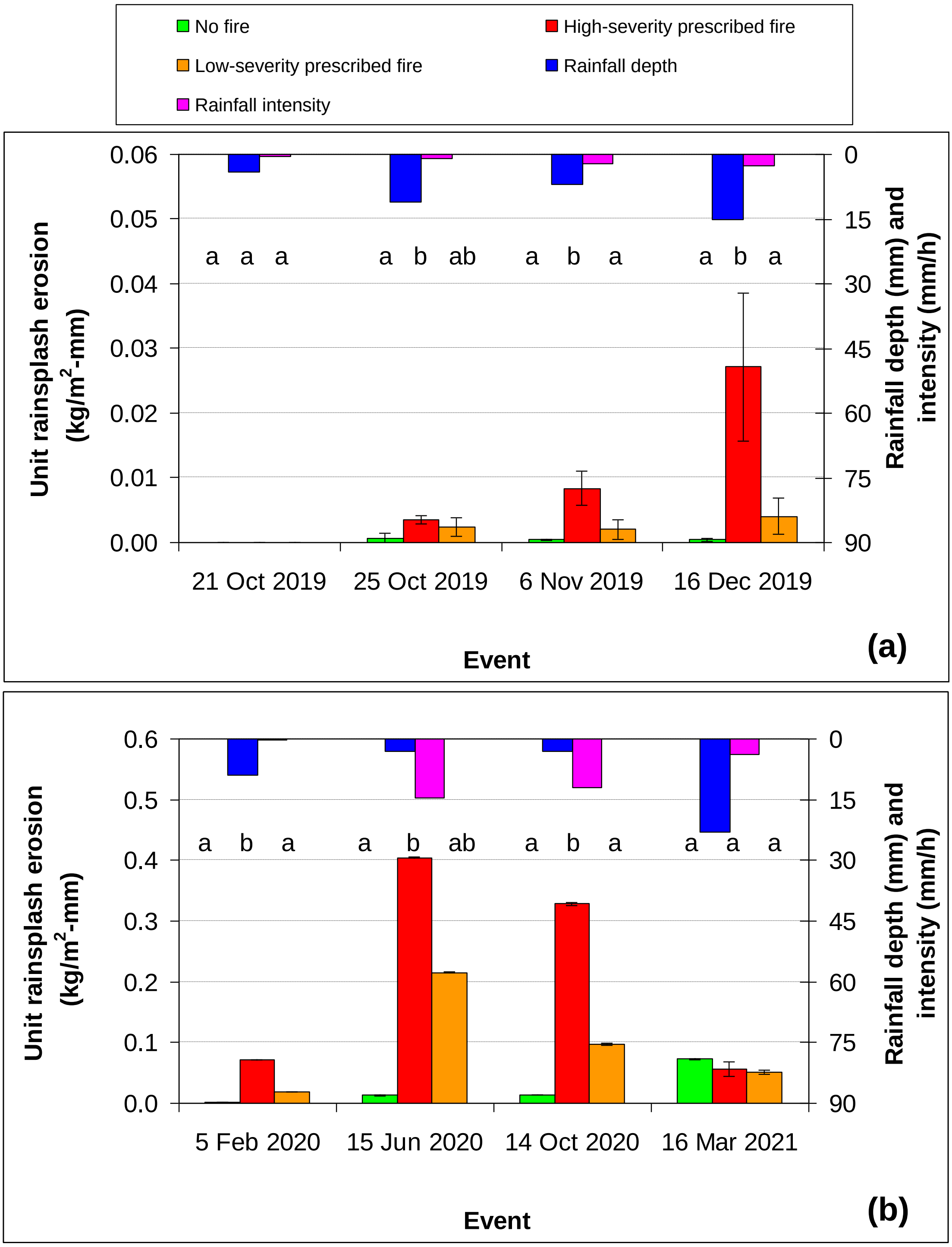


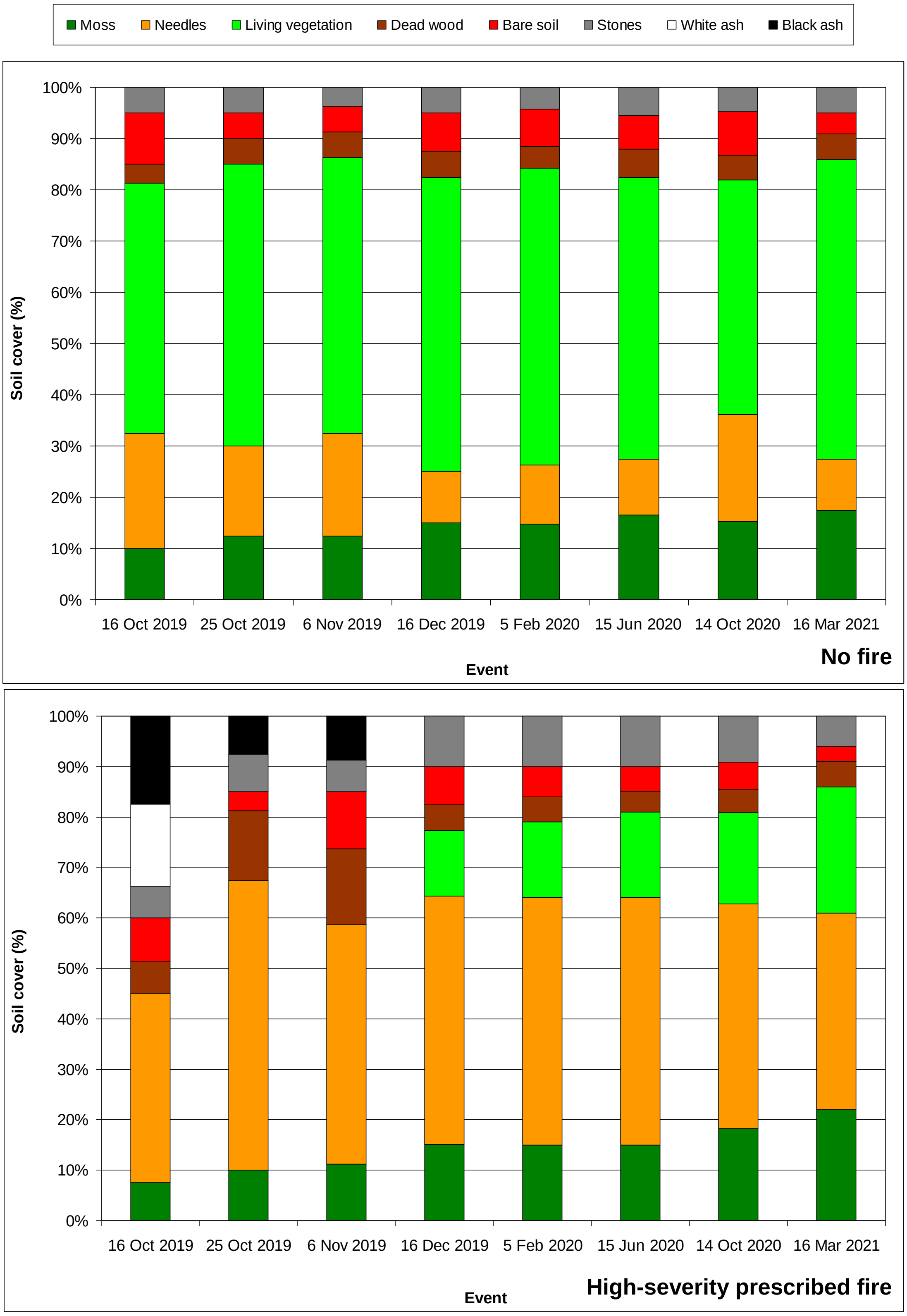
Figure 2 – Unit rainsplash erosion measured at the plot scale under three soil conditions (no fire, high-severity prescribed fire and low-severity prescribed fire) after eight precipitation events in La Moraleja forest (Castilla La Mancha, Spain). (a) Soil losses for the period 21 Oct 2019 – 16 Dec 2019. (b) Soil losses for the period 5 Feb 2020 – 16 Mar 2021. Different letters indicate significantly different mean unit rainsplash erosion rates among the soil conditions.

In the unburned soils, the rainsplash erosion was low for seven of the eight monitored events (from 0 to 0.04 ± 0.05 kg/m^2), and relatively high for the last precipitation (1.67 ± 0.74 kg/m^2 on 16 March 2022). For the first event (21 October 2019), no erosion was observed in any of the studied soil conditions. Over the study, the soil loss measured in the areas burned by low-severity prescribed fires was not significantly higher (from 0 to 1.18 ± 1.04 kg/m^2) compared to the unburned soils. In contrast, the rainsplash erosion in the sites burned by the high-severity fire (from 0.04 ± 0.01 to 1.21 ± 0.47 kg/m^2) was always significantly greater than the unburned area, except for the first event (soil loss equal to zero) and the largest precipitation event (1.29 ± 0.90 kg/m^2, 16 March 2021). For two rainfalls (25 October 2019 and 15 June 2020) the soil loss surveyed after high-intensity fires was not significantly different from the erosion measured in the sites burned at low-intensity (Figure 2).

The precipitation events occurring immediately after the fire (21 October, and 6 November 2019) resulted in lower unit rainsplash erosion under all the studied soil conditions (from 0 to 0.008 ± 0.003 kg/m^2-mm) compared to the subsequent rainfalls. After the event recorded on 16 December 2019, the unit rainsplash erosion increased, particularly in the soils burned by high-severity prescribed fires. In the plots burned by high-severity prescribed fire, the highest unit rainsplash erosion was measured on 15 June 2020 (0.41 ± 0.16 kg/m^2-mm). For the other sites, the maximum values of unit rainsplash erosion occurred on 15 June 2020 for the low-severity prescribed fire (0.22 ± 0.17 kg/m^2-mm), and on 16 March 2021 for the unburned site (0.07 ± 0.05 kg/m^2-mm). For the 16 March 2021 event, the unit rainsplash erosion detected in the unburned soil was even higher (although not significantly) compared to the other soil conditions (0.06 ± 0.04 kg/m^2-mm for the high-severity prescribed fire, and 0.05 ± 0.05 kg/m^2-mm for the low-severity prescribed fire) (Figure 2).

3.2. Prescribed fire effects on cover and physico-chemical properties of soil

The canopy cover was 30% in the unburned area, 40% in the site burned at lower severity and 35.8% in the soils affected by the high-severity prescribed fires. Concerning the ground cover of soils, the unburned plots had an average cover of green material (shrubs and herbaceous vegetation) of 53 ± 4%, while the other cover types were much lower (14-15% of moss and pine needles with minor amounts of dead wood and stones); the bare soil was 7 ± 2% (Figure 3). Fire produced ash in the burned soils, and this ash initially covered the plots (76 ± 5% of black ash and 24 ± 5% of white ash) in the soils burned by fire with high severity, while the ash cover was 34 ± 21% in the areas burned by the low-severity prescribed fire (16% of white ash and 18% of black ash). The remaining part of the low-severity plots was mainly covered by needles (44 ± 6%). Over time the ash cover disappeared, exposing the underlying covers. More specifically, the plots burned at high severity showed a cover of green material of 49 ± 20% and smaller areas with moss (13 ± 6%) and needles (11 ± 6%), while, in the sites affected by the low-severity prescribed fire, the ground cover mainly consisted of needles (44 ± 6%), moss (12 ± 4%) and dead wood (10 ± 5%). The bare soil was 10 ± 4% in these plots and 5 ± 2% in the plots burned by the fire with high severity (Figure 3).


Moss
Needles
Living vegetation
Dead wood
Bare soil
Stones
White ash
Black ash
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Soil cover (%)
16 Oct 2019
25 Oct 2019
6 Nov 2019
16 Dec 2019
5 Feb 2020
15 Jun 2020
14 Oct 2020
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Event
No fire
Soil cover (%)
Event
High-severity prescribed fire

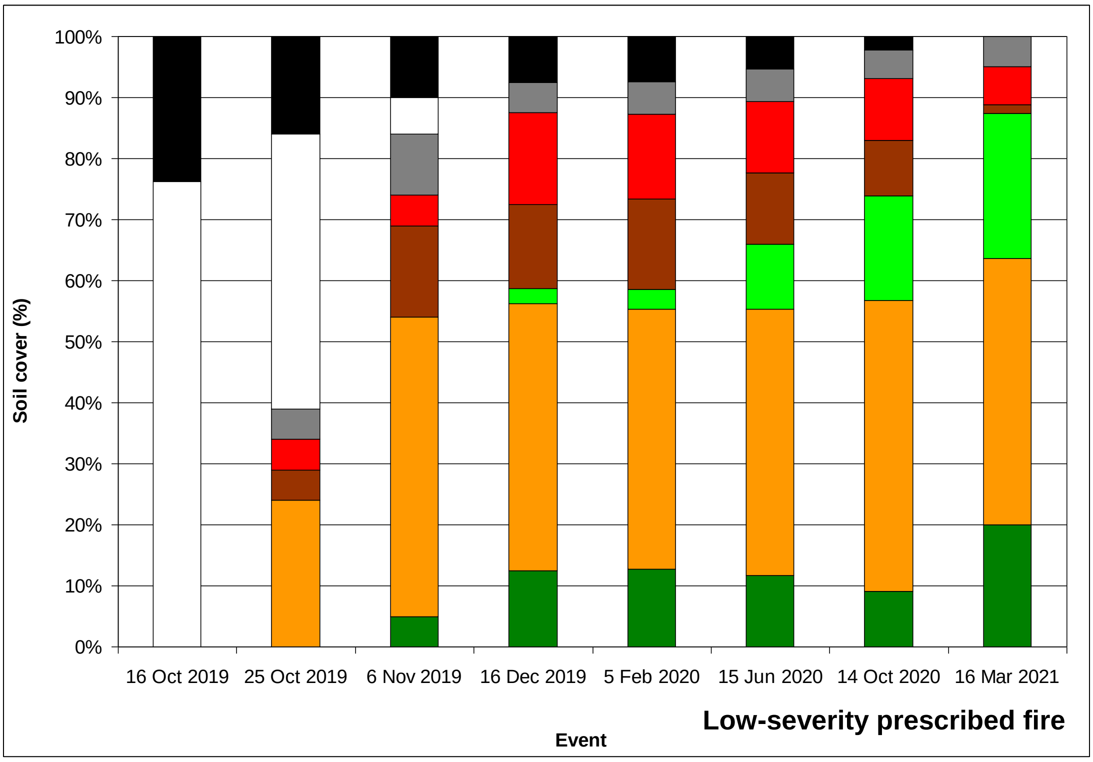


Figure 3 – Evolution of the soil covers in plots under three soil conditions (no fire (a), high-severity prescribed fire (b) and low-severity prescribed fire (c)) after the prescribed fire and eight precipitation events (excluding the first rainfall) in La Moraleja forest (Castilla La Mancha, Spain).

The statistical analysis showed that the cover of white ash was significantly different between the areas burned by high and low-severity prescribed fires, while the difference in the black ash cover was not significant (Figure 4). No significant differences were detected among the three soil conditions for the other ground covers, except for the green material, which was significantly higher in the unburned soils compared to the fire-affected plots. One and a half years after the fire, only the needle and green material covers were significantly different among the soil conditions, with the plots burned by low-severity prescribed fire having more needles and less green material than the unburned plots and the areas burned by the high-severity prescribed fire (Figure 4).

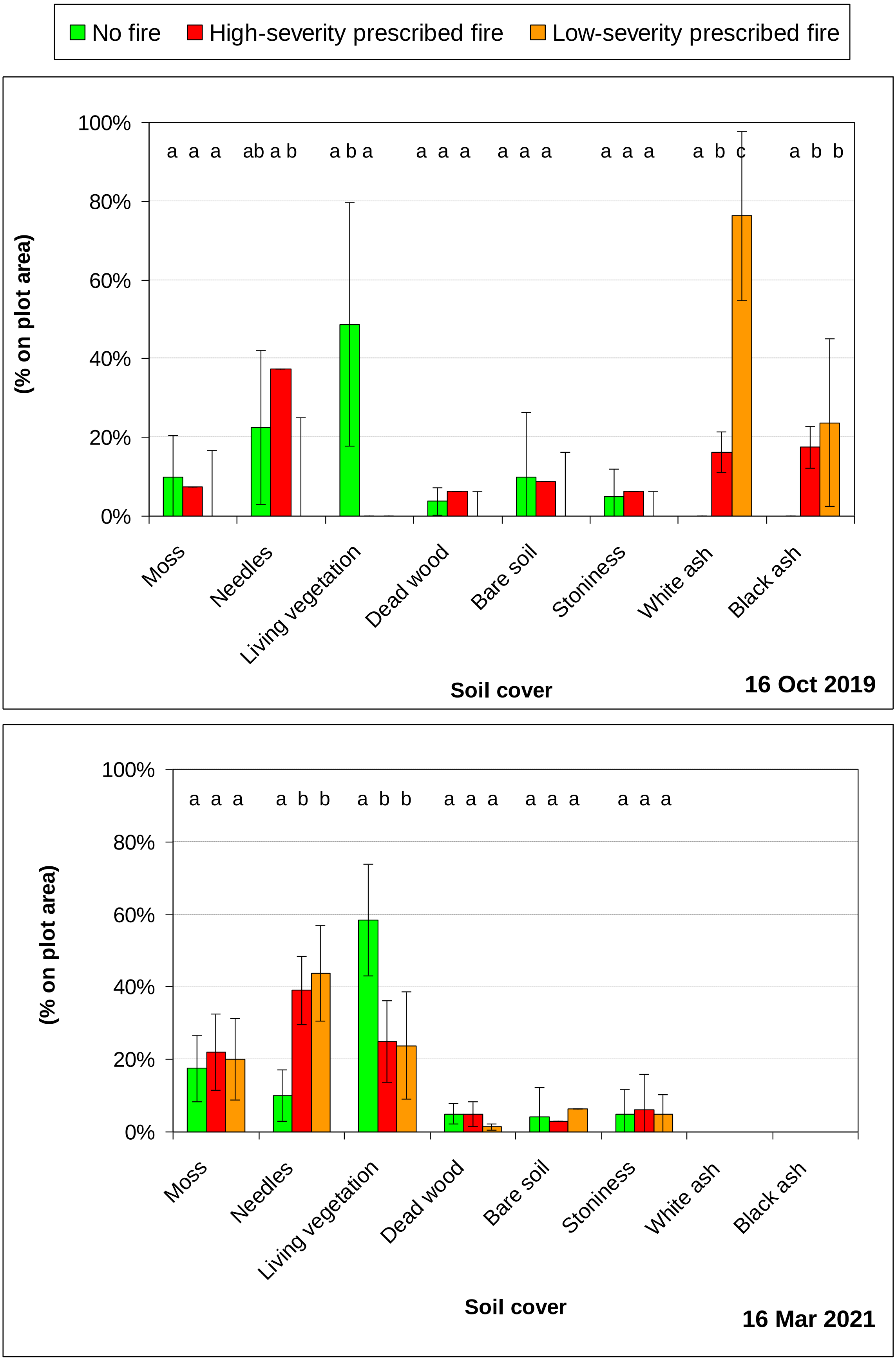
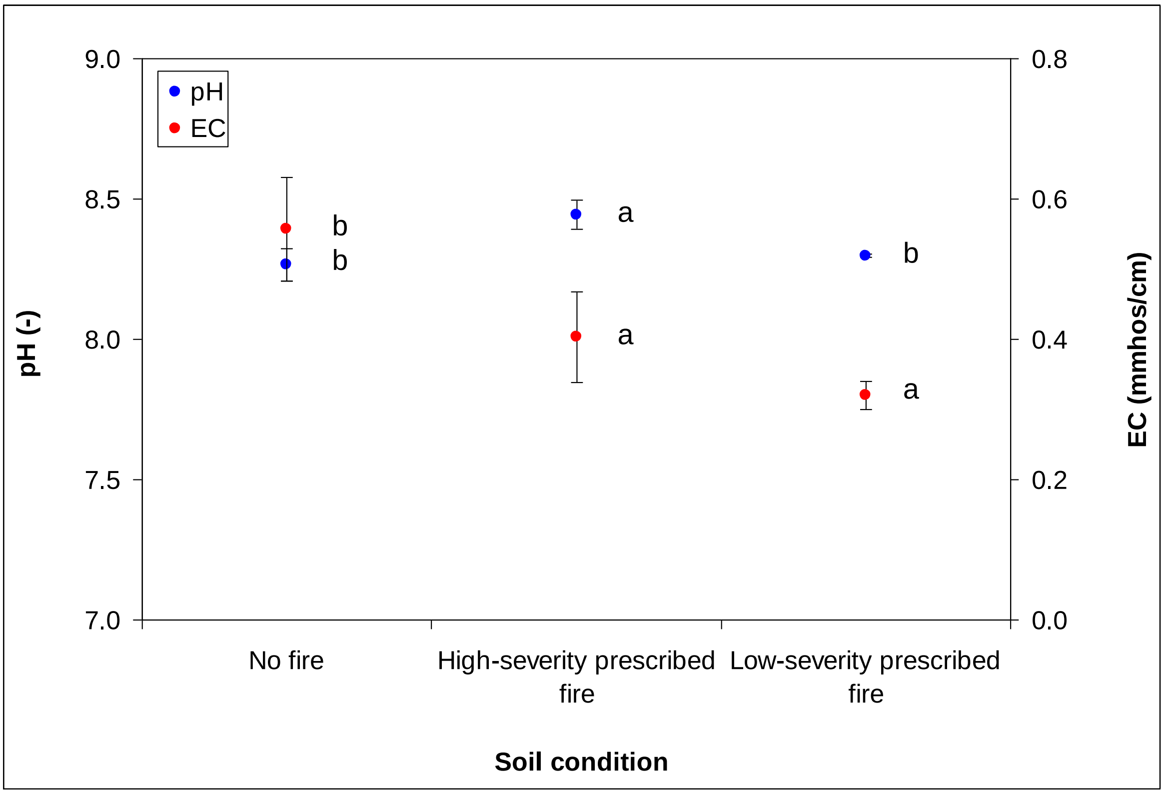
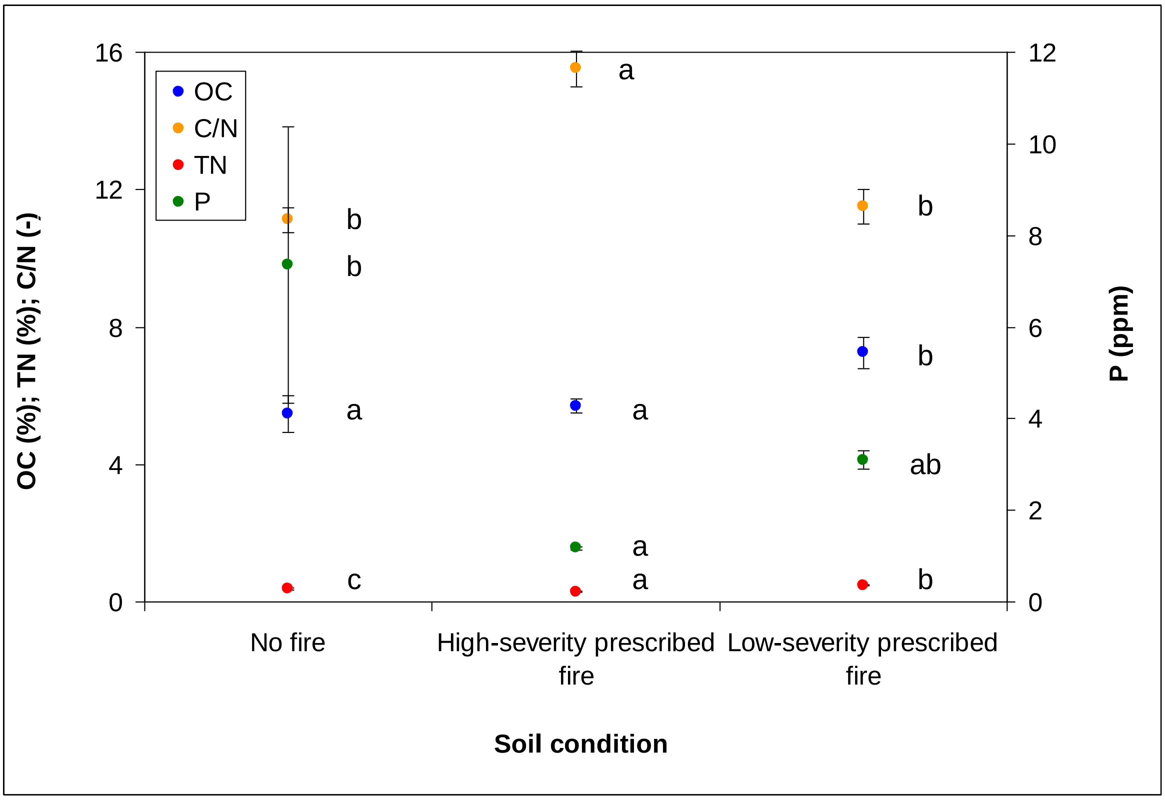


Figure 4 – Soil covers surveyed at two dates in plots under three soil conditions (no fire, high-severity prescribed fire and low-severity prescribed fire) (immediately after fire and one year

and a half after) in La Moraleja forest (Castilla La Mancha, Spain). Different letters indicate significantly different cover among the soil conditions.

Regarding the main physico-chemical properties, the pH was slightly higher in the burned plots (8.30 ± 0.01 for low-severity prescribed fire and 8.44 ± 0.05 for high-severity fire) compared to the unburned sites (8.27 ± 0.06) (Figure 5a). This effect was significant only for the plots burned by the fire with high severity. Compared to the unburned sites, which showed an OC content of 5.47 ± 0.55%, this parameter increased in both fire-affected plots, but the difference was only significant for the soils burned at high severity (7.25 ± 0.45%) (Figure 5b). TN was 0.28 ± 0.02% in unburned plots. This parameter increased in soils burned at low severity (0.36 ± 0.01%) and decreased in soils burned by the fire with high severity(0.22 ± 0.01%). Both these differences were significant according to the ANOVA results (Figure 5b). As a consequence of the variability in OC and N contents of the experimental soils, the C/N ratio significantly increased in soils with high severity (15.52 ± 0.52) and decreased, but without statistical significance, in the plots burned at the low severity (11.50 ± 0.50) in comparison to the unburned soils (11.12 ± 0.35) (Figure 5b). Strong decreases in P contents were detected in the burned plots (1.17 ± 0.04 ppm, high-severity prescribed fire, and 3.10 ± 0.20 ppm, low-severity prescribed fire) compared to the value measured in the unburned soils (7.35 ± 3.02 ppm) (Figure 5b). The statistical analysis revealed that only the difference between the unburned plots and the soils burned by the fire at high severity was significant; in contrast, no significant difference was found between the plots burned at different severity (Figure 5b). EC was equal to 0.56 ± 0.07 mmhos/cm in the unburned plots, and this value was significantly higher than the 0.32 ± 0.02 mmhos/cm in the plots burned by the low-severity prescribed fire and 0.40 ± 0.07 mmhos/cm in sites burned by the high-severity prescribed fire (Figure 5c). Concerning the cation contents of the soils, K^+ measured in the unburned soils (0.44 ± 0.01 meq/100 g) was not significantly different from the plots burned at high or low severity. Na^+ content slightly but not significantly varied among the burned and unburned soils (0.06 ± 0.05 meq/100 g). There were also slight but not significant differences in the CEC among the three soil conditions, which were similar as the value measured in the unburned soils (19.79 ± 8.50 meq/100 g) (Figure 5c).


pH
EC
9.0
8.5
8.0
7.5
7.0
0.8
0.6
0.4
0.2
0.0
pH (-)
EC (mmhos/cm)
b
b
a
a
b
a
No fire
High-severity prescribed fire
Low-severity prescribed fire
Soil condition


OC
C/N
TN
P
16
12
8
4
0
12
10
8
6
4
2
0
OC (%); TN (%); C/N (-)
P (ppm)
a
b
b
b
b
a
a
b
ab
a
c
a
b
No fire
High-severity prescribed fire
Low-severity prescribed fire
Soil condition

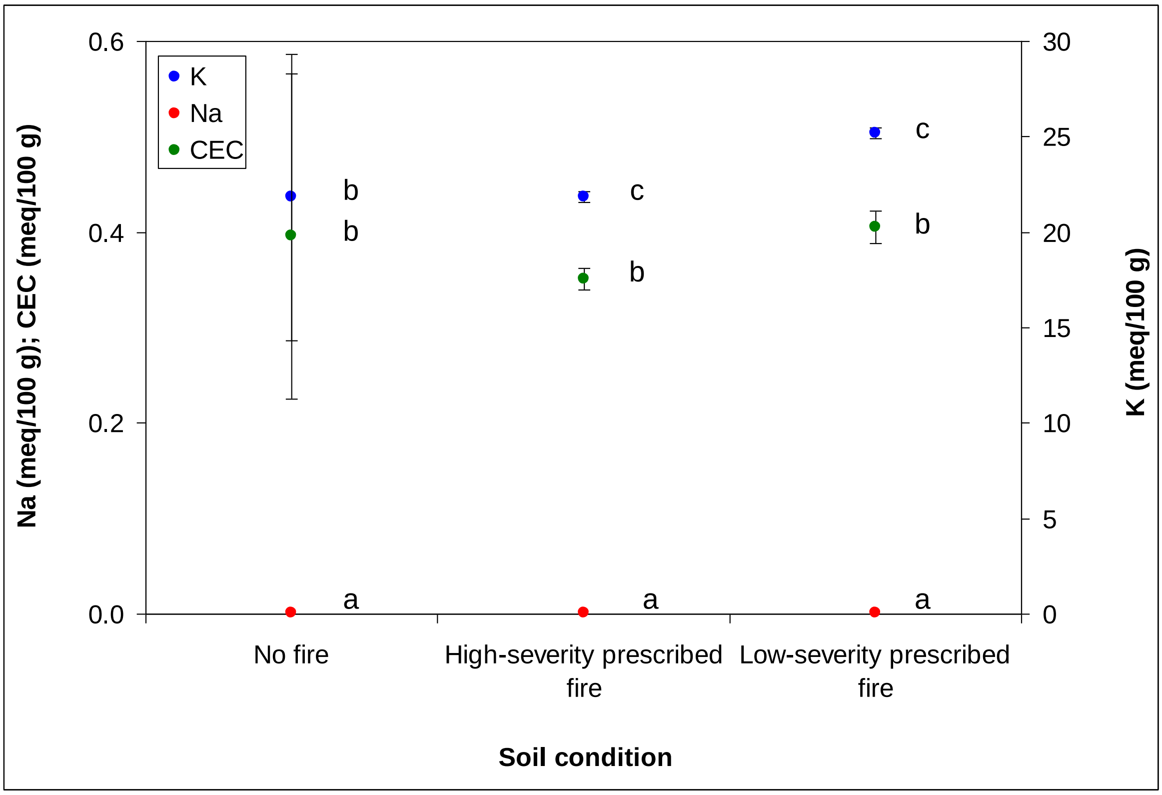


Figure 5 – Main physico-chemical properties of soils under three conditions (no fire, high-severity prescribed fire, and low-severity prescribed fire) immediately after burning (16 October 2019) in La Moraleja forest (Castilla La Mancha, Spain): pH and electrical conductivity (EC) (a); organic carbon (OC), carbon/nitrogen (C/N) ratio, total nitrogen (TN), and phosphorous (P) (b); and potassium (K^+), sodium (Na^+), and cation exchange capacity (CEC) (c). Different letters indicate significantly different properties among the soil conditions.

The PCA identified two Principal Components (PC1 and PC2), which together explained 73% of the variance of the original physico-chemical properties of soils; a third PC (PC3) explained another 21% of this variance. Of these soil parameters, pH, P, Na^+, and C/N had high loadings (> |0.736|) on the first PC, P had a positive loading (0.908), while the other properties had negative weights (> |-0.736|). EC, OC and TN significantly influenced the PC2 (positive for OC, 0.902, and TN, 0.814, and negative for EC, -0.676), while the PC3 was associated with high loadings to K^+ (-0.728) and CEC (0.771) (Figure 6a). The AHCA clustered the observations in two homogenous groups, of which the first cluster grouped all soil samples collected in the burned plots (both for high and low severity prescribed fires) and a few samples collected in the unburned sites and the second cluster consisted of only unburned soils (Figure 6b).

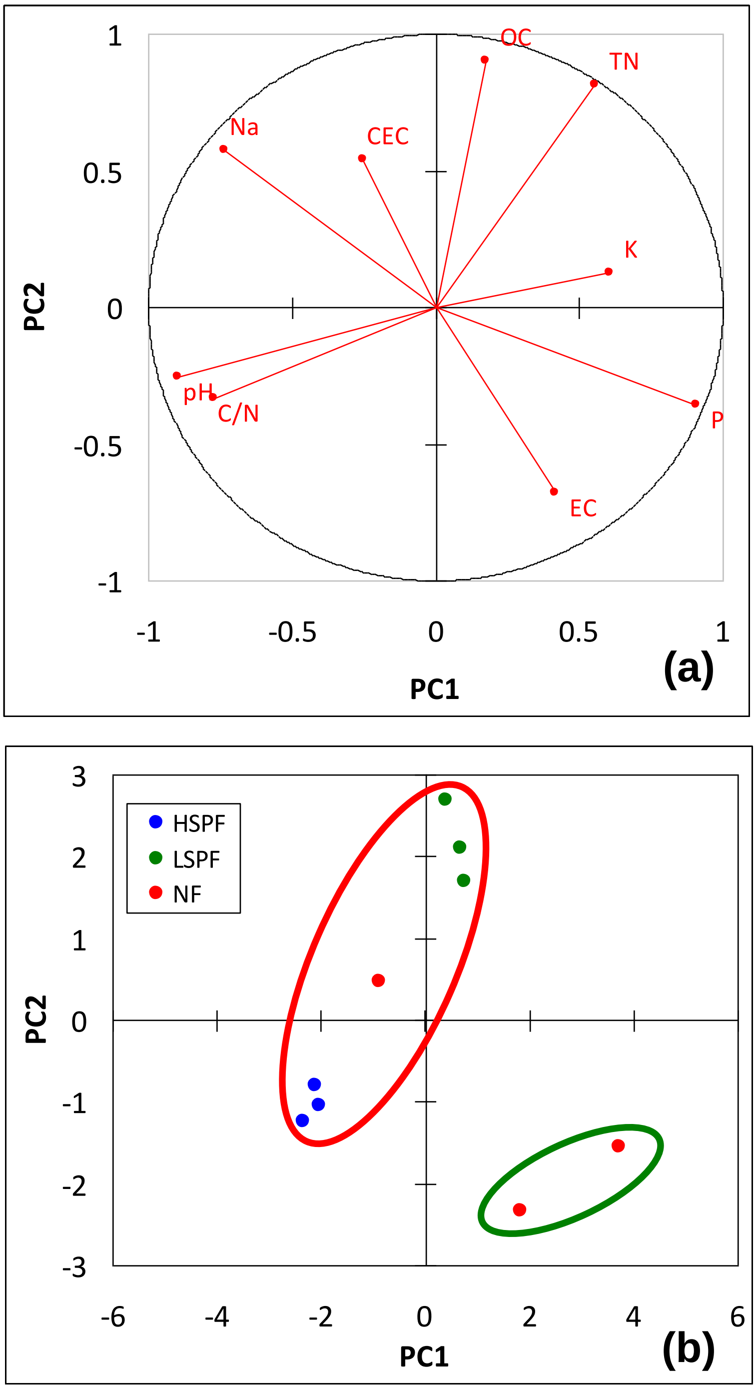


Figure 6 – Loadings of the original variables (a, physico-chemical properties of soil), and scores with relevant clusters (b) on the first two Principal Components (PC1 and PC2) provided by the Principal Component Analysis coupled by Analytical Hierarchical Cluster Analysis applied to soil samples under three soil conditions (no fire, NF; high-severity prescribed fire, HSF; low-severity prescribed fire, LSF) in the study area (La Moraleja forest,

Castilla La Mancha, Spain). Notes: EC = electrical conductivity; OC = organic carbon; TN = total nitrogen; C/N = carbon to nitrogen ratio; P = phosphorous; K^+ = potassium; Na^+ = sodium; CEC = cation exchange capacity.

4. DISCUSSIONS

4.1. Prescribed fire effects on rainsplash erosion

Rainsplash erosion is a key component of soil loss in forest environments, especially when the soil is exposed to short and intense rainfalls with high erosive power, as under the semi-arid Mediterranean climate. Fires with different severity (including the prescribed fires), burning vegetation and altering the physico-chemical properties of soils, may enhance rainsplash erosion with heavy in-site and off-site hydrological effects.

This study has explored the changes in the rainsplash erosion rates and in the main chemical properties of soil after prescribed fires with low and high severity in the short term, when the soil disturbance is high and the vegetation cover is absent or noticeably reduced. In this window of disturbance of fires (Prosser and Williams, 1998), the vegetal cover of soil was removed. The soil wass left bare and then exposed to rainfall erosivity. The impacts of prescribed fires with different severity (low and high) on the rainsplash erosion rates were not significantly different, as, conversely, they would be expected according to the literature (e.g., de Dios Benavides-Solorio and MacDonald, 2005; Pierson et al., 2009). As a matter of fact, no erosion was observed after the first rainfall events, and this contrasts with several studies that report increases in soil loss immediately after both prescribed burning and wildfire (e.g., Cawson et al., 2016; Lucas-Borja et al., 2020a). In our plots, the rainfall depths throughout the observation period were low: all eight events had amounts lower than 23 mm, and only two rainfalls are considered “erosive events” (depth over 13 mm) according to Wischmeier and Smith (1978). This means that precipitation for most of the events in the study was too low to cause measurable soil loss due to rainsplash erosion even in the soils burned by the high-severity prescribed fire.

For the first seven of the monitored events, rainsplash erosion (up to 0.04 kg/m^2-yr) was noticeably under the low end of the tolerance range of 0.3-1.1 kg/m^2-yr (Wischmeier and Smith, 1978; Bazzoffi, 2009). The soils burned by our low severity fire unexpectedly produced noticeable erosion after a very low rainfall, while, for larger precipitation events, the soil loss was lower. In contrast, in the severely-burned soils, the rainsplash erosion was negligible for the first three events, then, for the subsequent four precipitations, the soil loss increased. The main reason of the noticeable erosion recorded for an event with very low rainfall depth in the burned soil against a limited value of the unburned soil was the high rainfall intensity of this event compared to the other precipitations recorded in the observation period. However, other factors (such as the fire-induced soil water repellency and the reduction in infiltration) that were not measured in this investigation may have played a role on these differences. The burned soils showed a ground cover very similar as the values measured in the unburned soil. This means that rainsplash erosion, which is limited by the soil protection due to the presence of vegetation, litter, and stones, should also be comparable among the three soil conditions. In general, after fires with different intensities increase in surface runoff (and, therefore, in erosion) are expected. Limiting the attention to fire at low intensity, Carrà et al. (2022) showed a significant runoff generation (about 2 to 4-fold the values measured in the unburned plots) after a prescribed fire in forest stands of Southern Italy, while Vega et al. (2005) found increases in runoff between two and five times the unburned soils in shrublands of Northern Spain. Regarding erosion, the literature reports that this process is not minimal following low-intensity fires (Coelho et al., 2004; de Dios Benavides-Solorio and MacDonald, 2005; Morris et al., 2014). The reasons why the rainsplash erosion was negligible for the first three monitored events should be ascribed to different factors: (i) the effects of ash released by fires, which protects the soil surface from the raindrop impacts during low-intensity rainfall and absorbs part of the precipitation (Cerdà and Doerr, 2008); (ii) the immediate restoration of part of the pre-fire vegetation cover; (iii) the lack of erosive events. The role of soil water repellency induced by fire and the decrease in water infiltration may be also important in driving the post-fire hydrological processes (Plaza-Álvarez et al., 2019, 2018), but these variables could not be measured in this study, and this represents a limitation of the investigation.

4.2. Prescribed fire effects on cover and physico-chemical properties of soil

Fires with both severities exerted significant changes on some of the studied soil properties in comparison to the unburned soils. More specifically, the changes in pH were slight and significant only for the prescribed fire with high severity. The literature generally reports reductions in soil pH after low severity fires (e.g., Alcañiz et al., 2016; Valkó et al., 2016), while increases are common when the burn severity is high, as found in this study. In this case, soil pH increase is due to denaturation of organic acids (Certini, 2005) and the increase of sodium and potassium oxides, carbonates and hydroxides from heating (Pereira et al., 2018; Ulery et al., 1993).

The EC significantly decreased in burned soils, regardless of burn severity. This result is unexpected, since an increase in EC is reported by many authors (Alcañiz et al., 2020; Granged et al., 2011; Scharenbroch et al., 2012). The reasons of previously reported EC increases after fire are the incorporation of ash (Fonseca et al., 2017; Scharenbroch et al., 2012; Úbeda and Outeiro, 2009), release of soluble ions during the combustion of organic matter (Alcañiz et al., 2016), and formation of black carbon (Alcañiz et al., 2020). In contrast, other studies show that EC can decrease, especially after fires with low intensity (Alcañiz et al., 2020). Accordingly, we ascribe the decrease in EC measured in this study to the absence of leaching effect of ions from ash into the soil, due to the lack of rainfall after the fire, and the very short time of sampling after fire (two days against some time after appreciable precipitations of other studies). This explanation is in close accordance with Neary et al. (1999), who state that salts are quickly leached or transported by runoff after burning. Direct measurements of the ion contents in the soil should corroborate this hypothesis.

The fate of OC was different between low- and high-intensity fires. The significant increase detected after low-intensity fires may be due to partially pyrolyzed plant residues (Agbeshie et al., 2022; Caon et al., 2014), incomplete combustion of the organic matter (Alcañiz et al., 2020; Soto and Diaz-Fierros, 1993; Úbeda et al., 2005) and to forest floor decomposition (Scharenbroch et al., 2012). It is possible that litter combustion in addition to forest floor decomposition could have increased the OC content of the soil. According to some studies (e.g., Scharenbroch et al., 2012; Soto and Diaz-Fierros, 1993), OC increases in soils burned at low severity compared to unburned areas. In contrast, after the high-severity prescribed fire of this study, the OC was not different in comparison to the unburned plots. In general, fires with high severity determine the almost total combustion of OC with its mineralization, volatilization, and solubilisation (Rodriguez-Cardona et al., 2020), due to the very high temperature of fire. Soil heating at high temperatures generally reduces the amount and quality of OC (Merino et al., 2018), since severe wildfires are able to induce volatilization of high amounts of carbon and nitrogen, which start to vaporize at about 200 °C (Pereira et al., 2018), and are totally consumed lost over 550 °C (Gray and Dighton, 2006). However, in our study, the expected loss of OC due to soil heating could have been balanced by the supply of partially burned residues and charred leaves, falling on forest ground immediately after fire. Presumably, the total content of OC did not change, but it may be possible that the type of organic compounds did, although the relevant determinations were not made in this investigation.

Fires also induced noticeable changes in the nutrient content of soils, with significant decreases in TN and P after the high-severity fire. The low-severity fire resulted in an increase in TN and a decrease in P compared to the unburned conditions, and the plots burned at high severity had a decrease in TN and an even greater decrease in P than what observed in no fire condition. After burning, organic N decreases due to volatilisation (Binkley and Fisher, 2019; Turner et al., 2007), due to the soil heating. With low-severity fires, noticeable amounts of organic N can remain in the soil, but in different form than before the fire. In line with some authors (Giovannini et al., 1988; Grogan et al., 2000; Rivas et al., 2012; Smithwick et al., 2005), the increase in TN detected in this study in soils burned by the low-intensity fire is probably due to two factors: (i) the addition of partially pyrolyzed materials containing N (as explained earlier in the case of the OC) and (ii) the release of N in dead roots and compounds. Regarding the P dynamics, the reductions measured at both fire severities are ascribed to volatilisation due to high temperatures (Certini, 2005). The reduction in P contrasts some earlier studies, which reported that fires result in an enrichment of available P (Macadam, 1987; Serrasolsas and Khanna, 1995), which then rapidly declines. The increases in P after low intensity fires is generally ascribed to the release of basic cations from the organic matter, ash formation and its incorporation into the soil (Kennard and Gholz, 2001).

The measurements of cation contents of the burned soils in this study did not show significant changes compared to the unburned plots. Only slight increases of K^+, Na^+ and CEC were detected in soils affected by the fire at low severity. Increases in available cations, such as Na^+ and K^+, are common in soils burned by low-severity prescribed fires (e.g., Arocena and Opio, 2003; Kennard and Gholz, 2001; Scharenbroch et al., 2012). In our soils burned by prescribed fires at high severity, the contents of these cations varied compared to the unburned soils: the CEC decreased, no difference in K^+, and increased Na^+. These slight changes contrast several previous studies that showed more significant increases (e.g., Elliott et al., 2013; Khanna and Raison, 1986; Shrestha and Chen, 2010). As with the EC results above, the lack of cation response in the plots burned by prescribed fires at high severity may have been due to the immobilization of these compounds into ashes (Pereira et al., 2018) that were not yet leached into the burned soils (Alcañiz et al., 2020; Cawson et al., 2012). This lack of response is relevant to the cations studied, but this could have been also observed because major cations were not analysed. Declines in CEC are mainly due to the combustion of soil organic matter and the transformation of clay minerals, especially at very high temperatures (Zavala et al., 2014), and this explains what we observed in this study after high-severity prescribed fires.

The combined analysis of the physico-chemical properties of the soil through PCA shows an evident mismatching between the dynamics of OC and TN (associated with the PC1) and the other elements or compounds, such as P, K^+ and Na^+ (linked to the other two PCs). Moreover, the PCA coupled to AHCA reveals a clear discrimination between burned soils, regardless of burn severity, and all but one unburned area. This demonstrates that fire can change the physico-chemical properties of soils, but these changes are often not so noticeable to create a disrupting differentiation in soil conditions.

Overall, the results of this study suggest to land managers caution in applying prescribed fires with high burn severity, since burning can increase the erosion rates in the short term. Changes in some important physico-chemical properties of soils can be expected, and this requires suitable post-fire management actions, when these modifications become noticeable with specific regard to carbon and nitrogen contents of the burned soils. For instance, soil mulching with vegetal residues may be beneficial to reduce rainsplash erosion when the soil is left bare due to burning. The application of mulch material could also balance the loss of carbon and nitrogen compounds due to burning. Log erosion barriers or contour felled log debris may be locally installed (for instance, when sheetwash may be generated), in order to control the overland and rill erosion.

5. CONCLUSIONS

Replying to the first research question, the study has shown that rainsplash erosion in forest soils burned by prescribed fires with high severity under Mediterranean conditions may be on average higher by 160% and 95% compared to the unburned plots and areas affected by prescribed fires with low severity, respectively. Regarding the second research question, the study has highlighted that high-severity prescribed fires can change some important soil properties (e.g., pH, EC, TN and P), but some changes are not always significant (e.g., OC and cations) compared to the unburned soils. Also, low-severity prescribed fires can significantly change some chemical properties of soils (e.g., EC, OC and TN), while, for other soil parameters, the changes are negligible (e.g., pH and cations) in comparison to unburned soils. However, the differences in post-fire soil changes were limited, but those in soil temperatures during burning were large between the high- and low-severity prescribed fires. This discrimination was not always sharp compared to the unburned sites.

Overall, this study can help to support a better understanding of a key process such as rainsplash erosion and the related changes in soil chemistry due to fire. Land managers should be aware that prescribed fires can increase the erosion rates and change some important physico-chemical properties of soils in the short term. Therefore, a proper control of the erosion rates and the main properties of burned soils are suggested together with the possible adoption of effective post-fire management actions, in order to limit these negative fire impacts.

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