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

3
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22
23 **ABSTRACT**

24
25 Prescribed burning with different severity may induce erosion and change many physico-
26 chemical properties of forest soils. Few studies have compared the effects of prescribed fires
27 with different severity on rainsplash erosion and soil properties under natural rainfalls.
28 Therefore, there is the need to better understand these variables of forest soils burned by
29 prescribed fires with low and high severity under natural conditions. Rainsplash erosion, and
30 covers and physico-chemical properties of surface soil have been evaluated in the short term
31 (15 months) in micro-plots of a burned pine forest of Central-Eastern Spain in comparison to
32 unburned areas. The results of the investigation have shown that the high-severity fires gave
33 higher rainsplash erosion (by 160% and 95%, respectively) compared to the unburned plots
34 and areas affected by prescribed fires with low severity. The high-severity prescribed fires

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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

69 processes in soils are very complex, due to the large variability of the influential factors (e.g.,
70 ash amount, level of vegetation removal, site morphology, weather and post-fire management)
71 (Pereira et al., 2018; Robichaud et al., 2020; Salis et al., 2019). This variability can lead to
72 unexpected responses of soil to fire. In other words, even low-severity prescribed fires can
73 significantly change soil properties (e.g., Carra et al., 2021; Cawson et al., 2016; Hueso-
74 González et al., 2018). In more detail, soil's physical and biological properties are more
75 severely affected by prescribed fires than are its chemical properties (with the electrical
76 conductivity and soil water repellency being the most sensitive soil properties) (Cawson et al.,
77 2016; Hueso-González et al., 2018), and these effects also depend on the time elapsed from
78 the fire application. Conversely, the effects of high-severity prescribed fires are more known,
79 and therefore their impacts can be better anticipated (e.g., Mataix-Solera et al., 2011).
80 These potentially contrasting results in runoff rates and erosion, and soil properties of burned
81 areas in forests suggest the need of more research about the fire effects on soil hydrology and
82 properties, with particular attention to the fire severity (Cawson et al., 2013). In particular,
83 rainsplash erosion is considered an essential process driving the overall soil loss from burned
84 or disturbed forest hillslopes. Due to the kinetic energy of the rainfall, soil particles are
85 displaced by the raindrop impact, and fall at a distance from their original position.
86 Rainsplash is the first stage of erosion, which detaches a large share of soil particles that can
87 be entrained by overland flow and transported downstream. Insight about this process is very
88 important for land managers, in order to choose the most effective anti-erosive practice (for
89 instance, mulching or erosion barriers). Post-fire surface runoff and soil erosion rates have
90 been largely investigated across the Mediterranean ecosystems under a variety of pedological,
91 climatic and management conditions. This problem is also felt in other environments,
92 especially where soils are highly erodible and rainfall shows high erosivity associated with
93 low soil cover (Russell-Smith et al., 2006). Much attention has also been paid to rainsplash
94 erosion in forests burned by wildfire (e.g., Fernández-Raga et al., 2021; Lucas-Borja et al.,
95 2022; Zavala et al., 2009). In more detail, Fernández-Raga et al. (2021) found high splash
96 erosion in severely-burned drylands of NW Spain, and ascribed this soil loss mainly to the
97 presence of bare soil and the low vegetation recovery rate. Lucas-Borja et al. (2022) reported
98 that rainsplash erosion in semi-arid lands covered by *Macrochloa tenacissima* was much
99 lower compared to the burned areas with the same species and bare soils. Zavala et al. (2009)
100 demonstrated that undisturbed ash and charred litter reduced post-wildfire rainsplash erosion.
101 However, the majority of the published studies have focused on wildfire (Fernández-Raga et
102 al., 2017).

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

110 In contrast to those investigations, few studies have explored the magnitude of rainsplash
111 erosion after prescribed fire. To summarise, de Dios Benavides-Solorio and MacDonald
112 (2005) and Pierson et al. (2009) evaluated the prescribed-fire effects on rill and interrill
113 (rainsplash and sheetwash) erosion in pine forest and mountainous sagebrush landscape of
114 Colorado and Idaho, respectively, using simulated rainfalls. Again in the USA (Great Basin
115 Region), Williams et al. (2020) used small-plot (0.5 m²) rainfall simulations, and overland
116 flow experiments (9 m²) to quantify the effects of prescribed fire on rainsplash, sheetflow, and
117 concentrated flow erosion processes at two woodlands 9-yr after burning. In Mediterranean
118 areas, Jordán et al. (2016) studied the effect of wettable and water-repellent ash on the
119 intensity of splash erosion in a shrubland burned by a low-severity prescribed fire. Carrà et al.
120 (2021) evaluated rainsplash erosion after a prescribed fire and soil mulching, using a rainfall
121 simulator, in three forests of Southern Italy. From this short state-of-the-art, it is evident that:
122 (i) the published studies generally used simulated rainfalls that do not take into account the
123 natural variability of precipitation as well as the repeated occurrence of rainfalls on the same
124 site; (ii) the comparison of the effects of prescribed fires with low and high severity was never
125 carried out; (iii) the changes in soil properties resulting from the fire application and
126 rainsplash erosion are rarely available (except in the study by Jordán et al., 2016). It is
127 therefore evident that the the knowledge about the rainsplash erosion and modifications in soil
128 properties due to fire is still not sufficient to easily establish forest management practices that
129 mitigate post-fire hydrological risks (Moody et al., 2013; Shakesby, 2011).

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

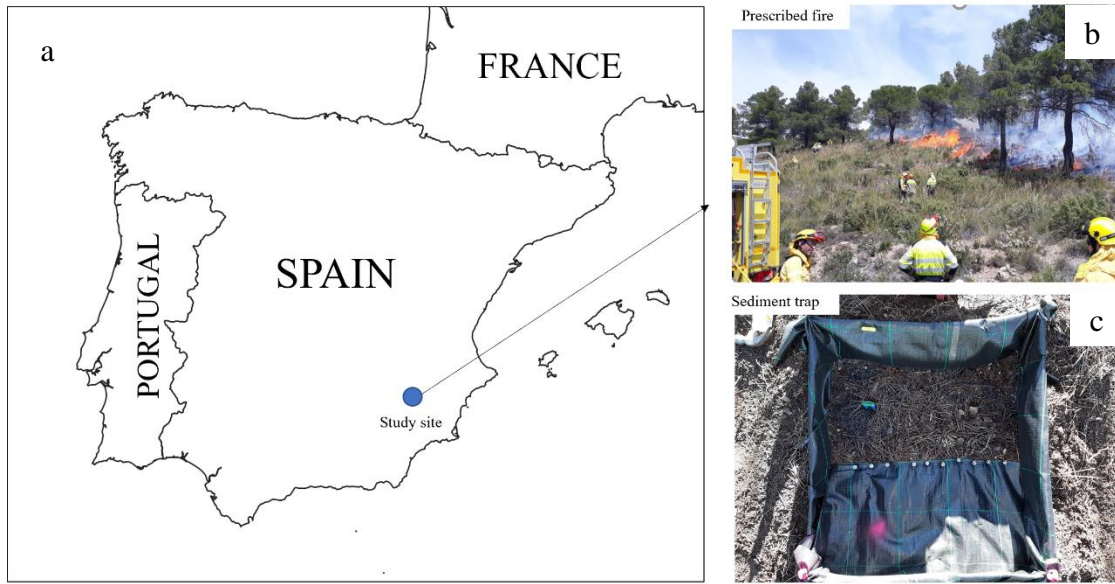
137 The two research questions this study addresses are: (i) how much erosion by rainsplash is
138 higher in soils burned by high-severity prescribed fires compared to unburned areas or sites
139 subjected to low-severity fires?; and (ii) which and to what extent physico-chemical
140 properties of the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

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

148 **2. MATERIAL AND METHODS**

150 **2.1. Study area**

151
152 The study area (La Moraleja forest) is located in the southern part of the Albacete province
153 (Castilla La Mancha region, Central Eastern Spain) at a mean altitude of 1130 m a.s.l. (Figure
154 1a). According to the Köppen-Geiger classification, the climate area can be classified as Csa
155 (Mediterranean climate with warm summers (Kottek et al., 2006). The average annual
156 temperature is 14.1 °C, and the total precipitation is 406 mm per year, according to the
157 National Meteorological Agency of Spain (AEMET) records collected at the Hellín weather
158 station (period of 2000–2020). The soils of the study area are classified as cambisols, with a
159 cambic horizon characterized by clay minerals and iron oxides (Chesworth et al., 2008). In
160 geological terms, the area lies among Beti-Iberian Mountain chains with calcareous
161 formations alternating with marly intercalations that date back to the quaternary, according to
162 the map prepared by the National Geographic Institute of Spain in 2006. The current
163 vegetation is mainly composed of *Pinus pinaster* A. at the tree level, whereas *Juniperus*
164 *oxycedrus* L. is the main shrub species. The understory vegetation is mainly composed of
165 *Macrochloa tenacissima* (L.), *Quercus coccifera* L., *Pistacia lentiscus* L., and *Salvia*
166 *rosmarinus* L. In general, the tree density in the area approximately ranges from 500 to 600
167 trees per ha, with diameters of 15 to 25 cm and height of 8 to 15 m. The forest area has not
168 received active management since the early 2000s. In addition, no perturbations, such us
169 forest fires or extreme storms, have been recorded in the study area.



171
 172 Figure 1 - Geographical location (a) of the study area (La Moraleja forest, Province of
 173 Albacete, Castilla La Mancha region, Spain); prescribed fire application (b); sediment trap to
 174 monitor rainsplash erosion (c).

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 177 **2.2. Prescribed fire operations**

178
 179 Prescribed burning was carried out in part of the study area by the Regional Forest Service on
 180 16 October 2019 (Figure 1b). The safety measures were observed by applying the prescribed
 181 fire along fire lines separated by 1 m in the opposite direction to dominant winds, to minimize
 182 the flame length and height (avoiding that the fire catches up more energy), to reduce the
 183 consumed organic matter, and to lower the fire temperatures (Hidalgo et al., 2000). The fire
 184 started at 12:30 CET (mean air temperature of 12.3 °C, mean relative humidity of 47% and
 185 wind speed of 2.6 km/h with SE direction). The burned area in the site covered 6 ha
 186 (coordinates 38°31'12.20"N; -2°11'28.30"E).

187
 188 **2.3. Plot preparation and experimental design**

189
 190 Ten plots of about 2-m² each were installed inside the burned area prior to burning. Before
 191 prescribed fire application, the forest fuel and litter quantity were measured in each plot
 192 (Table 1). Moreover and in order to generate high and low severity fire, forest fuel was
 193 manually accumulated on each plot (Table 1). The forest fuel was composed mainly of *Pinus*
 194 *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.

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

226 Five plots with similar characteristics were selected in a neighbouring unburned area
227 (coordinates 38°31'35.62" N; -2°11'25.60" E). This area was not treated with prescribed fire
228 and was used as an experimental control (hereafter indicated as "no fire").

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

232

233 **2.4. Data collection**

234

235 *2.4.1. Measurement of rainsplash erosion*

236

237 Immediately after the prescribed fire application, a 50 cm x 50 cm sediment trap was installed
238 at each 2-m² plot, one trap per plot (Figure 1c). The sediment trap was delimited by a
239 geotextile fabric fixed to posts and trenched around the outside, to prevent external inputs of
240 runoff or erosion. The bottom part of the sediment trap was protected with geotextile fabric
241 fixed to the soil, to enable periodic sediment collection after each rain event. Therefore, a net
242 area of 0.12 m² (30 x 40 cm²) was exposed to rain drop impact. At each trap, the sediment
243 collected is the soil lost by rainsplash detachment, and this sediment is usually entrapped by
244 the overland flow in its downstream path. However, due to the very small size of the sediment
245 trap, it is unlikely that the overland flow begins, and therefore the installed device is able to
246 measure only the sediment lost by rainsplash erosion, and not by sheet flow. Moreover, no
247 visual indications of other erosion forms were identified in the sediment traps after each
248 rainfall event (e.g., initiating rills, tracks of laminar flow, etc.), and this confirms the fact that
249 this device was able to estimate only rainsplash erosion.

250 The eroded soil stored in each sediment trap was periodically collected, oven-dried and
251 weighed in the laboratory. Following the methodology used by (Keizer et al., 2018), the
252 following soil covers were measured in the area contributing to each sediment trap: moss,
253 needles, living vegetation (shrub and herbaceous layers), stoniness, dead wood (dead forms of
254 organic material, principally dead plant parts), bare soil and ash (black and white). These
255 covers were measured one day after the prescribed fire application and after each rainfall

256 event (excluding the first date). A weather station (WatchDog 2000 Series model) was placed
257 in the study area to measure the total daily precipitation, rainfall intensity and air temperature
258 during the study period. The soil loss was divided by the precipitation for the period of
259 sediment accumulation (hereafter “unit rainsplash erosion”).

261 *2.4.2. Measurement of the physico-chemical properties of soil*

262
263 In each plot, outside the sediment trap and according to previous studies (Lucas-Borja et al.,
264 2020b), three composite soil samples were collected two days after the prescribed fire and the
265 main physico-chemical properties of the soil sample were analysed. Before sample collection,
266 litter and stones were removed from a 15 × 15 cm square on the soil surface. A ruler
267 (precision of 1 mm) and trowel with markings (precision of 1 cm) were inserted into the soil
268 to remove the top 2-3 cm of soil within the square for each sample. The following physico-
269 chemical properties were analysed: clay, silt and sand contents (determined by the
270 international Robinson pipette method, Gee and Or, 2002), pH, electrical conductivity (EC)
271 (both in deionized water, 1:2.5 and 1:5 w/w, respectively, at 20 °C), organic carbon (SOC, by
272 the potassium dichromate oxidation method, Nelson and Sommers, 1996), total nitrogen (TN,
273 Bremner, 1982), available phosphorus (P, Olsen, 1982), sodium (Na⁺), potassium (K⁺), and
274 cation exchange capacity (CEC, Roig et al., 1980). The soil texture was calculated based on
275 the measured soil contents of clay, silt and sand, using the Soil Texture Calculator, prepared
276 by the USDA-Soil Survey Staff in 2014.

278 **2.5. Statistical analysis**

279
280 The statistical analysis was carried out using the XLSTAT release 2019 software. A one-way
281 ANOVA was applied for statistical processing of data about soil loss and physico-chemical
282 properties. In the first case, an ANOVA with repeated measures (one per each monitored
283 precipitation event) was applied to soil loss as dependent or response variable. In the other
284 case, the ANOVA was applied to the three sample measurements of each soil property
285 (dependent or response variable). In both cases, the independent variable (ANOVA factor)
286 was the soil condition with three levels (“no fire”, “low-severity prescribed fire”, and “high-
287 severity prescribed fire”). The pairwise comparison by Tukey’s test (at $p < 0.05$) was also
288 used to evaluate the statistical significance of the differences among the soil conditions in
289 each response variable. In order to satisfy the assumptions of equality of variance and normal

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290 distribution, the data were square root-transformed when necessary. A Principal Components
291 Analysis (PCA) was used to identify representative derivative variables (Principal
292 Components, PCs) from the original dataset of soil properties (Lee Rodgers and Nicewander,
293 1988). In this study, PCA was carried out by standardizing the original variables (expressed
294 by different measuring units) and using Pearson’s method to compute the correlation matrix.
295 The first two PCs, explaining at least 70% of the original variance, were retained. Finally, the
296 observations were grouped in clusters using Agglomerative Hierarchical Cluster Analysis
297 (AHCA), a distribution-free ordination technique to group samples with similar characteristics
298 by considering an original group of variables. Euclidean distance was used as the similarity-
299 dissimilarity measure.

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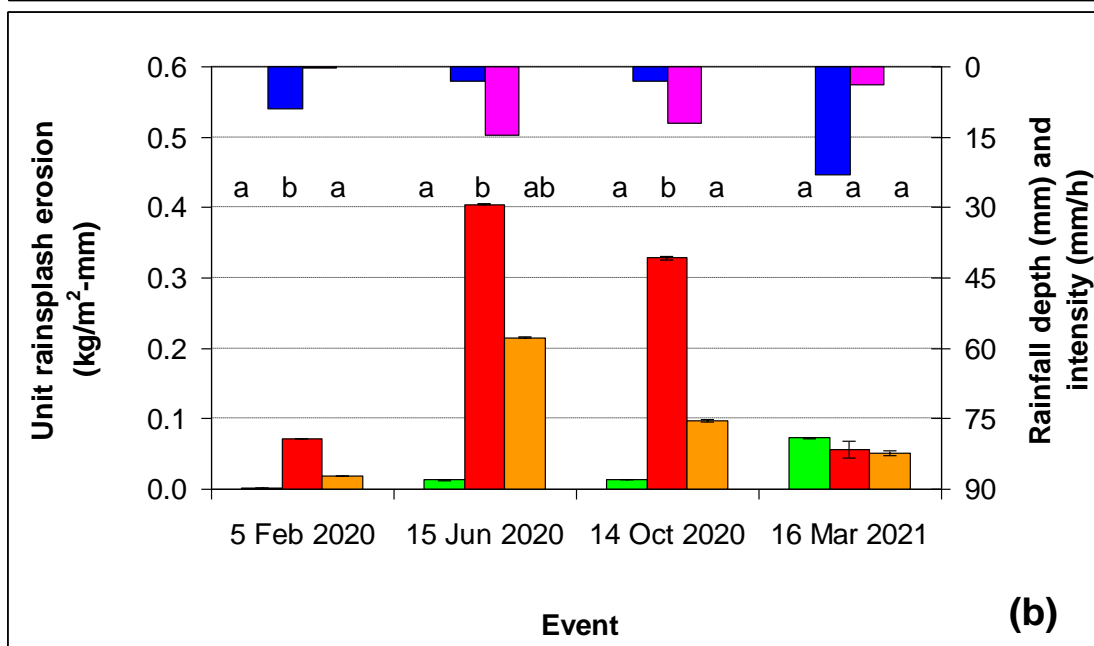
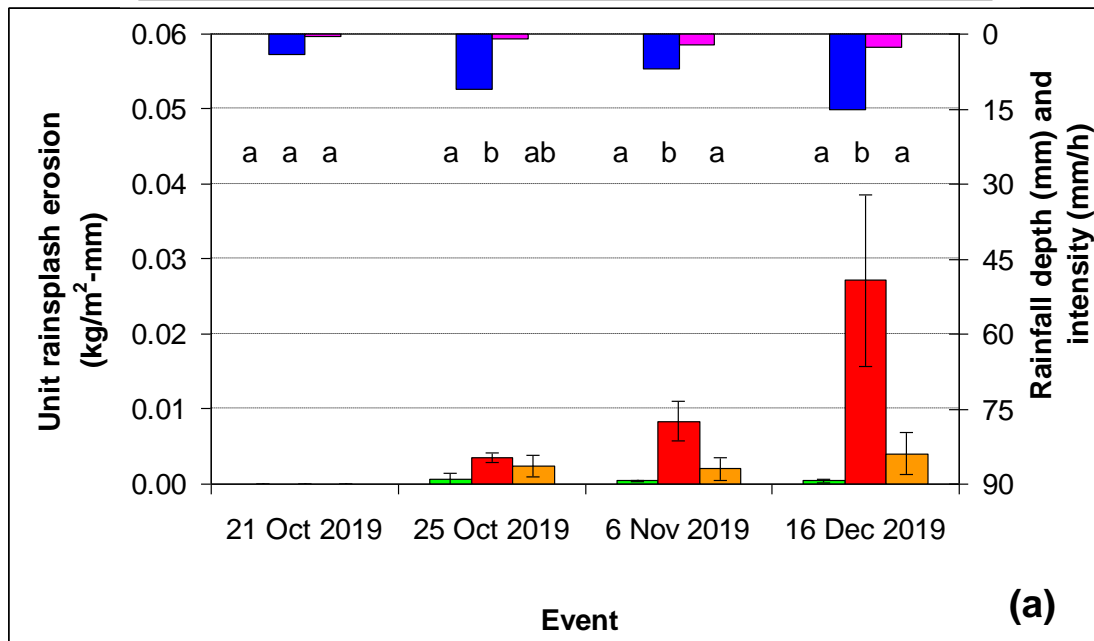
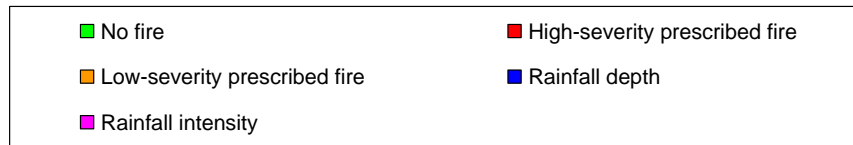
301 **3. RESULTS**

302

303 *3.1. Prescribed fire effects on rainsplash erosion*

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



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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.

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318 In the unburned soils, the rainsplash erosion was low for seven of the eight monitored events
319 (from 0 to 0.04 ± 0.05 kg/m²), and relatively high for the last precipitation (1.67 ± 0.74 kg/m²
320 on 16 March 2022). For the first event (21 October 2019), no erosion was observed in any of
321 the studied soil conditions. Over the study, the soil loss measured in the areas burned by low-
322 severity prescribed fires was not significantly higher (from 0 to 1.18 ± 1.04 kg/m²) compared
323 to the unburned soils. In contrast, the rainsplash erosion in the sites burned by the high-
324 severity fire (from 0.04 ± 0.01 to 1.21 ± 0.47 kg/m²) was always significantly greater than the
325 unburned area, except for the first event (soil loss equal to zero) and the largest precipitation
326 event (1.29 ± 0.90 kg/m², 16 March 2021). For two rainfalls (25 October 2019 and 15 June
327 2020) the soil loss surveyed after high-intensity fires was not significantly different from the
328 erosion measured in the sites burned at low-intensity (Figure 2).

329 The precipitation events occurring immediately after the fire (21 October, and 6 November
330 2019) resulted in lower unit rainsplash erosion under all the studied soil conditions (from 0 to
331 0.008 ± 0.003 kg/m²-mm) compared to the subsequent rainfalls. After the event recorded on
332 16 December 2019, the unit rainsplash erosion increased, particularly in the soils burned by
333 high-severity prescribed fires. In the plots burned by high-severity prescribed fire, the highest
334 unit rainsplash erosion was measured on 15 June 2020 (0.41 ± 0.16 kg/m²-mm). For the other
335 sites, the maximum values of unit rainsplash erosion occurred on 15 June 2020 for the low-
336 severity prescribed fire (0.22 ± 0.17 kg/m²-mm), and on 16 March 2021 for the unburned site
337 (0.07 ± 0.05 kg/m²-mm). For the 16 March 2021 event, the unit rainsplash erosion detected in
338 the unburned soil was even higher (although not significantly) compared to the other soil
339 conditions (0.06 ± 0.04 kg/m²-mm for the high-severity prescribed fire, and 0.05 ± 0.05
340 kg/m²-mm for the low-severity prescribed fire) (Figure 2).

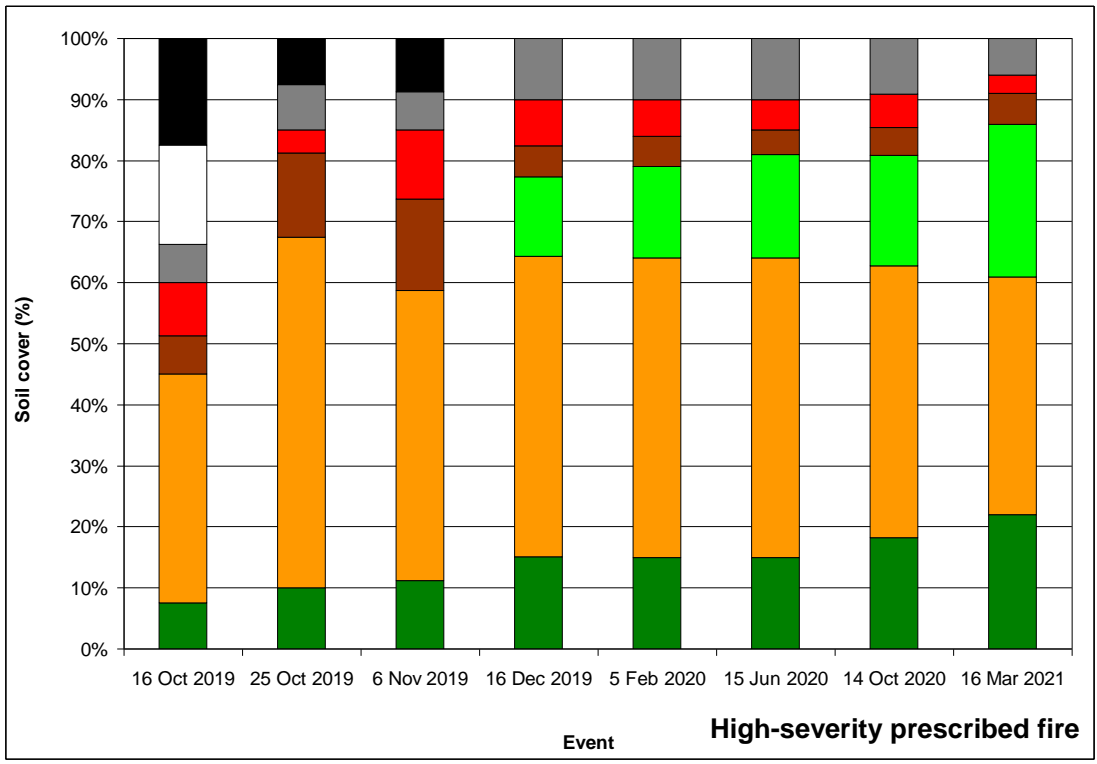
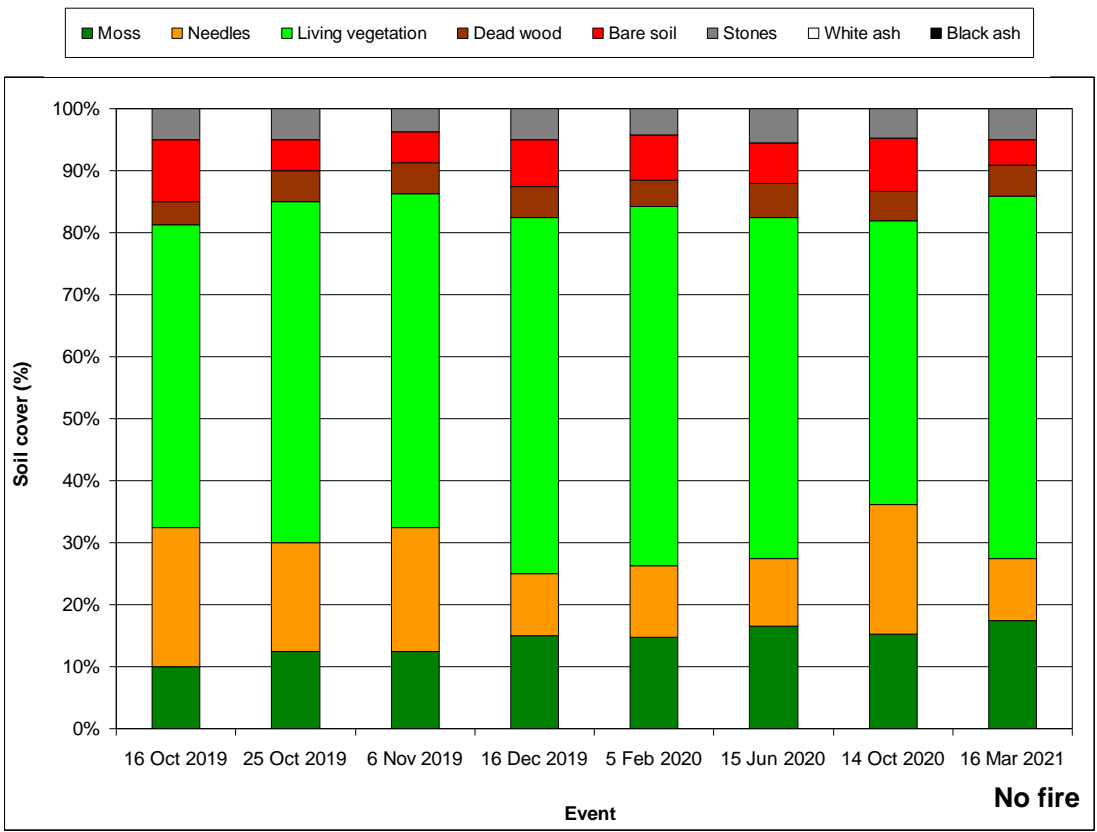
341 342 ***3.2. Prescribed fire effects on cover and physico-chemical properties of soil*** 343

344 The canopy cover was 30% in the unburned area, 40% in the site burned at lower severity and
345 35.8% in the soils affected by the high-severity prescribed fires. Concerning the ground cover
346 of soils, the unburned plots had an average cover of green material (shrubs and herbaceous
347 vegetation) of $53 \pm 4\%$, while the other cover types were much lower (14-15% of moss and
348 pine needles with minor amounts of dead wood and stones); the bare soil was $7 \pm 2\%$ (Figure
349 3). Fire produced ash in the burned soils, and this ash initially covered the plots ($76 \pm 5\%$ of
350 black ash and $24 \pm 5\%$ of white ash) in the soils burned by fire with high severity, while the
351 ash cover was $34 \pm 21\%$ in the areas burned by the low-severity prescribed fire (16% of white

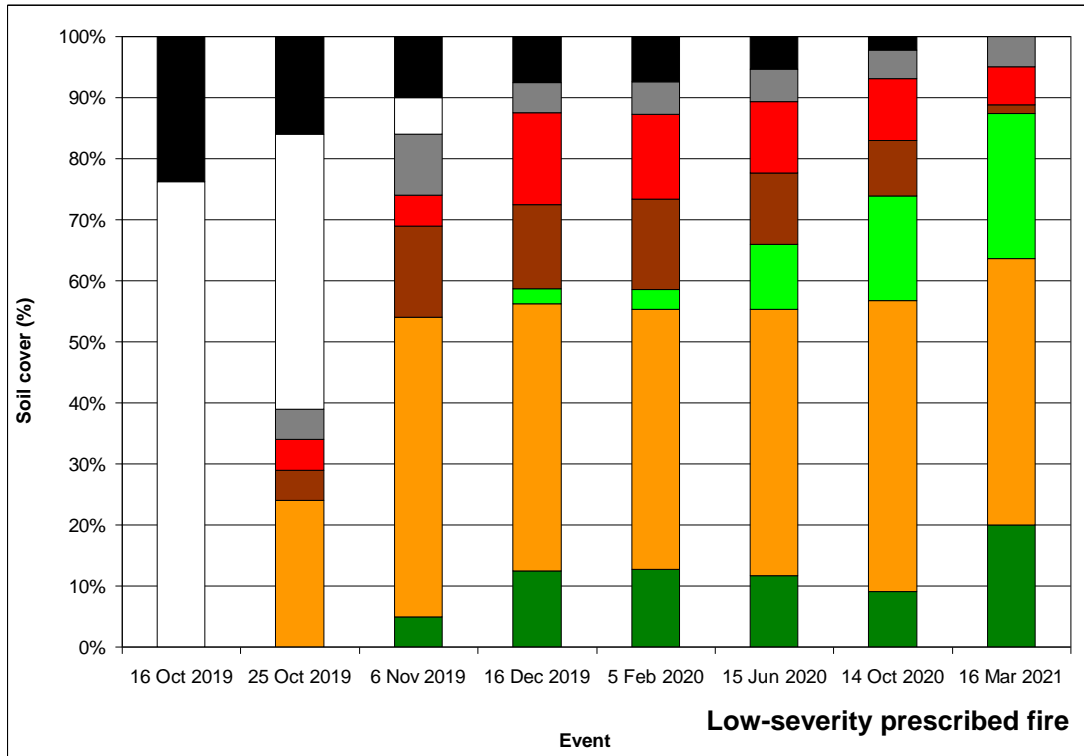
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352 ash and 18% of black ash). The remaining part of the low-severity plots was mainly covered
353 by needles ($44 \pm 6\%$). Over time the ash cover disappeared, exposing the underlying covers.
354 More specifically, the plots burned at high severity showed a cover of green material of $49 \pm$
355 20% and smaller areas with moss ($13 \pm 6\%$) and needles ($11 \pm 6\%$), while, in the sites
356 affected by the low-severity prescribed fire, the ground cover mainly consisted of needles (44
357 $\pm 6\%$), moss ($12 \pm 4\%$) and dead wood ($10 \pm 5\%$). The bare soil was $10 \pm 4\%$ in these plots
358 and $5 \pm 2\%$ in the plots burned by the fire with high severity (Figure 3).

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

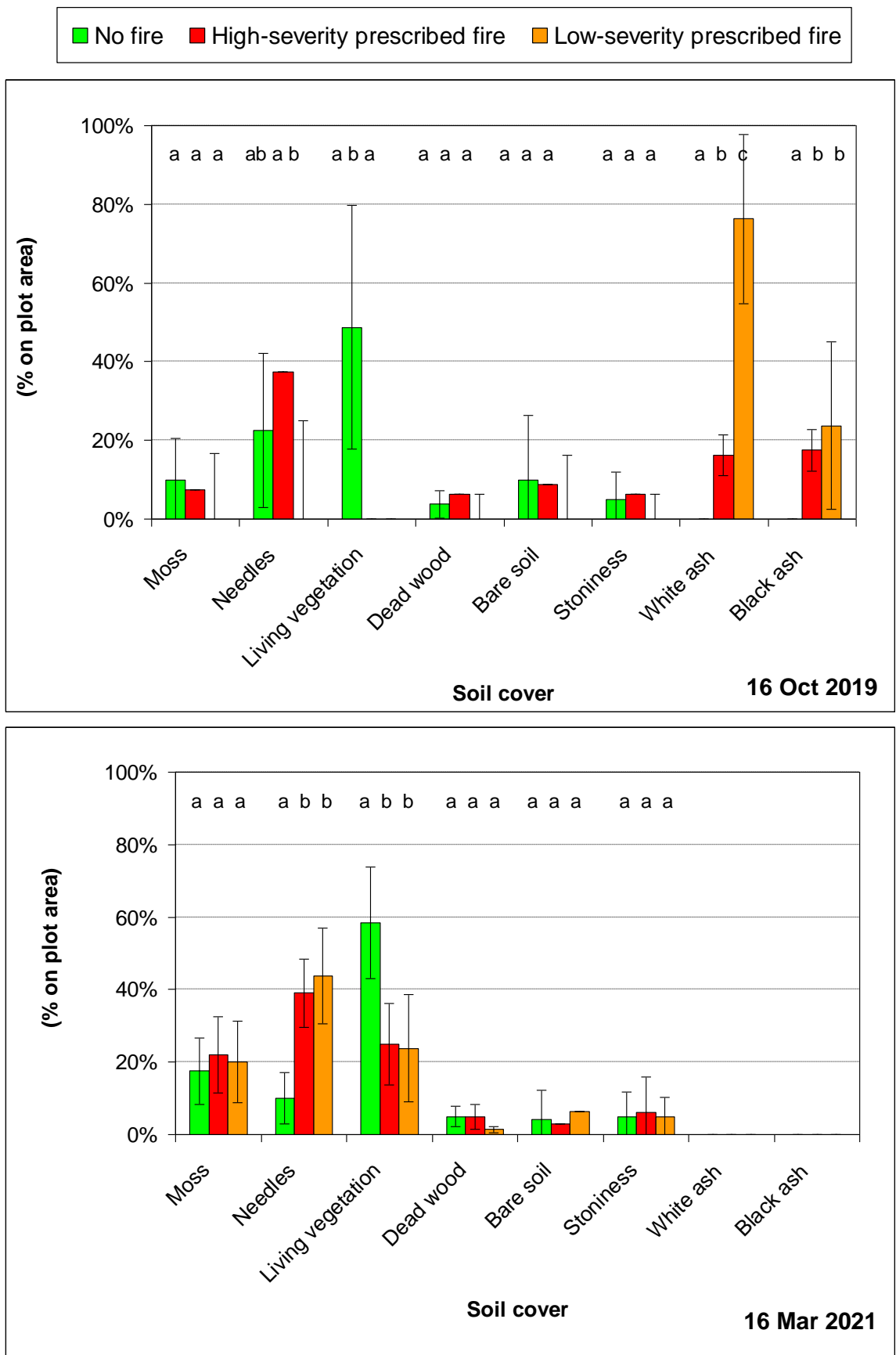
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367 The statistical analysis showed that the cover of white ash was significantly different between
 368 the areas burned by high and low-severity prescribed fires, while the difference in the black
 369 ash cover was not significant (Figure 4). No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

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

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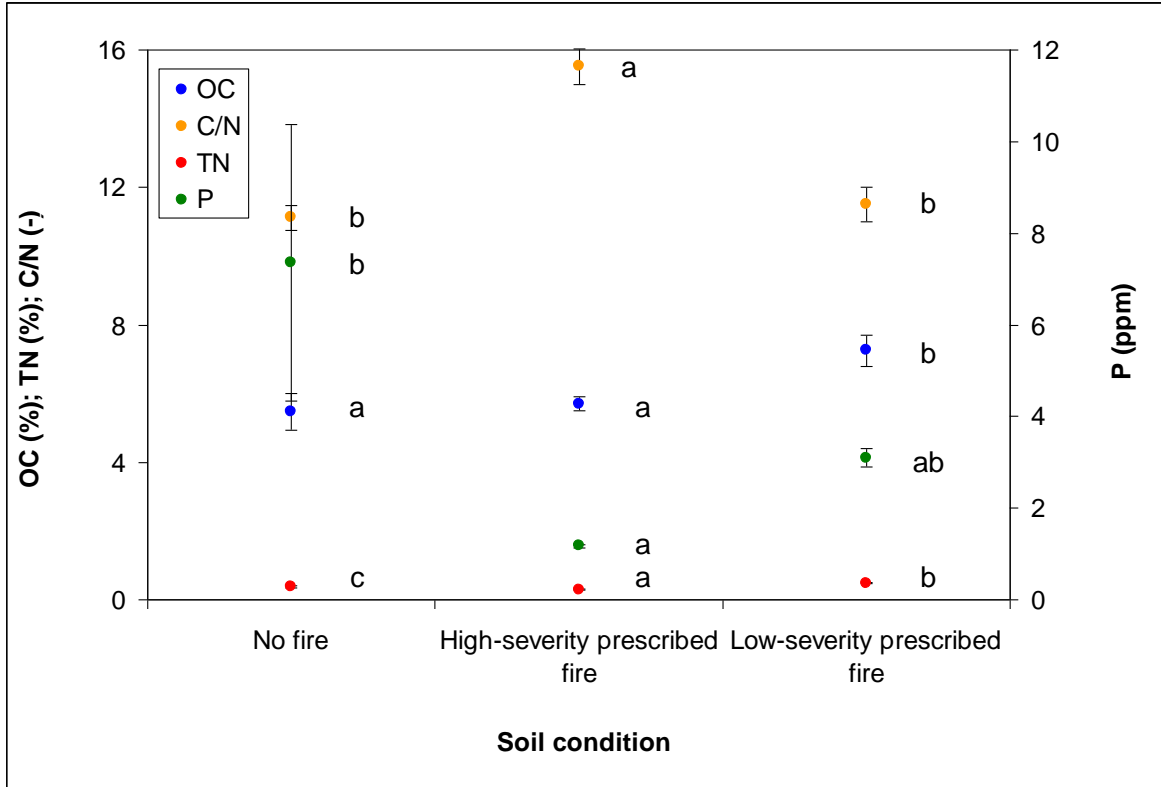
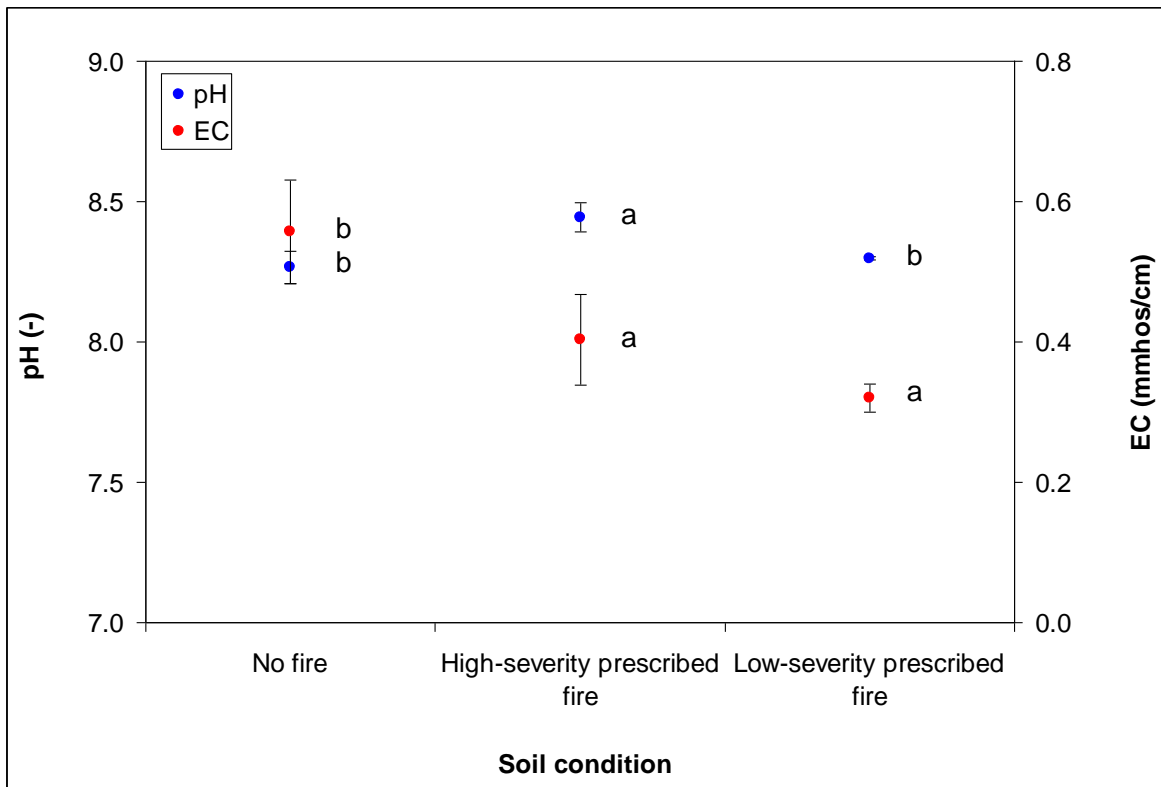
380 and a half after) in La Moraleja forest (Castilla La Mancha, Spain). Different letters indicate
381 significantly different cover among the soil conditions.

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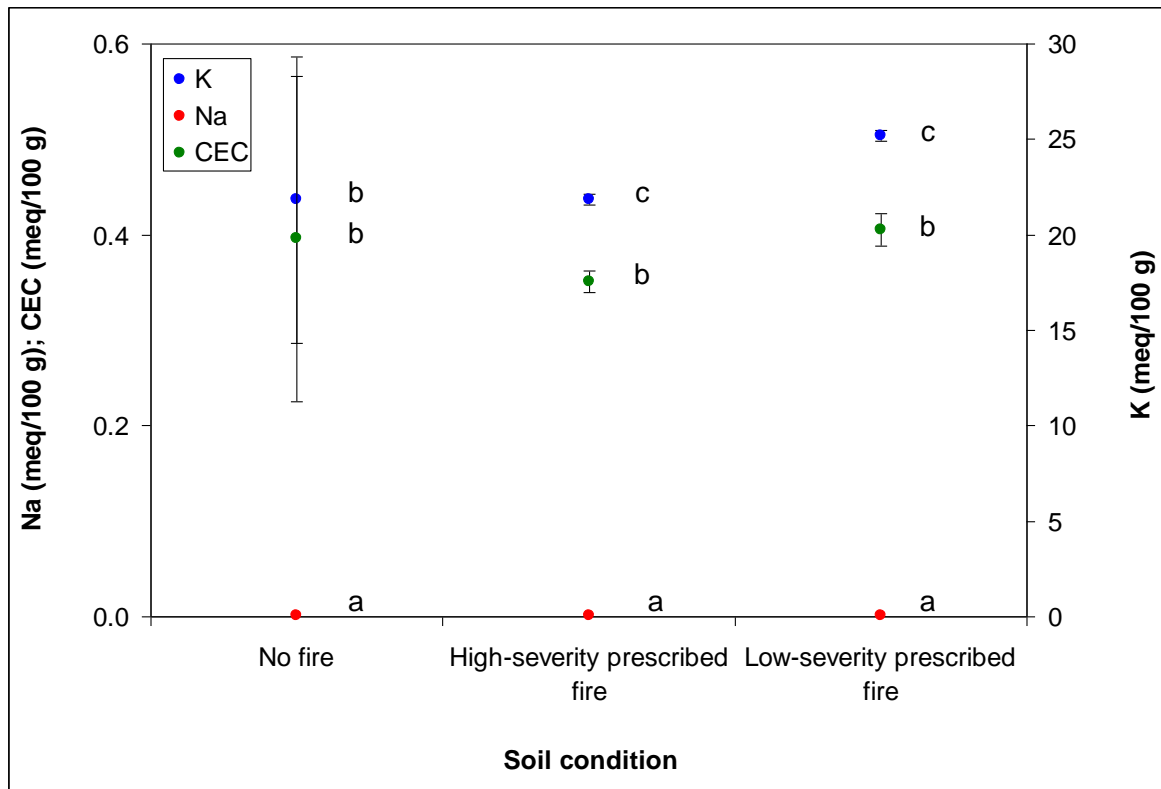
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384 Regarding the main physico-chemical properties, the pH was slightly higher in the burned
385 plots (8.30 ± 0.01 for low-severity prescribed fire and 8.44 ± 0.05 for high-severity fire)
386 compared to the unburned sites (8.27 ± 0.06) (Figure 5a). This effect was significant only for
387 the plots burned by the fire with high severity. Compared to the unburned sites, which showed
388 an OC content of $5.47 \pm 0.55\%$, this parameter increased in both fire-affected plots, but the
389 difference was only significant for the soils burned at high severity ($7.25 \pm 0.45\%$) (Figure
390 5b). TN was $0.28 \pm 0.02\%$ in unburned plots. This parameter increased in soils burned at low
391 severity ($0.36 \pm 0.01\%$) and decreased in soils burned by the fire with high severity ($0.22 \pm$
392 0.01%). Both these differences were significant according to the ANOVA results (Figure 5b).
393 As a consequence of the variability in OC and N contents of the experimental soils, the C/N
394 ratio significantly increased in soils with high severity (15.52 ± 0.52) and decreased, but
395 without statistical significance, in the plots burned at the low severity (11.50 ± 0.50) in
396 comparison to the unburned soils (11.12 ± 0.35) (Figure 5b). Strong decreases in P contents
397 were detected in the burned plots (1.17 ± 0.04 ppm, high-severity prescribed fire, and $3.10 \pm$
398 0.20 ppm, low-severity prescribed fire) compared to the value measured in the unburned soils
399 (7.35 ± 3.02 ppm) (Figure 5b). The statistical analysis revealed that only the difference
400 between the unburned plots and the soils burned by the fire at high severity was significant; in
401 contrast, no significant difference was found between the plots burned at different severity
402 (Figure 5b). EC was equal to 0.56 ± 0.07 mmhos/cm in the unburned plots, and this value was
403 significantly higher than the 0.32 ± 0.02 mmhos/cm in the plots burned by the low-severity
404 prescribed fire and 0.40 ± 0.07 mmhos/cm in sites burned by the high-severity prescribed fire
405 (Figure 5c). Concerning the cation contents of the soils, K^+ measured in the unburned soils
406 (0.44 ± 0.01 meq/100 g) was not significantly different from the plots burned at high or low
407 severity. Na^+ content slightly but not significantly varied among the burned and unburned
408 soils (0.06 ± 0.05 meq/100 g). There were also slight but not significant differences in the
409 CEC among the three soil conditions, which were similar as the value measured in the
410 unburned soils (19.79 ± 8.50 meq/100 g) (Figure 5c).

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

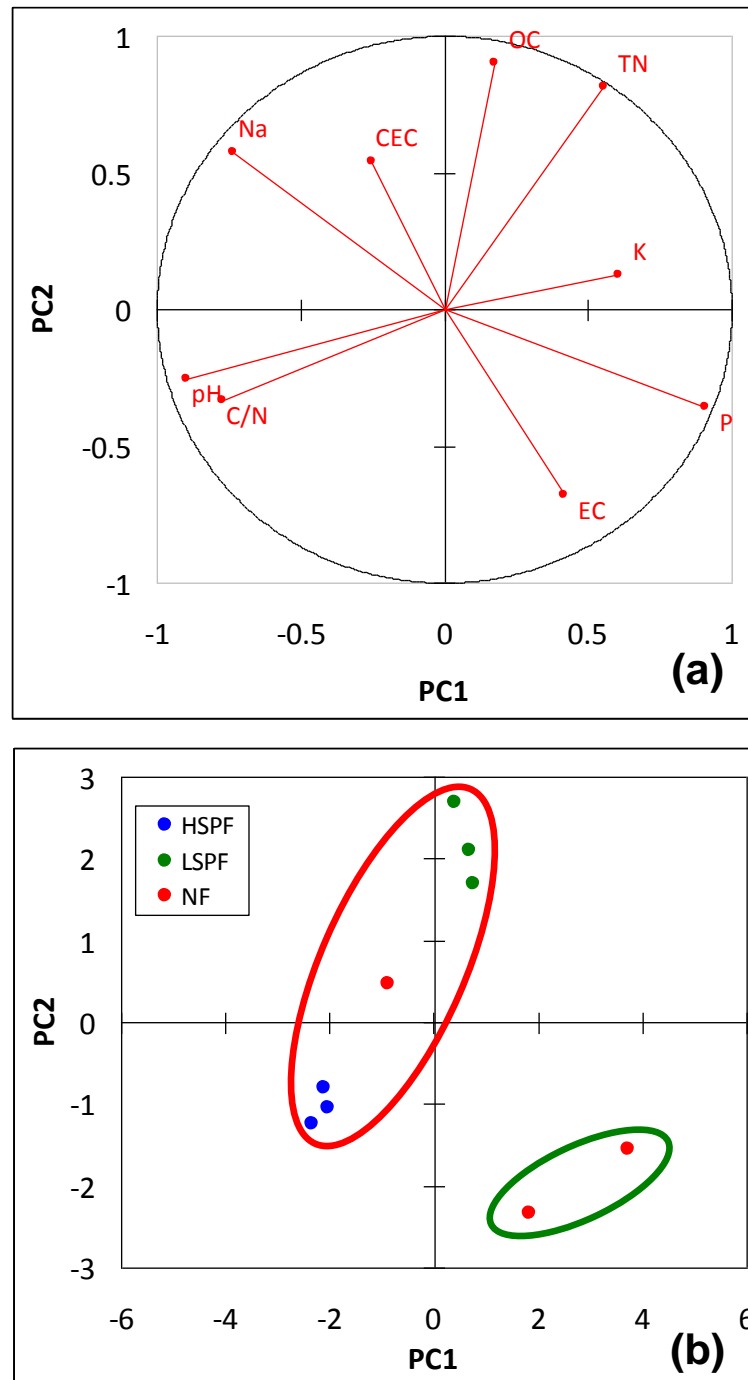
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423 The PCA identified two Principal Components (PC1 and PC2), which together explained 73%
 424 of the variance of the original physico-chemical properties of soils; a third PC (PC3)
 425 explained another 21% of this variance. Of these soil parameters,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

432 a few samples collected in the unburned sites and the second cluster consisted of only
433 unburned soils (Figure 6b).

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

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

445 **4. DISCUSSIONS**

447 *4.1. Prescribed fire effects on rainsplash erosion*

448
449 Rainsplash erosion is a key component of soil loss in forest environments, especially when
450 the soil is exposed to short and intense rainfalls with high erosive power, as under the semi-
451 arid Mediterranean climate. Fires with different severity (including the prescribed fires),
452 burning vegetation and altering the physico-chemical properties of soils, may enhance
453 rainsplash erosion with heavy in-site and off-site hydrological effects.

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

470 For the first seven of the monitored events, rainsplash erosion (up to 0.04 kg/m²-yr) was
471 noticeably under the low end of the tolerance range of 0.3-1.1 kg/m²-yr (Wischmeier and
472 Smith, 1978; Bazzoffi, 2009). The soils burned by our low severity fire unexpectedly
473 produced noticeable erosion after a very low rainfall, while, for larger precipitation events, the
474 soil loss was lower. In contrast, in the severely-burned soils, the rainsplash erosion was

1 475 negligible for the first three events, then, for the subsequent four precipitations, the soil loss
2 476 increased. The main reason of the noticeable erosion recorded for an event with very low
3 477 rainfall depth in the burned soil against a limited value of the unburned soil was the high
4 478 rainfall intensity of this event compared to the other precipitations recorded in the observation
5 479 period. However, other factors (such as the fire-induced soil water repellency and the
6 480 reduction in infiltration) that were not measured in this investigation may have played a role
7 481 on these differences. The burned soils showed a ground cover very similar as the values
8 482 measured in the unburned soil. This means that rainsplash erosion, which is limited by the soil
9 483 protection due to the presence of vegetation, litter, and stones, should also be comparable
10 484 among the three soil conditions. In general, after fires with different intensities increase in
11 485 surface runoff (and, therefore, in erosion) are expected. Limiting the attention to fire at low
12 486 intensity, Carrà et al. (2022) showed a significant runoff generation (about 2 to 4-fold the
13 487 values measured in the unburned plots) after a prescribed fire in forest stands of Southern
14 488 Italy, while Vega et al. (2005) found increases in runoff between two and five times the
15 489 unburned soils in shrublands of Northern Spain. Regarding erosion, the literature reports that
16 490 this process is not minimal following low-intensity fires (Coelho et al., 2004; de Dios
17 491 Benavides-Solorio and MacDonald, 2005; Morris et al., 2014). The reasons why the
18 492 rainsplash erosion was negligible for the first three monitored events should be ascribed to
19 493 different factors: (i) the effects of ash released by fires, which protects the soil surface from
20 494 the raindrop impacts during low-intensity rainfall and absorbs part of the precipitation (Cerdà
21 495 and Doerr, 2008); (ii) the immediate restoration of part of the pre-fire vegetation cover; (iii)
22 496 the lack of erosive events. The role of soil water repellency induced by fire and the decrease
23 497 in water infiltration may be also important in driving the post-fire hydrological processes
24 498 (Plaza-Álvarez et al., 2019, 2018), but these variables could not be measured in this study,
25 499 and this represents a limitation of the investigation.

26 500

27 501 ***4.2. Prescribed fire effects on cover and physico-chemical properties of soil***

28 502

29 503 Fires with both severities exerted significant changes on some of the studied soil properties in
30 504 comparison to the unburned soils. More specifically, the changes in pH were slight and
31 505 significant only for the prescribed fire with high severity. The literature generally reports
32 506 reductions in soil pH after low severity fires (e.g., Alcañiz et al., 2016; Valkó et al., 2016),
33 507 while increases are common when the burn severity is high, as found in this study. In this
34 508 case, soil pH increase is due to denaturation of organic acids (Certini, 2005) and the increase

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509 of sodium and potassium oxides, carbonates and hydroxides from heating (Pereira et al.,
510 2018; Ulery et al., 1993).

511 The EC significantly decreased in burned soils, regardless of burn severity. This result is
512 unexpected, since an increase in EC is reported by many authors (Alcañiz et al., 2020;
513 Granged et al., 2011; Scharenbroch et al., 2012). The reasons of previously reported EC
514 increases after fire are the incorporation of ash (Fonseca et al., 2017; Scharenbroch et al.,
515 2012; Úbeda and Outeiro, 2009), release of soluble ions during the combustion of organic
516 matter (Alcañiz et al., 2016), and formation of black carbon (Alcañiz et al., 2020). In contrast,
517 other studies show that EC can decrease, especially after fires with low intensity (Alcañiz et
518 al., 2020). Accordingly, we ascribe the decrease in EC measured in this study to the absence
519 of leaching effect of ions from ash into the soil, due to the lack of rainfall after the fire, and
520 the very short time of sampling after fire (two days against some time after appreciable
521 precipitations of other studies). This explanation is in close accordance with Neary et al.
522 (1999), who state that salts are quickly leached or transported by runoff after burning. Direct
523 measurements of the ion contents in the soil should corroborate this hypothesis.

524 The fate of OC was different between low- and high-intensity fires. The significant increase
525 detected after low-intensity fires may be due to partially pyrolyzed plant residues (Agbeshie et
526 al., 2022; Caon et al., 2014), incomplete combustion of the organic matter (Alcañiz et al.,
527 2020; Soto and Diaz-Fierros, 1993; Úbeda et al., 2005) and to forest floor decomposition
528 (Scharenbroch et al., 2012). It is possible that litter combustion in addition to forest floor
529 decomposition could have increased the OC content of the soil. According to some studies
530 (e.g., Scharenbroch et al., 2012; Soto and Diaz-Fierros, 1993), OC increases in soils burned at
531 low severity compared to unburned areas. In contrast, after the high-severity prescribed fire of
532 this study, the OC was not different in comparison to the unburned plots. In general, fires with
533 high severity determine the almost total combustion of OC with its mineralization,
534 volatilization, and solubilisation (Rodriguez-Cardona et al., 2020), due to the very high
535 temperature of fire. Soil heating at high temperatures generally reduces the amount and
536 quality of OC (Merino et al., 2018), since severe wildfires are able to induce volatilization of
537 high amounts of carbon and nitrogen, which start to vaporize at about 200 °C (Pereira et al.,
538 2018), and are totally consumed lost over 550 °C (Gray and Dighton, 2006). However, in our
539 study, the expected loss of OC due to soil heating could have been balanced by the supply of
540 partially burned residues and charred leaves, falling on forest ground immediately after fire.
541 Presumably, the total content of OC did not change, but it may be possible that the type of

1 542 organic compounds did, although the relevant determinations were not made in this
2 543 investigation.
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4 544 Fires also induced noticeable changes in the nutrient content of soils, with significant
5 545 decreases in TN and P after the high-severity fire. The low-severity fire resulted in an increase
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7 546 in TN and a decrease in P compared to the unburned conditions, and the plots burned at high
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9 547 severity had a decrease in TN and an even greater decrease in P than what observed in no fire
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11 548 condition. After burning, organic N decreases due to volatilisation (Binkley and Fisher, 2019;
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13 549 Turner et al., 2007), due to the soil heating. With low-severity fires, noticeable amounts of
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15 550 organic N can remain in the soil, but in different form than before the fire. In line with some
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17 551 authors (Giovannini et al., 1988; Grogan et al., 2000; Rivas et al., 2012; Smithwick et al.,
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19 552 2005), the increase in TN detected in this study in soils burned by the low-intensity fire is
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21 553 probably due to two factors: (i) the addition of partially pyrolyzed materials containing N (as
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23 554 explained earlier in the case of the OC) and (ii) the release of N in dead roots and compounds.
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25 555 Regarding the P dynamics, the reductions measured at both fire severities are ascribed to
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27 556 volatilisation due to high temperatures (Certini, 2005). The reduction in P contrasts some
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29 557 earlier studies, which reported that fires result in an enrichment of available P (Macadam,
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31 558 1987; Serrasolsas and Khanna, 1995), which then rapidly declines. The increases in P after
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33 559 low intensity fires is generally ascribed to the release of basic cations from the organic matter,
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35 560 ash formation and its incorporation into the soil (Kennard and Gholz, 2001).
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37 561 The measurements of cation contents of the burned soils in this study did not show significant
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39 562 changes compared to the unburned plots. Only slight increases of K^+ , Na^+ and CEC were
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41 563 detected in soils affected by the fire at low severity. Increases in available cations, such as
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43 564 Na^+ and K^+ , are common in soils burned by low-severity prescribed fires (e.g., Arocena and
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45 565 Opio, 2003; Kennard and Gholz, 2001; Scharenbroch et al., 2012). In our soils burned by
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47 566 prescribed fires at high severity, the contents of these cations varied compared to the
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49 567 unburned soils: the CEC decreased, no difference in K^+ , and increased Na^+ . These slight
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51 568 changes contrast several previous studies that showed more significant increases (e.g., Elliott
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53 569 et al., 2013; Khanna and Raison, 1986; Shrestha and Chen, 2010). As with the EC results
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55 570 above, the lack of cation response in the plots burned by prescribed fires at high severity may
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57 571 have been due to the immobilization of these compounds into ashes (Pereira et al., 2018) that
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59 572 were not yet leached into the burned soils (Alcañiz et al., 2020; Cawson et al., 2012). This
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61 573 lack of response is relevant to the cations studied, but this could have been also observed
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63 574 because major cations were not analysed. Declines in CEC are mainly due to the combustion
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65 575 of soil organic matter and the transformation of clay minerals, especially at very high

1 576 temperatures (Zavala et al., 2014), and this explains what we observed in this study after high-
2 577 severity prescribed fires.

3 578 The combined analysis of the physico-chemical properties of the soil through PCA shows an
4 579 evident mismatching between the dynamics of OC and TN (associated with the PC1) and the
5 580 other elements or compounds, such as P, K⁺ and Na⁺ (linked to the other two PCs). Moreover,
6 581 the PCA coupled to AHCA reveals a clear discrimination between burned soils, regardless of
7 582 burn severity, and all but one unburned area. This demonstrates that fire can change the
8 583 physico-chemical properties of soils, but these changes are often not so noticeable to create a
9 584 disrupting differentiation in soil conditions.

10 585
11 586 Overall, the results of this study suggest to land managers caution in applying prescribed fires
12 587 with high burn severity, since burning can increase the erosion rates in the short term.
13 588 Changes in some important physico-chemical properties of soils can be expected, and this
14 589 requires suitable post-fire management actions, when these modifications become noticeable
15 590 with specific regard to carbon and nitrogen contents of the burned soils. For instance, soil
16 591 mulching with vegetal residues may be beneficial to reduce rainsplash erosion when the soil is
17 592 left bare due to burning. The application of mulch material could also balance the loss of
18 593 carbon and nitrogen compounds due to burning. Log erosion barriers or contour felled log
19 594 debris may be locally installed (for instance, when sheetwash may be generated), in order to
20 595 control the overland and rill erosion.

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23 598 **5. CONCLUSIONS**

24 599
25 600 Replying to the first research question, the study has shown that rainsplash erosion in forest
26 601 soils burned by prescribed fires with high severity under Mediterranean conditions may be on
27 602 average higher by 160% and 95% compared to the unburned plots and areas affected by
28 603 prescribed fires with low severity, respectively. Regarding the second research question, the
29 604 study has highlighted that high-severity prescribed fires can change some important soil
30 605 properties (e.g., pH, EC, TN and P), but some changes are not always significant (e.g., OC
31 606 and cations) compared to the unburned soils. Also, low-severity prescribed fires can
32 607 significantly change some chemical properties of soils (e.g., EC, OC and TN), while, for other
33 608 soil parameters, the changes are negligible (e.g., pH and cations) in comparison to unburned
34 609 soils. However, the differences in post-fire soil changes were limited, but those in soil

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610 temperatures during burning were large between the high- and low-severity prescribed fires.
611 This discrimination was not always sharp compared to the unburned sites.
612 Overall, this study can help to support a better understanding of a key process such as
613 rainsplash erosion and the related changes in soil chemistry due to fire. Land managers should
614 be aware that prescribed fires can increase the erosion rates and change some important
615 physico-chemical properties of soils in the short term. Therefore, a proper control of the
616 erosion rates and the main properties of burned soils are suggested together with the possible
617 adoption of effective post-fire management actions, in order to limit these negative fire
618 impacts.

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