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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: | <p>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.</p> |
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1 **Short-term effects of prescribed fires with different severity on rainsplash erosion**
2 **and physico-chemical properties of surface soil in Mediterranean forests**

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Cover letter

Albacete (Spain), 9th August 2022

To the Editor(s)
of “*Journal of Environmental Management*”

Dear Prof. Kyriazopoulos,

Thank You for the second possibility to revise our manuscript. We would be grateful if You could reconsider the manuscript for publication in *Journal of Environmental Management*. Thank you again for your attention.

Kind regards.

Manuel Esteban Lucas Borja
(on behalf of the co-authors)



AUTHORS' REPLIES TO THE COMMENTS OF THE REVIEWERS

Comment

Reviewer #2: The authors have addressed all the suggestions and comments from the reviewers. Therefore, I recommend the paper to be accepted for publication.

Reply

Dear Prof./Dr., thank You again for the time You spent on our work, which allows a further improvement of our paper. We are happy to see you recommend the paper for publication.

Comment

Reviewer #3: The reviewer improved the manuscript of the earlier instruction except statistical analysis. I think this is split-plot design experiment rather than randomized blocked cluster design experiment and one-way anova is not appropriate for this work. I could not determine which design was (M&M description did not provide enough information about this). However, it seems there are several papers also being published like this. To be fair, I would like to rely on the decision.

Reply

Dear Prof./Dr., thank You again for the time You spent on our work. Your comments are highly valuable. As you mentioned, this experimental design and statistical analyses have been previously published in different international journals. See for example the last publication in which we measure soil infiltration at high, low and unburnt plots following similar procedures.

Manuel Esteban Lucas-Borja, Cristina Fernández, Pedro Antonio Plaza-Alvarez, Demetrio Antonio Zema 2022. Variability of hydraulic conductivity and water repellency of soils with fire severity in pine forests and reforested areas under Mediterranean conditions. First published: 24 August 2022 <https://doi.org/10.1002/eco.2472>.

[\(Variability of hydraulic conductivity and water repellency of soils with fire severity in pine forests and reforested areas under Mediterranean conditions - Lucas- Borja - Ecohydrology - Wiley Online Library\)](#)

1 **Highlights**

2

3 • Immediately after fire, no rainsplash erosion was measured in both fire
4 conditions

5 • High-severity fires gave higher rainsplash erosion after 75% of rainfalls

6 • High-severity fires gave higher rainsplash erosion (+95% compared to low-
7 severity)

8 • High-severity fires changed pH, electrical conductivity, nitrogen and phosphorus

9 • Low-severity fires changed electrical conductivity, organic carbon, and nitrogen

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2 **physico-chemical properties of surface soil in Mediterranean forests**

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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).

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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).

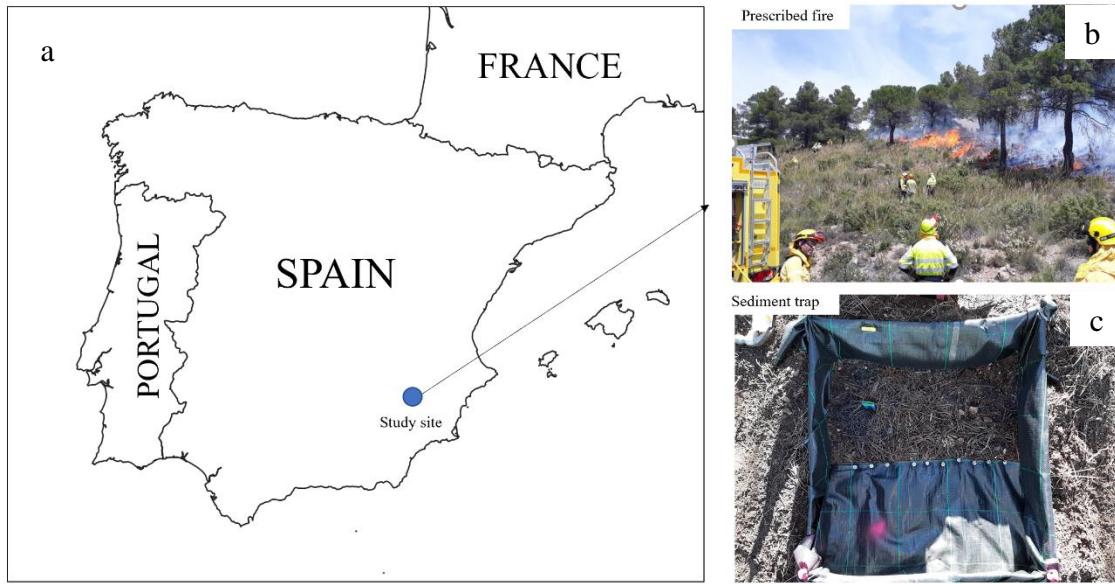
137 The two research questions this study addresses are: (i) how much erosion by rainsplash is
138 higher in soils burned by high-severity prescribed fires compared to unburned areas or sites
139 subjected to low-severity fires?; and (ii) which and to what extent physico-chemical
140 properties of the 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 Betic-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 as
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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176
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.

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

202 Table 1 – Main characteristics of the prescribed fire under three soil conditions (no fire, high-
 203 severity prescribed fire and low-severity prescribed fire prescribed fire). Soil temperatures
 204 were recorded at a 2 cm depth. Mean fuel and litter load were measured at each plot prior to
 205 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 |

207
 208 After the prescribed fire, the burn severity at each plot was classified according to Parson et
 209 al. (2010). Following Keeley (2009), the term “burn severity” has caused some confusion,
 210 because it is often used interchangeably with fire severity. In this study, two soil conditions
 211 for the burn severity of the prescribed fire will be identified: (i) “low-severity prescribed fire”;
 212 and (ii) “high-severity prescribed fire”. Parson et al. (2010) have proposed some visual
 213 indicators to identify the burn severity of soils affected by prescribed fires. In more detail, in
 214 the soil treated by the “low-severity prescribed fire”, surface organic layers are not completely
 215 consumed and are still recognisable, and the ground surface appears brown or black (lightly
 216 charred), while the tree canopies appear green. In contrast, a “high-severity prescribed fire”
 217 consumes all or nearly all of the pre-fire ground cover and surface organic matter (litter, duff,
 218 and fine roots), and charring may be visible on larger roots; the prevailing colour of the site is
 219 often “black”, due to extensive charring, white or gray ash indicates that considerable ground
 220 cover or fuels were consumed. Soil is often gray, orange, or reddish at the ground surface
 221 where large fuels were concentrated and consumed.

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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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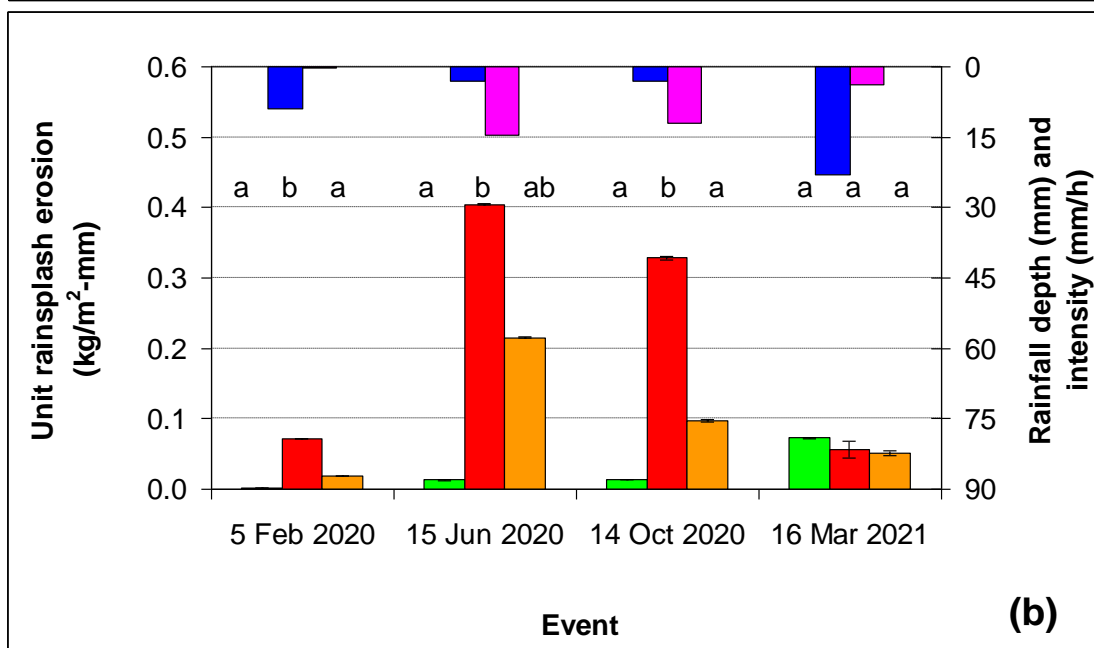
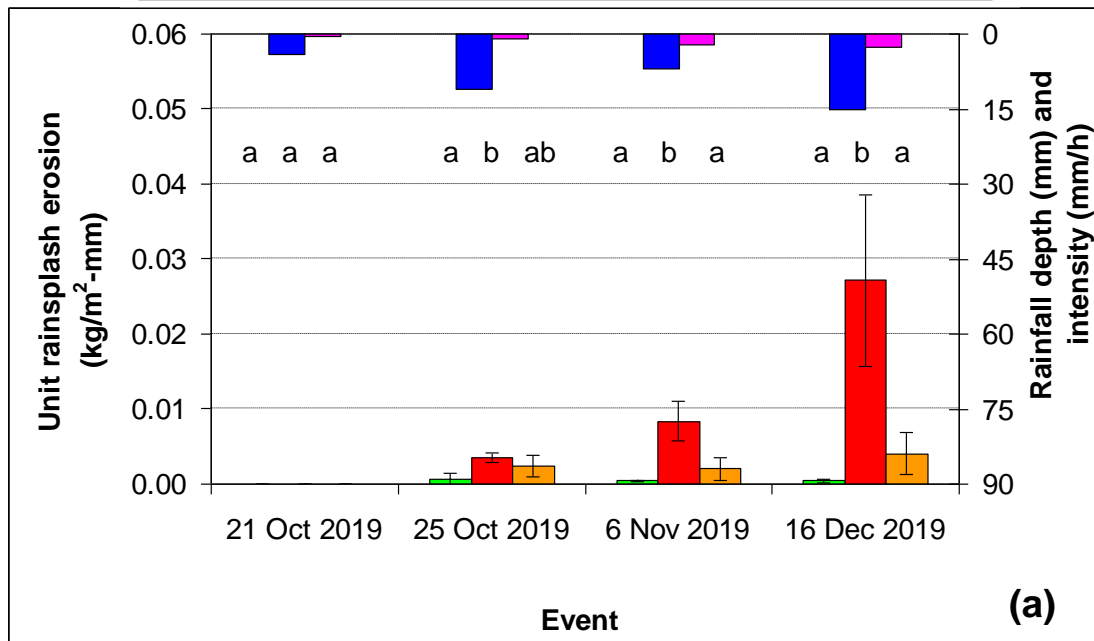
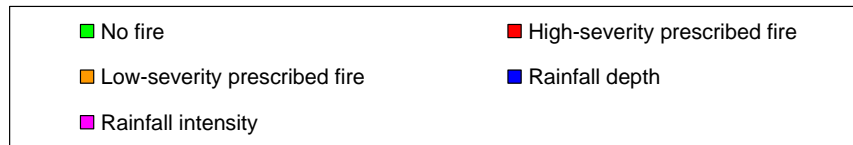
301 **3. RESULTS**

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).

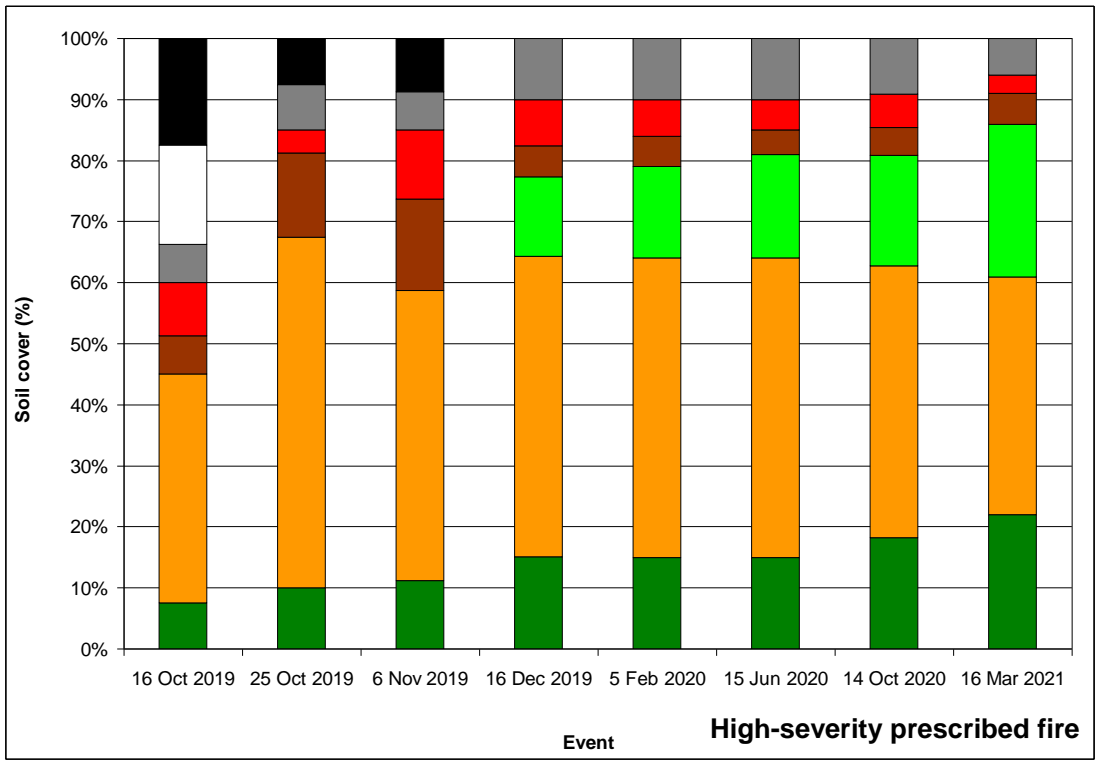
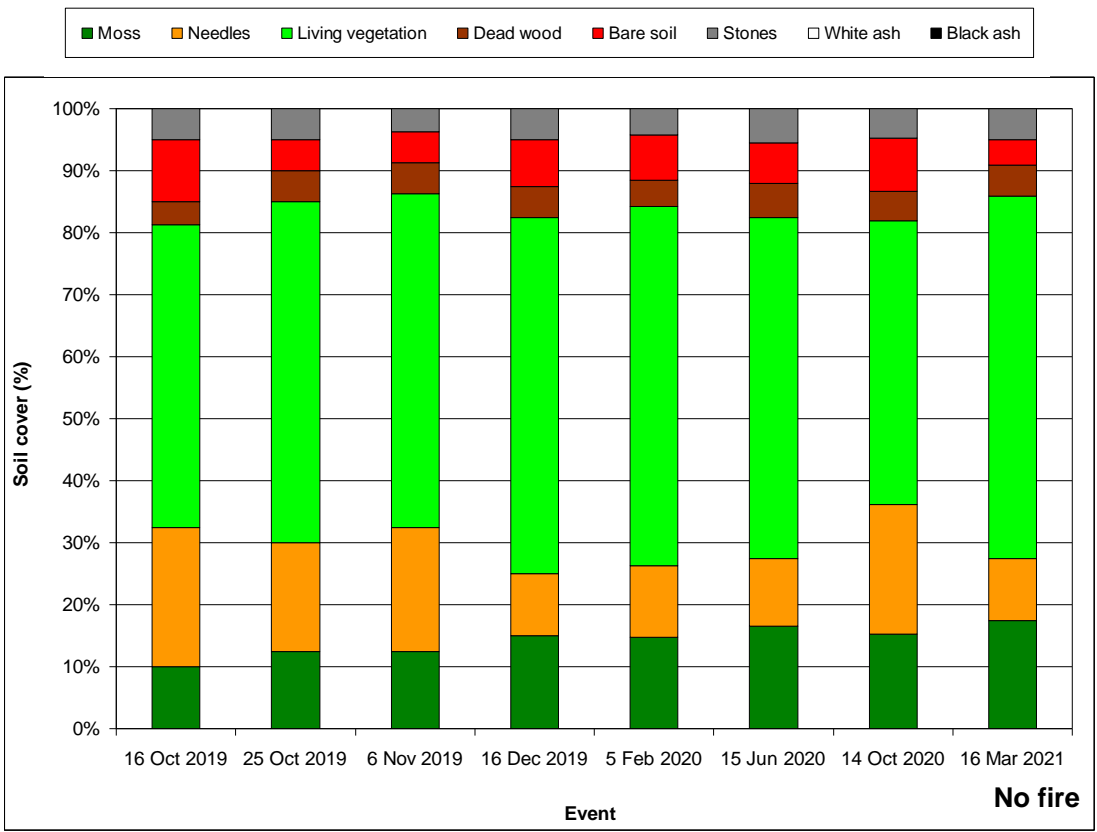
342 ***3.2. Prescribed fire effects on cover and physico-chemical properties of soil***

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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

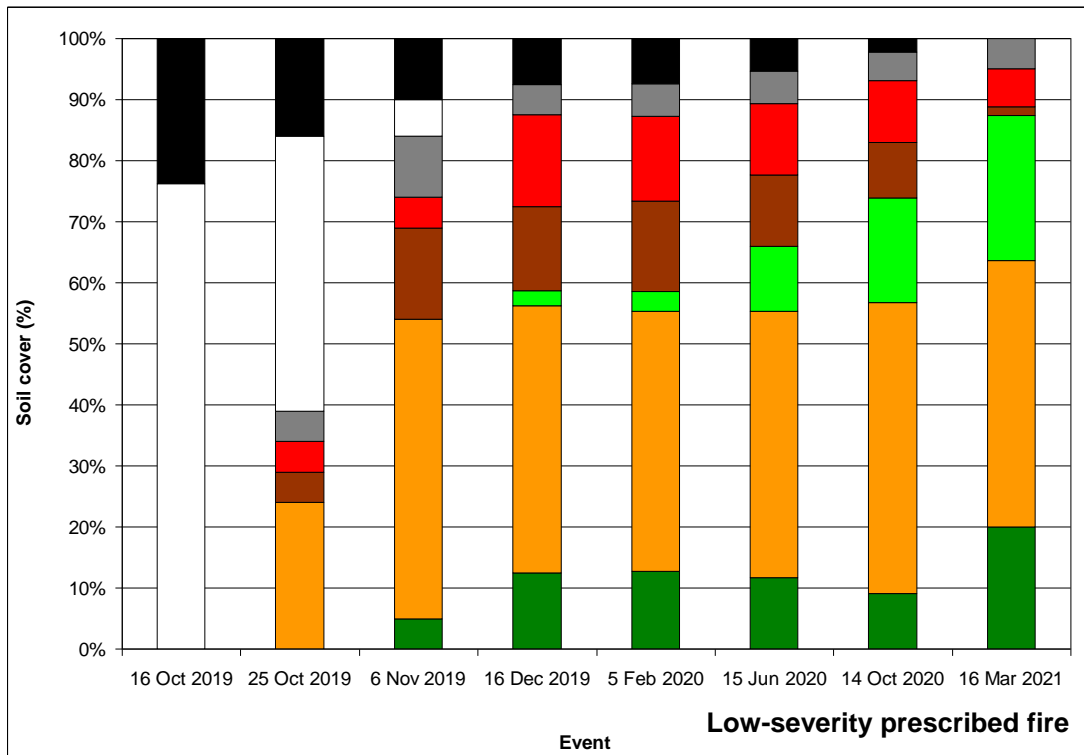
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352 ash and 18% of black ash). The remaining part of the low-severity plots was mainly covered
353 by needles ($44 \pm 6\%$). Over time the ash cover disappeared, exposing the underlying covers.
354 More specifically, the plots burned at high severity 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).

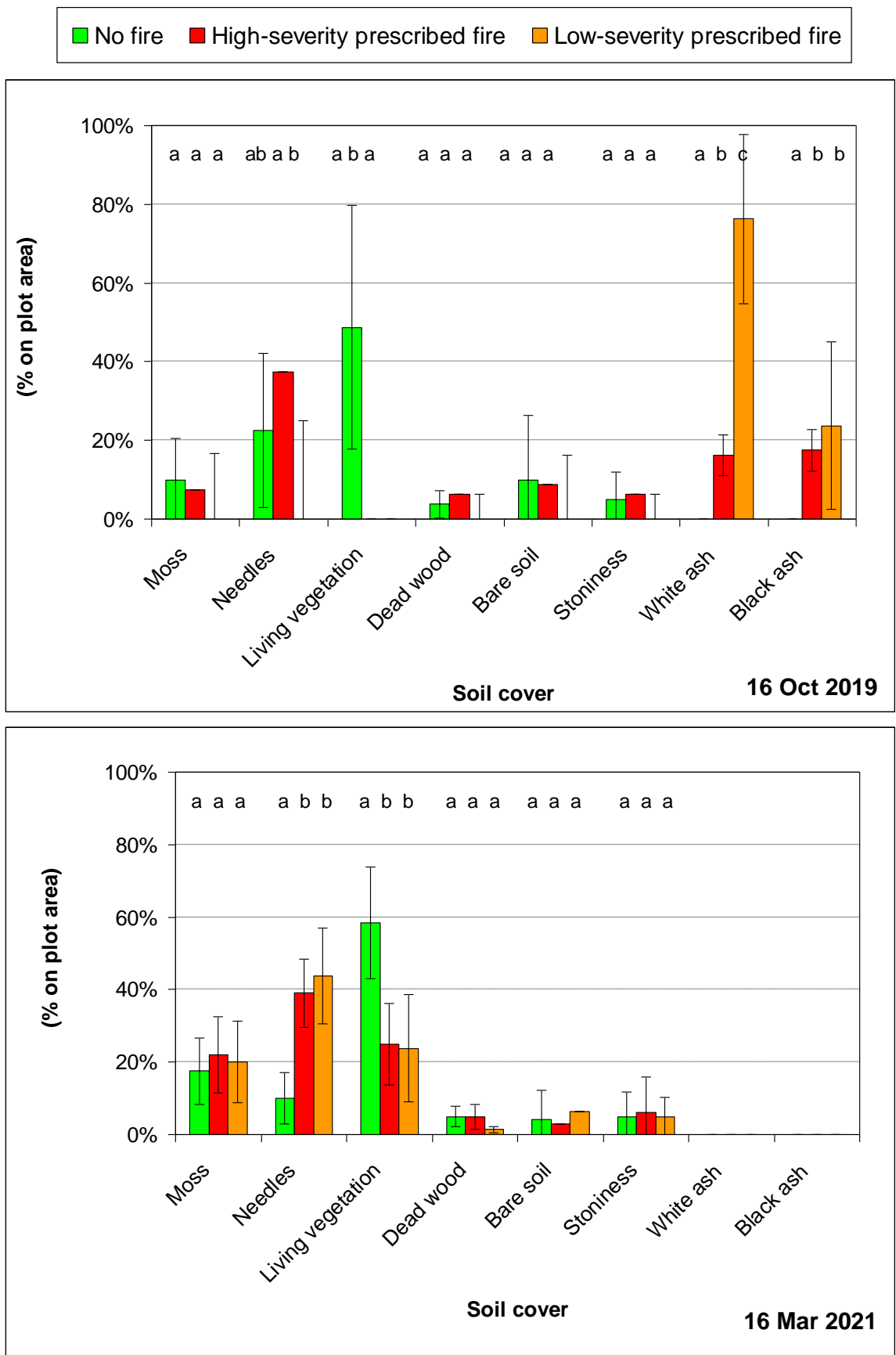
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367 The statistical analysis showed that the cover of white ash was significantly different between
 368 the areas burned by high and low-severity prescribed fires, while the difference in the black
 369 ash cover was not significant (Figure 4). No 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

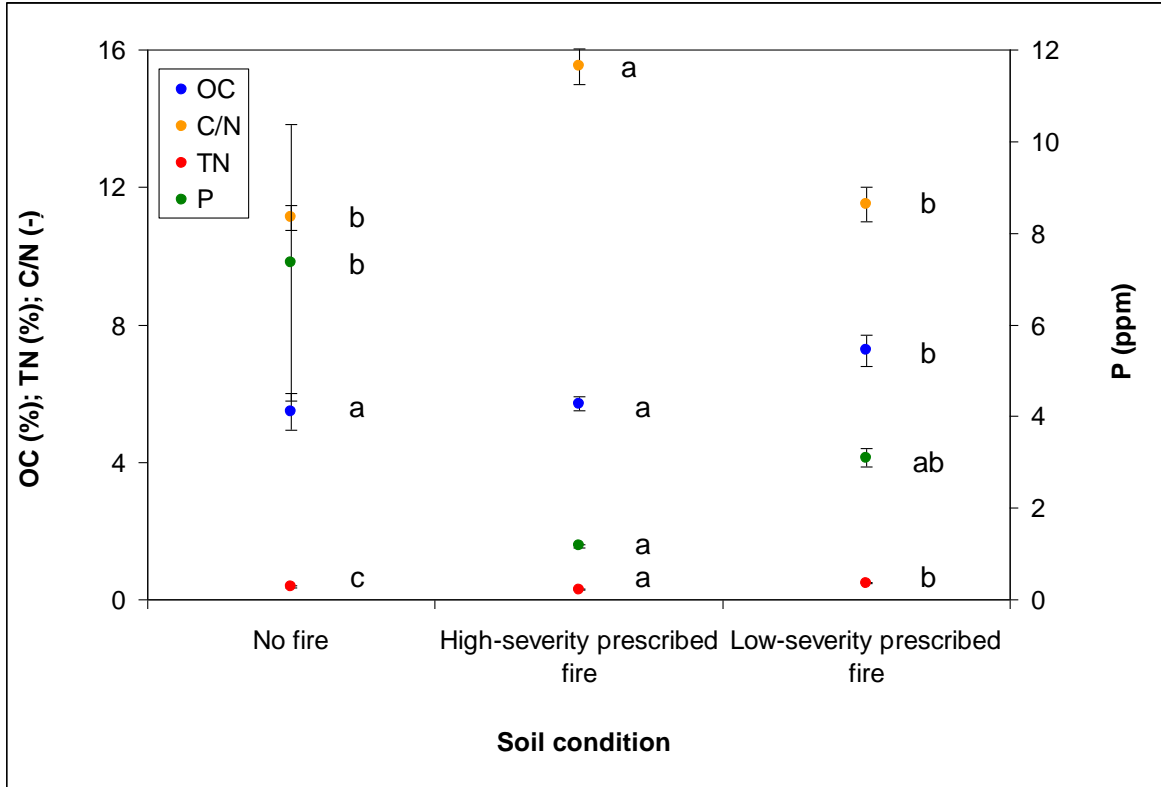
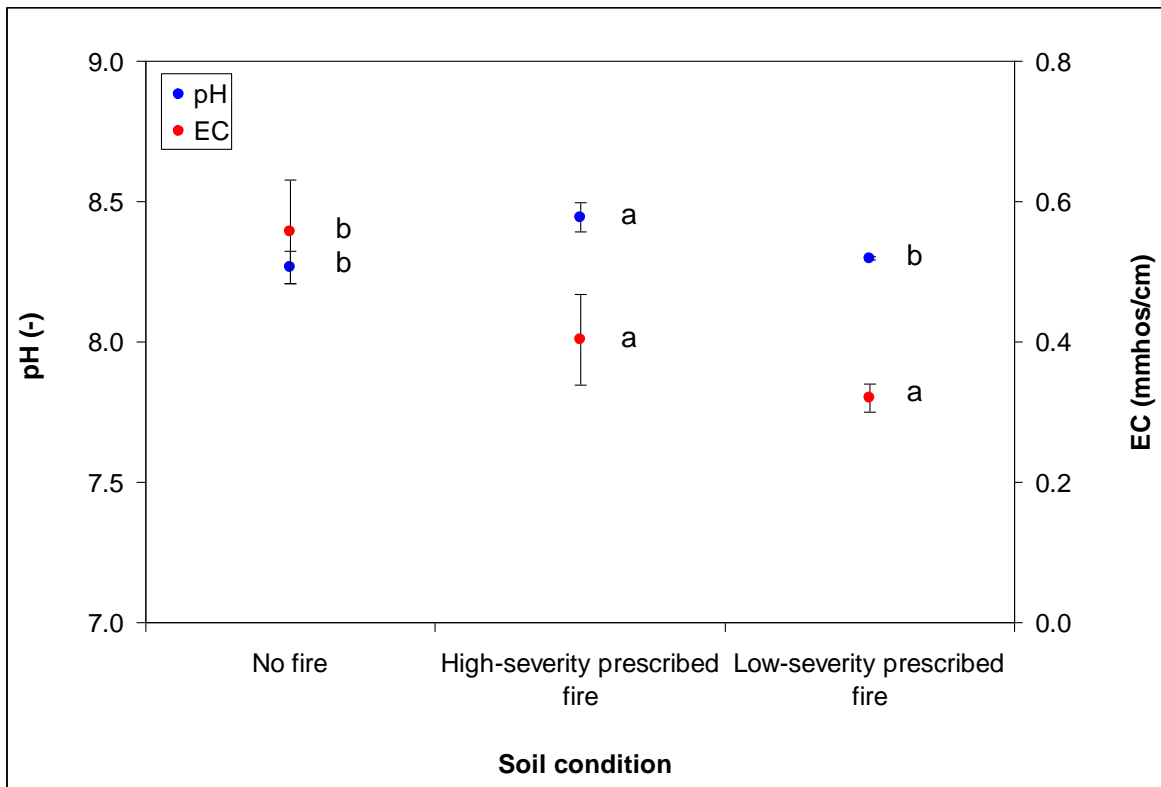
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380 and a half after) in La Moraleja forest (Castilla La Mancha, Spain). Different letters indicate
381 significantly different cover among the soil conditions.

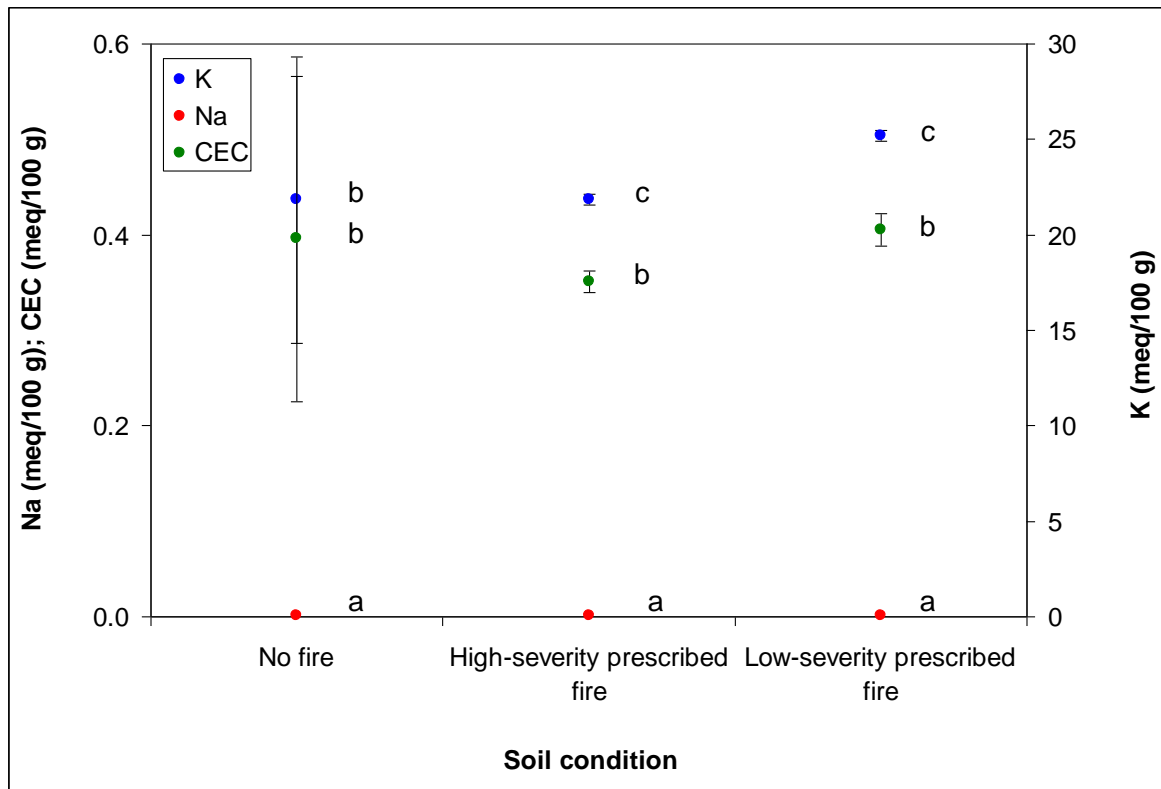
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384 Regarding the main physico-chemical properties, the pH was slightly higher in the burned
385 plots (8.30 ± 0.01 for low-severity prescribed fire and 8.44 ± 0.05 for high-severity fire)
386 compared to the unburned sites (8.27 ± 0.06) (Figure 5a). 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.

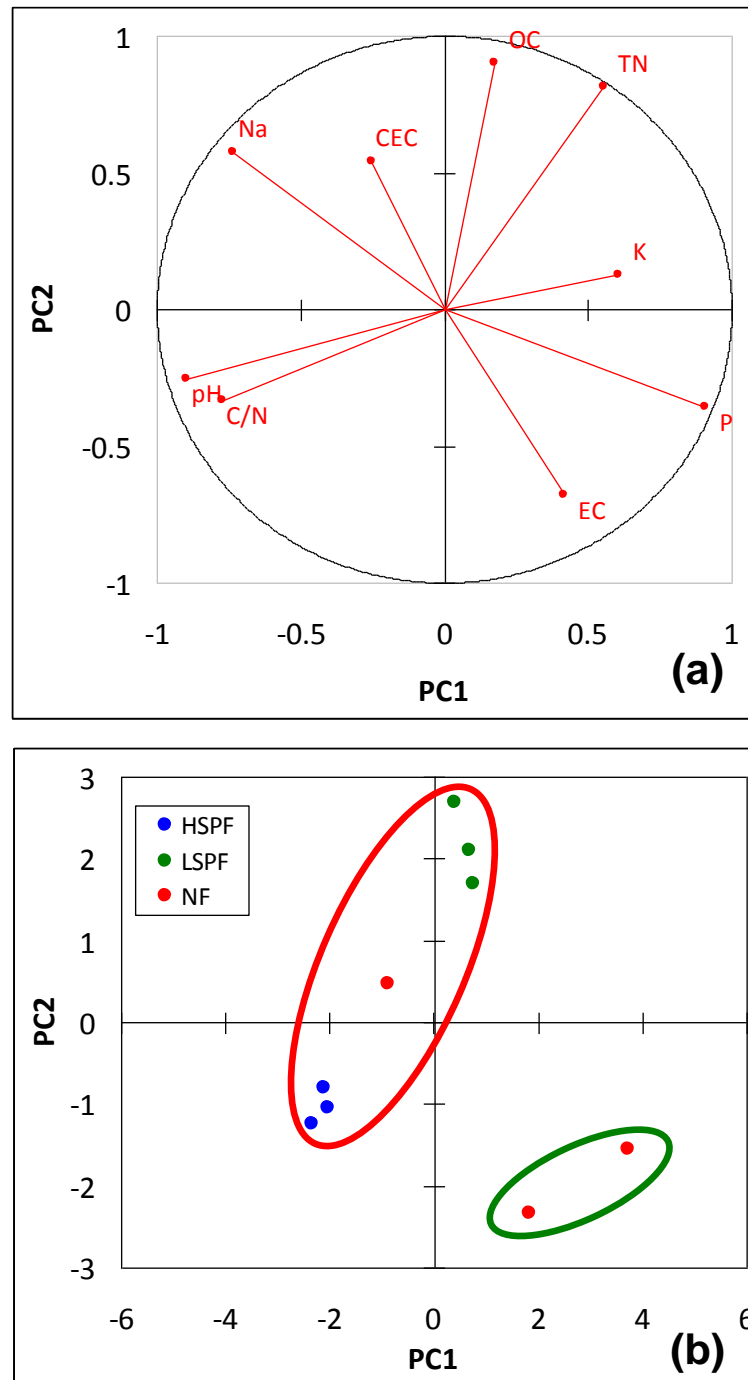
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423 The PCA identified two Principal Components (PC1 and PC2), which together explained 73%
 424 of the variance of the original physico-chemical properties of soils; a third PC (PC3)
 425 explained another 21% of this variance. Of these soil parameters, 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.

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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.
3 544 Fires also induced noticeable changes in the nutrient content of soils, with significant
4 545 decreases in TN and P after the high-severity fire. The low-severity fire resulted in an increase
5 546 in TN and a decrease in P compared to the unburned conditions, and the plots burned at high
6 547 severity had a decrease in TN and an even greater decrease in P than what observed in no fire
7 548 condition. After burning, organic N decreases due to volatilisation (Binkley and Fisher, 2019;
8 549 Turner et al., 2007), due to the soil heating. With low-severity fires, noticeable amounts of
9 550 organic N can remain in the soil, but in different form than before the fire. In line with some
10 551 authors (Giovannini et al., 1988; Grogan et al., 2000; Rivas et al., 2012; Smithwick et al.,
11 552 2005), the increase in TN detected in this study in soils burned by the low-intensity fire is
12 553 probably due to two factors: (i) the addition of partially pyrolyzed materials containing N (as
13 554 explained earlier in the case of the OC) and (ii) the release of N in dead roots and compounds.
14 555 Regarding the P dynamics, the reductions measured at both fire severities are ascribed to
15 556 volatilisation due to high temperatures (Certini, 2005). The reduction in P contrasts some
16 557 earlier studies, which reported that fires result in an enrichment of available P (Macadam,
17 558 1987; Serrasolsas and Khanna, 1995), which then rapidly declines. The increases in P after
18 559 low intensity fires is generally ascribed to the release of basic cations from the organic matter,
19 560 ash formation and its incorporation into the soil (Kennard and Gholz, 2001).
20 561 The measurements of cation contents of the burned soils in this study did not show significant
21 562 changes compared to the unburned plots. Only slight increases of K^+ , Na^+ and CEC were
22 563 detected in soils affected by the fire at low severity. Increases in available cations, such as
23 564 Na^+ and K^+ , are common in soils burned by low-severity prescribed fires (e.g., Arocena and
24 565 Opio, 2003; Kennard and Gholz, 2001; Scharenbroch et al., 2012). In our soils burned by
25 566 prescribed fires at high severity, the contents of these cations varied compared to the
26 567 unburned soils: the CEC decreased, no difference in K^+ , and increased Na^+ . These slight
27 568 changes contrast several previous studies that showed more significant increases (e.g., Elliott
28 569 et al., 2013; Khanna and Raison, 1986; Shrestha and Chen, 2010). As with the EC results
29 570 above, the lack of cation response in the plots burned by prescribed fires at high severity may
30 571 have been due to the immobilization of these compounds into ashes (Pereira et al., 2018) that
31 572 were not yet leached into the burned soils (Alcañiz et al., 2020; Cawson et al., 2012). This
32 573 lack of response is relevant to the cations studied, but this could have been also observed
33 574 because major cations were not analysed. Declines in CEC are mainly due to the combustion
34 575 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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1 **Short-term effects of prescribed fires with different severity on rainsplash erosion and**
2 **physico-chemical properties of surface soil in Mediterranean forests**

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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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35 changed some soil properties (e.g., pH, electrical conductivity, total nitrogen and phosphorus),
36 while no significant changes were observed in others (e.g., organic carbon and cations). Also
37 low-severity prescribed fires played a significant disturbance on soils (e.g., on electrical
38 conductivity, organic carbon, and total nitrogen), although this disturbance was negligible for
39 some soil properties (e.g., pH and cations) in comparison to unburned soils. The multivariate
40 analysis using the Principal Component Analysis coupled to Analytical Hierarchical Cluster
41 Analysis has demonstrated that fire is able to discriminate unburned and burned soils,
42 especially about organic carbon and nitrogen dynamics. However, this discrimination is not
43 always sharp compared to the unburned sites. This smooth difference was mainly due to the
44 limited soil changes after fire, despite the very high differences in soil temperatures during
45 burning. Overall, this study supports a better understanding of hydrological processes and
46 changes in soil chemistry due to fire with different severity, towards a more effective planning
47 of pre- and post-fire management in fire-affected areas.

48
49 **KEYWORDS:** prescribed fire; fire-severity; soil loss; soil covers; organic matter; nutrients.

50 51 **1. INTRODUCTION**

52
53 The hydrological and physico-chemical changes in soils due to fire depend on several factors,
54 such as the fire intensity and severity, amount, type, and water content of fuel, air humidity,
55 wind speed, topography of the site (Certini, 2005). Among these factors, the magnitude of
56 these soil changes is strictly linked to the fire intensity (i.e., the energy release by fire) and
57 severity (i.e., the entity of changes in the burned ecosystem) (Certini, 2005; Zavala et al.,
58 2014). The latter fire characteristic is considered as a key descriptor of the magnitude of the
59 soil changes after fire (Fernández et al., 2020; Fernández and Vega, 2016). More specifically,
60 for low-severity prescribed fires (the planned use of generally low-intensity fire to reduce
61 future wildfire risk in forests), soil heating is low and the impact on soil properties is limited,
62 including erosion (e.g., Cawson et al., 2012; Morris et al., 2014). However, the prescribed
63 fires may have low and high severity, which can variably alter soil hydrological properties.
64 Sometime, their use has been questioned due to some uncertainties over effectiveness and
65 consequences (Altangerel and Kull, 2013). In the soils burned by high-severity prescribed
66 fires, such as fires used to burn piles of logging slash, the burning temperatures are very high,
67 and the fire-induced changes in soil properties are strong and often irreversible (Certini, 2005;
68 Zavala et al., 2014; Zema, 2021). However, the post-fire physico-chemical and biological

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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., [Alcañiz et al., 2018](#); Carra et al., 2021; Cawson et
74 al., 2016; Hueso-González et al., 2018). In more detail, [Alcañiz et al. \(2018\)](#) report that soil's
75 physical and biological properties are more severely affected by prescribed fires than are its
76 chemical properties (with the electrical conductivity and soil water repellency being the most
77 sensitive soil properties) (Cawson et al., 2016; Hueso-González et al., 2018), and these effects
78 also depend on the time elapsed from the fire application ([Carra et al., 2021b](#)). Conversely,
79 [the effects of high-severity prescribed fires are more generally known, and therefore their](#)
80 [impacts so the effect](#) can be better anticipated (e.g., [Lucas-Borja et al., 2019](#); Mataix-Solera
81 et al., 2011).

82 These potentially contrasting results in runoff rates and erosion, and soil properties of burned
83 areas in forests suggest the need of more research about the fire effects on soil hydrology and
84 properties, with particular attention to the fire severity (Cawson et al., 2013). In particular,
85 rainsplash erosion is considered an essential process driving the overall soil loss from burned
86 or disturbed forest hillslopes. Due to the kinetic energy of the rainfall, soil particles are
87 displaced by the raindrop impact, and fall at a distance from their original position.
88 Rainsplash is the first stage of erosion, which detaches a large share of soil particles that can
89 be entrained by overland flow and transported downstream. Insight about this process is very
90 important for land managers, in order to choose the most effective anti-erosive practice (for
91 instance, mulching or erosion barriers). Post-fire surface runoff and soil erosion rates have
92 been largely investigated across the Mediterranean ecosystems under a variety of pedological,
93 climatic and management conditions. This problem is also felt in other environments,
94 especially where soils are highly erodible and rainfall shows high erosivity associated with
95 low soil cover (Russell-Smith et al., 2006). Much attention has also been paid to rainsplash
96 erosion in forests burned by wildfire (e.g., Fernández-Raga et al., 2021; Lucas-Borja et al.,
97 2022; Zavala et al., 2009). In more detail, Fernández-Raga et al. (2021) found high splash
98 erosion in severely-burned drylands of NW Spain, and ascribed this soil loss mainly to the
99 presence of bare soil and the low vegetation recovery rate. Lucas-Borja et al. (2022) reported
100 that rainsplash erosion in semi-arid lands covered by *Macrochloa tenacissima* was much
101 lower compared to the burned areas with the same species and bare soils. Zavala et al. (2009)
102 demonstrated that undisturbed ash and charred litter reduced post-wildfire rainsplash erosion.

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103 However, the majority of the published studies have focused on wildfire (Fernández-Raga et al., 2017).

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105 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.

112 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 m²) rainfall simulations, and overland flow experiments (9 m²) 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; ~~Wagenbrenner et al., 2021~~).

131 To fill ~~this-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. ~~More specifically, these post fire variables have been assessed at several microplots for 15 months in fire managed (with different~~

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8 137 ~~prescribed burning severities) and undisturbed pine forests of South Eastern Spain. Soil cover~~
9 138 ~~was also monitored to assess its evolution over time. This study is the first investigation~~
10 139 ~~comparing the rainsplash erosion rates in pine forests of Western Europe burned by prescribed~~
11 140 ~~fires with different severity. In these areas, the soils are particularly prone to erosion, given~~
12 141 ~~their specific climatic and geomorphological characteristics (soils that are shallow and poor in~~
13 142 ~~organic matter, rainstorms that are frequent and very intense).~~

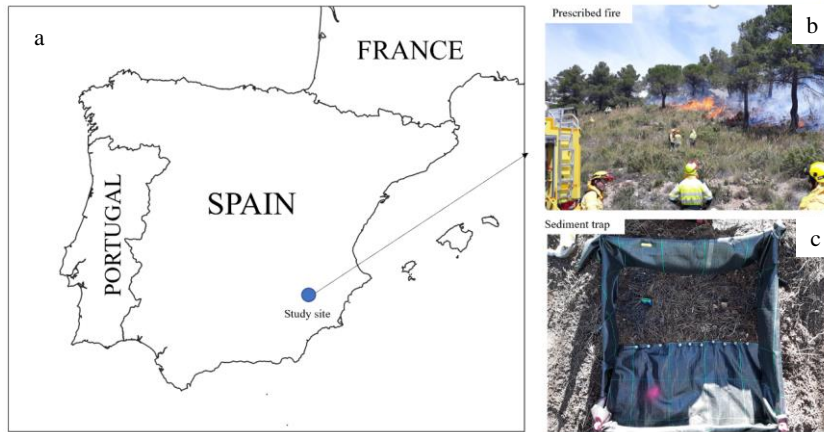
14 143 The two research questions ~~this study addresses to whom the study tries to reply~~ are: (i) how
15 144 much erosion by rainsplash is higher in soils burned by high-severity prescribed fires
16 145 compared to unburned areas or sites subjected to low-severity fires?; and (ii) which and to
17 146 what extent physico-chemical properties of the burned soils change after high-severity and
18 147 low-severity prescribed fires? The replies to these questions should demonstrate whether
19 148 prescribed fires of different severity are able to noticeably and significantly alter the
20 149 rainsplash erosion rates as well as other important soil properties. ~~This study is the first~~
21 150 ~~investigation comparing the rainsplash erosion rates in pine forests of Western Europe burned~~
22 151 ~~by prescribed fires with different severity. In these areas, the soils are particularly prone to~~
23 152 ~~erosion, given their specific climatic and geomorphological characteristics (soils that are~~
24 153 ~~shallow and poor in organic matter, rainstorms that are frequent and very intense).~~
25 154 ~~Therefore,~~ the results of this study can help to support a better understanding of this key
26 155 erosional process and the related changes in soil chemistry due to fire, towards to a more
27 156 informed planning of prescribed fire and post-fire management.
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29 158 **2. MATERIAL AND METHODS**

30 159 **2.1. Study area**

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33 162 The study area (La Moraleja forest) is located in the southern part of the Albacete province
34 163 (Castilla La Mancha region, Central Eastern Spain) at a mean altitude of 1130 m a.s.l. (Figure
35 164 1a). According to the Köppen-Geiger classification, the climate area can be classified as Csa
36 165 (Mediterranean climate with warm summers (Kottek et al., 2006). The average annual
37 166 temperature is 14.1 °C, and the total precipitation is 406 mm per year, according to the
38 167 National Meteorological Agency of Spain (AEMET) records collected at the Hellín weather
39 168 station (period of 2000–2020). The soils of the study area are classified as cambisols, with a
40 169 cambic horizon characterized by clay minerals and iron oxides (Chesworth et al., 2008). In
41 170 geological terms, the area lies among Betic-Iberian Mountain chains with calcareous

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8 171 formations alternating with marly intercalations that date back to the quaternary, according to
9 172 the map prepared by the National Geographic Institute of Spain in 2006. The current
10 173 vegetation is mainly composed of *Pinus pinaster* A. at the tree level, whereas *Juniperus*
11 174 *oxycedrus* L. is the main shrub species. The understory vegetation is mainly composed of
12 175 *Macrochloa tenacissima* (L.), *Quercus coccifera* L., *Pistacia lentiscus* L., and *Salvia*
13 176 *rosmarinus* L. In general, the tree density in the area approximately ranges from 500 to 600
14 177 trees per ha, with diameters of 15 to 25 cm and height of 8 to 15 m. The forest area has not
15 178 received active management since the early 2000s. In addition, no perturbations, such us
16 179 forest fires or extreme storms, have been recorded in the study area.
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182 Figure 1 - Geographical location (a) of the study area (La Moraleja forest, Province of
183 Albacete, Castilla La Mancha region, Spain); prescribed fire application (b); sediment trap to
184 monitor rainsplash erosion (c).

185 186 187 2.2. Prescribed fire operations

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189 Prescribed burning was carried out in part of the study area by the Regional Forest Service on
190 16 October 2019 (Figure 1b). The safety measures were observed by applying the prescribed
191 fire along fire lines separated by 1 m in the opposite direction to dominant winds, to minimize
192 the flame length and height (avoiding that the fire catches up more energy), to reduce the
193 consumed organic matter, and to lower the fire temperatures (Hidalgo et al., 2000). The fire
194 started at 12:30 CET (mean air temperature of 12.3 °C, mean relative humidity of 47% and
195 wind speed of 2.6 km/h with SE direction). The burned area in the site covered ~~six~~ 6 ha
196 (coordinates 38°31'12.20"N; -2°11'28.30"E).

197 198 2.3. Plot preparation and experimental design

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200 Ten plots of about 2-m² each were installed inside the burned area prior to burning. Before
201 prescribed fire application, the forest fuel and litter quantity were measured in each plot
202 (Table 1). Moreover and in order to generate high and low severity fire, forest fuel was
203 manually accumulated on each plot (Table 1). The forest fuel was composed mainly of Pinus
204 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. Ten plots of about 2 m² each were installed randomly selected inside the burned area prior to burning, adopting a split plot design treatment. Five plots were selected in the area burned by low severity prescribed fire, and five other plots were identified in the site burned by high severity fire. 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 slopes (between 20 and 25%) and aspect (north), to ensure comparability among the plots. Prior to prescribed fire application, the forest fuel and litter quantity were measured in each plot (Table 1). Forest fuel, which was manually accumulated on each plot, 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.

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

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8 232 for the burn severity of the prescribed fire will be identified: (i) “low-severity prescribed fire”;
9 233 and (ii) “high-severity prescribed fire”. Parson et al. (2010) have proposed some visual
10 234 indicators to identify the burn severity of soils affected by prescribed fires. In more detail, in
11 235 the soil treated by the “low-severity prescribed fire”, surface organic layers are not completely
12 236 consumed and are still recognisable, and the ground surface appears brown or black (lightly
13 237 charred), while the ~~tree canopy~~ ~~and understory vegetation~~ appear green. In contrast, a
14 238 “high-severity prescribed fire” consumes all or nearly all of the pre-fire ground cover and
15 239 surface organic matter (litter, duff, and fine roots), and charring may be visible on larger
16 240 roots; the prevailing colour of the site is often “black”, due to extensive charring, white or
17 241 gray ash indicates that considerable ground cover or fuels were consumed. Soil is often gray,
18 242 orange, or reddish at the ground surface where large fuels were concentrated and consumed.
19 243 Soil temperatures during the burn were measured at the soil surface and at a depth of 2 cm
20 244 (Table 1), using three thermocouples with dataloggers in each plot. The residence time of heat
21 245 on the ground barely exceeded one hour in the low-severity prescribed fire plots, and five
22 246 hours in high-severity prescribed fire plots.
23 247 Five plots with similar characteristics were selected in a neighbouring unburned area
24 248 (coordinates 38°31’35.62” N; -2°11’25.60” E). This area was not treated with prescribed fire
25 249 and was used as an experimental control (hereafter indicated as “no fire”).
26 250 Therefore, the experimental design consisted of three soil conditions (“no fire”, “low-severity
27 251 prescribed fire”, and “high-severity prescribed fire”), each ~~one with five plots as~~ ~~with five~~
28 252 replications, totalling 15 plots.

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30 254 **2.4. Data collection**

31 255

32 256 *2.4.1. Measurement of rainsplash erosion*

33 257

34 258 Immediately after the prescribed fire application, a 50 cm x 50 cm sediment trap was installed
35 259 at each 2-m² plot, ~~one trap per plot~~ (Figure 1c). The sediment trap was delimited by a
36 260 geotextile fabric fixed to posts and trenched around the outside, to prevent external inputs of
37 261 runoff or erosion. The bottom part of the sediment trap was protected with geotextile fabric
38 262 fixed to the soil, to enable periodic sediment collection after each rain event. Therefore, a net
39 263 area of 0.12 m² (30 x 40 cm²) was exposed to rain drop impact. At each trap, the sediment
40 264 collected is the soil lost by rainsplash detachment, and this sediment is usually entrapped by
41 265 the overland flow in its downstream path. However, due to the very small size of the sediment

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8 266 trap, it is unlikely that the overland flow begins, and therefore the installed device is able to
9 267 measure only the sediment lost by rainsplash erosion, and not by sheet flow. Moreover, no
10 268 visual indications of other erosion forms were identified in the sediment traps after each
11 269 rainfall event (e.g., initiating rills, tracks of laminar flow, etc.), and this confirms the fact that
12 270 this device was able to estimate only rainsplash erosion.

14 271 The eroded soil stored in each sediment trap was periodically collected, oven-dried and
15 272 weighed in the laboratory. Following the methodology used by (Keizer et al., 2018), the
16 273 following soil covers were measured in the area contributing to each sediment trap: moss,
17 274 needles, living vegetation (shrub and herbaceous layers), stoniness, dead wood (dead forms of
18 275 organic material, principally dead plant parts), bare soil and ash (black and white). These
19 276 covers were measured one day after the prescribed fire application and after each rainfall
20 277 event (excluding the first date). A weather station (WatchDog 2000 Series model) was placed
21 278 in the study area to measure the total daily precipitation, rainfall intensity and air temperature
22 279 during the study period. The soil loss was divided by the precipitation for the period of
23 280 sediment accumulation (hereafter “unit rainsplash erosion”).

24 281 25 282 *2.4.2. Measurement of the physico-chemical properties of soil*

26 283
27 284 In each plot, outside the sediment trap and according to previous studies (Lucas-Borja et al.,
28 285 2020b), three composite soil samples were collected two days after the prescribed fire and the
29 286 main physico-chemical properties of the soil sample were analysed. Before sample collection,
30 287 litter and stones were removed from a 15 × 15 cm square on the soil surface. A ruler
31 288 (precision of 1 mm) and trowel with markings (precision of 1 cm) were inserted into the soil
32 289 to remove the top 2-3 cm of soil within the square for each sample. The following physico-
33 290 chemical properties were analysed: clay, silt and sand contents (determined by the
34 291 international Robinson pipette method_ (Gee and Or, 2002), pH, electrical conductivity (EC)
35 292 (both in deionized water, 1:2.5 and 1:5 w/w, respectively, at 20 °C), organic carbon (SOC, by
36 293 the potassium dichromate oxidation method, Nelson and Sommers, 1996), total nitrogen (TN,
37 294 Bremner, 1982), available phosphorus (P, Olsen, 1982), sodium (Na⁺), potassium (K⁺), and
38 295 cation exchange capacity (CEC, Roig et al., 1980). The soil texture was calculated based on
39 296 the measured soil contents of clay, silt and sand, using the Soil Texture Calculator, prepared
40 297 by the USDA-Soil Survey Staff in 2014.

41 298 42 299 **2.5. Statistical analysis**

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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 ~~a three-levels factor for land condition~~ (“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 ~~land 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 ~~(Zema et al., 2015)~~.

3. RESULTS

3.1. Prescribed fire effects on rainsplash erosion

This study has analysed the [short-term rainsplash erosion](#) ~~due to the prescribed fires in the short-term, that this~~ 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), [determined-caused](#) rainsplash erosion (Figure 2).

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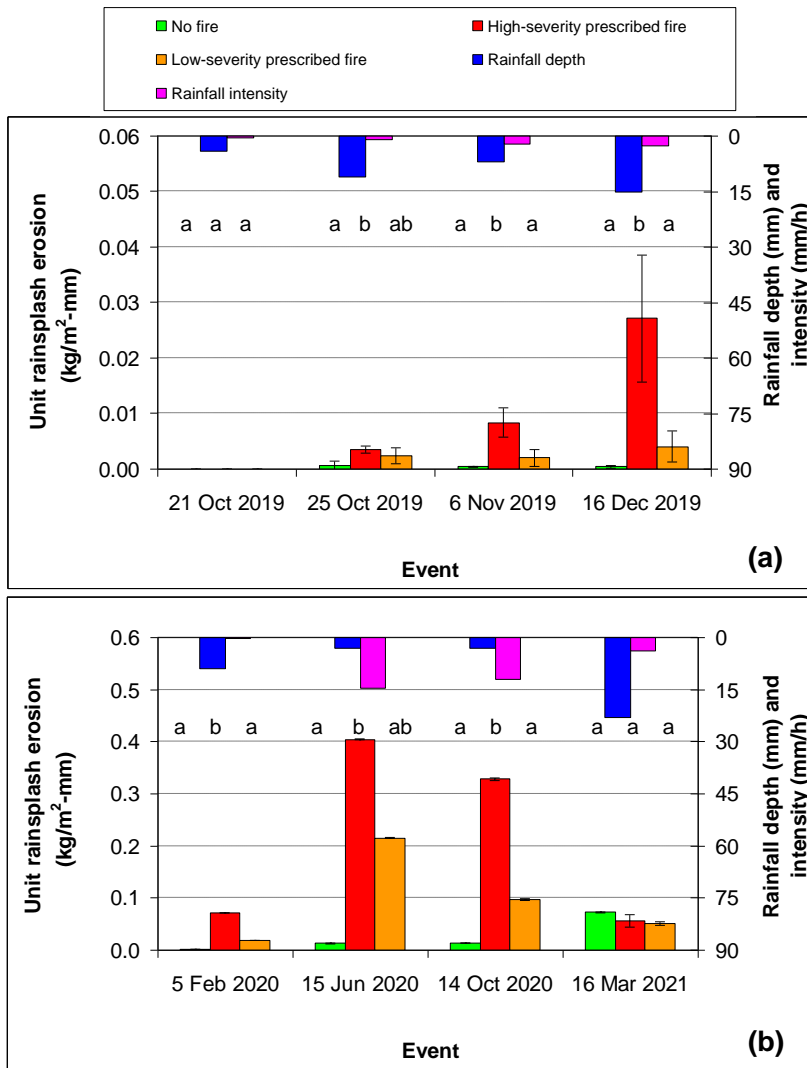


Figure 2 – Unit rainsplash erosion measured at the plot scale under three soil conditions (no fire, high-severity prescribed fire and low-severity prescribed fire) after eight precipitation events in La Moraleja forest (Castilla La Mancha, Spain). (a) Soil losses for the period 21 Oct 2019 – 16 Dec 2019. (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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342 In the unburned soils, the rainsplash erosion was low for seven of the eight monitored events
343 (from 0 to $0.04 \pm 0.05 \text{ kg/m}^2$), and relatively high for the last precipitation ($1.67 \pm 0.74 \text{ kg/m}^2$
344 on 16 March 2022). For the first event (21 October 2019), no erosion was observed in any of
345 the studied soil conditions. Over the study, the soil loss measured in the areas burned by low-
346 severity prescribed fires was not significantly higher (from 0 to $1.18 \pm 1.04 \text{ kg/m}^2$) compared
347 to the unburned soils. In contrast, the rainsplash erosion in the sites burned by the high-
348 severity fire (from 0.04 ± 0.01 to $1.21 \pm 0.47 \text{ kg/m}^2$) was always significantly greater than the
349 unburned area, except for the first event (soil loss equal to zero) and the largest precipitation
350 event ($1.29 \pm 0.90 \text{ kg/m}^2$, 16 March 2021). For two rainfalls (25 October 2019 and 15 June
351 2020) the soil loss surveyed after high-intensity fires was not significantly different from the
352 erosion measured in the sites burned at low-intensity (Figure 2).

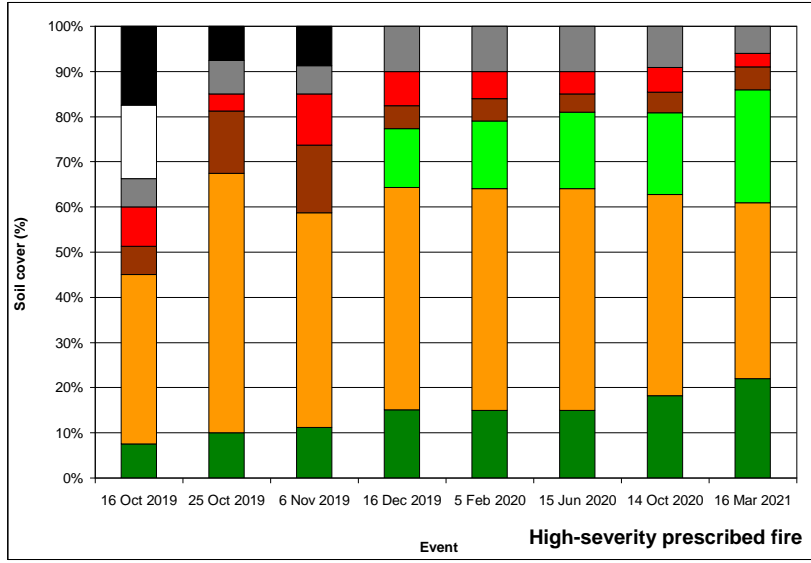
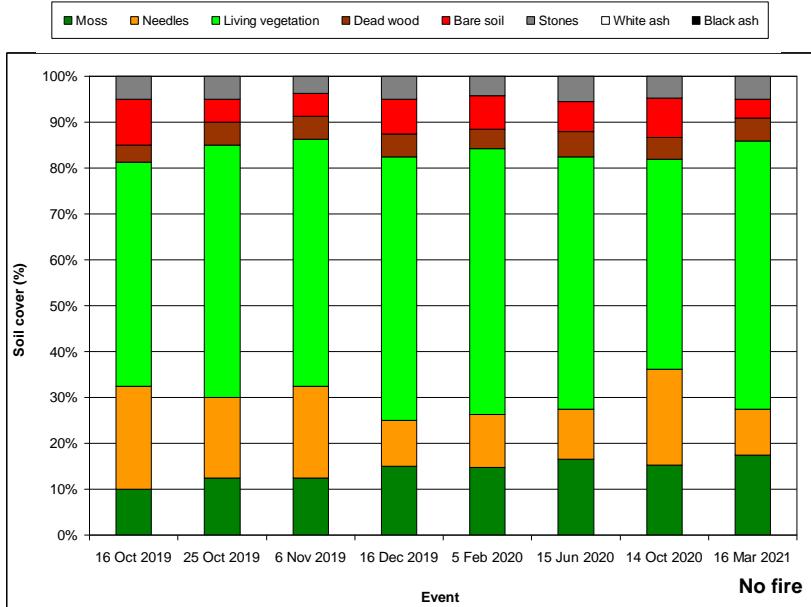
353 The precipitation events occurring immediately after the fire (21 October, and 6 November
354 2019) resulted in lower unit rainsplash erosion under all the studied soil conditions (from 0 to
355 $0.008 \pm 0.003 \text{ kg/m}^2\text{-mm}$) compared to the subsequent rainfalls. After the event recorded on
356 16 December 2019, the unit rainsplash erosion increased, particularly in the soils burned by
357 high-severity prescribed fires. In the plots burned by high-severity prescribed fire, the highest
358 unit rainsplash erosion was measured on 15 June 2020 ($0.41 \pm 0.16 \text{ kg/m}^2\text{-mm}$). For the other
359 sites, the maximum values of unit rainsplash erosion occurred on 15 June 2020 for the low-
360 severity prescribed fire ($0.22 \pm 0.17 \text{ kg/m}^2\text{-mm}$), and on 16 March 2021 for the unburned site
361 ($0.07 \pm 0.05 \text{ kg/m}^2\text{-mm}$). For the 16 March 2021 event, the unit rainsplash erosion detected in
362 the unburned soil was even higher (although not significantly) compared to the other soil
363 conditions ($0.06 \pm 0.04 \text{ kg/m}^2\text{-mm}$ for the high-severity prescribed fire, and 0.05 ± 0.05
364 $\text{kg/m}^2\text{-mm}$ for the low-severity prescribed fire) (Figure 2).

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

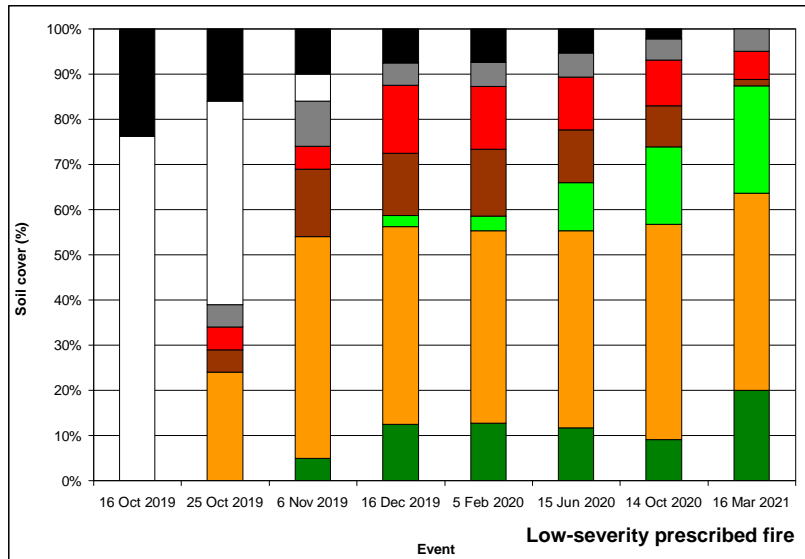
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368 The canopy cover was 30% in the unburned area, 40% in the site burned at lower severity and
369 35.8% in the soils affected by the high-severity prescribed fires. Concerning the ground cover
370 of soils, the unburned plots had an average cover of green material (shrubs and herbaceous
371 vegetation) of $53 \pm 4\%$, while the other cover types were much lower (14-15% of moss and
372 pine needles with minor amounts of dead wood and stones); the bare soil was $7 \pm 2\%$ (Figure
373 3). Fire released-produced ash in the burned soils, and this ash initially covered the plots ($76 \pm$
374 5% of black ash and $24 \pm 5\%$ of white ash) in the soils burned by fire with high severity,
375 while the ash cover was $34 \pm 21\%$ in the areas burned by the low-severity prescribed fire

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8 376 (16% of white ash and 18% of black ash). The remaining part of the low-severity plots was
9 377 mainly covered by needles ($44 \pm 6\%$). Over time the ash cover disappeared, exposing the
10 378 underlying covers. More specifically, the plots burned at high severity showed a cover of
11 379 green material of $49 \pm 20\%$ and smaller areas with moss ($13 \pm 6\%$) and needles ($11 \pm 6\%$),
12 380 while, in the sites affected by the low-severity prescribed fire, the ground cover mainly
13 381 consisted of needles ($44 \pm 6\%$), moss ($12 \pm 4\%$) and dead wood ($10 \pm 5\%$). The bare soil was
14 382 $10 \pm 4\%$ in these plots and $5 \pm 2\%$ in the plots burned by the fire with high severity (Figure
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 386 Figure 3 – Evolution of the soil covers in plots under three soil conditions (no fire (a), high-
 387 severity prescribed fire (b) and low-severity prescribed fire (c) after the prescribed fire and
 388 eight precipitation events (excluding the first rainfall) in La Moraleja forest (Castilla La
 389 Mancha, Spain).

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

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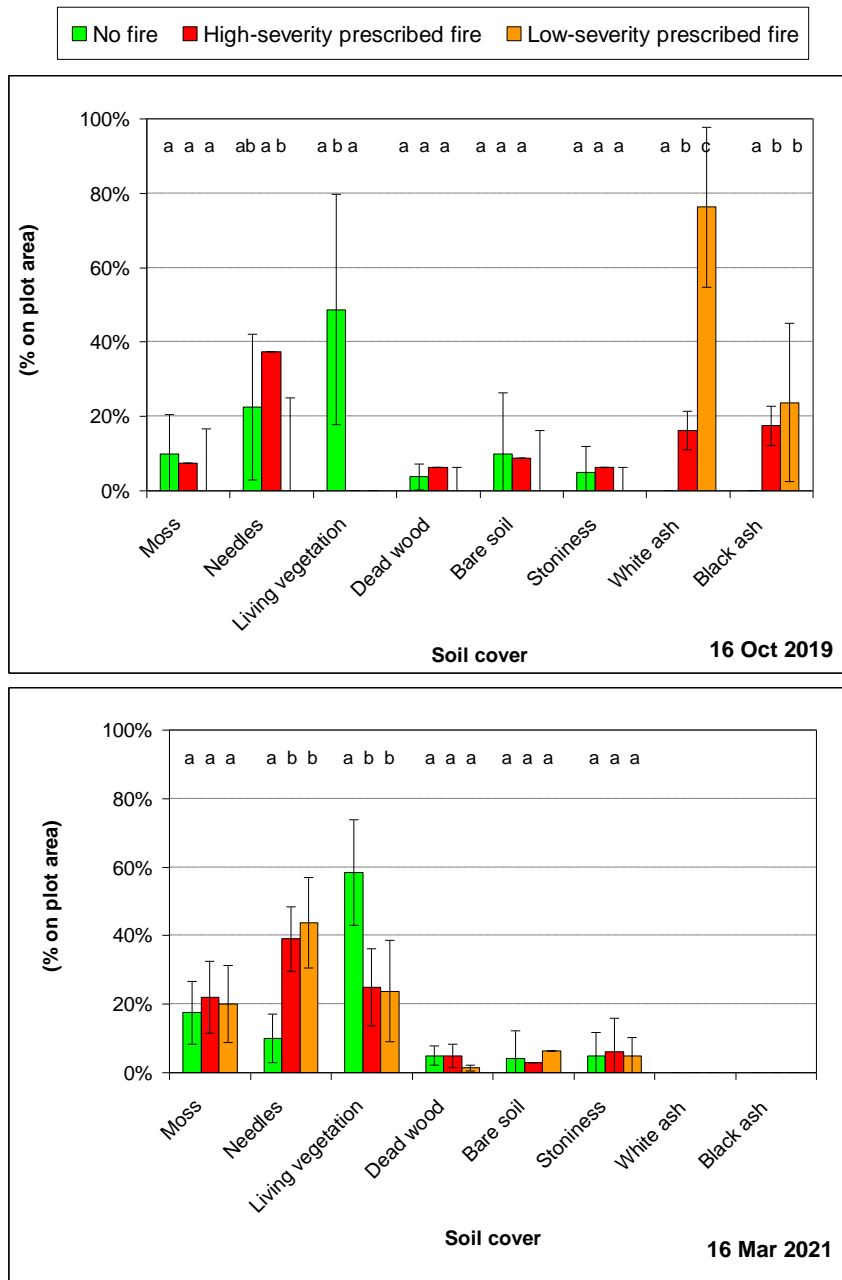


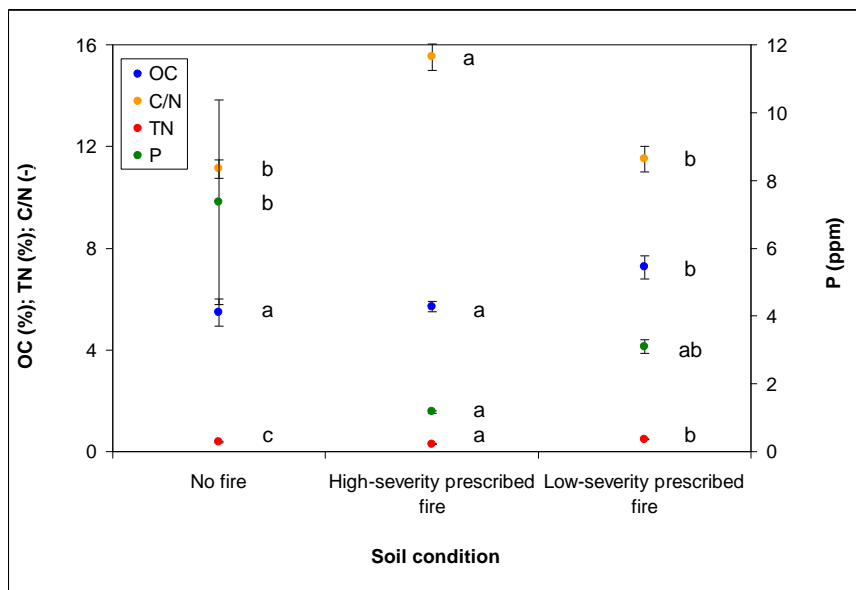
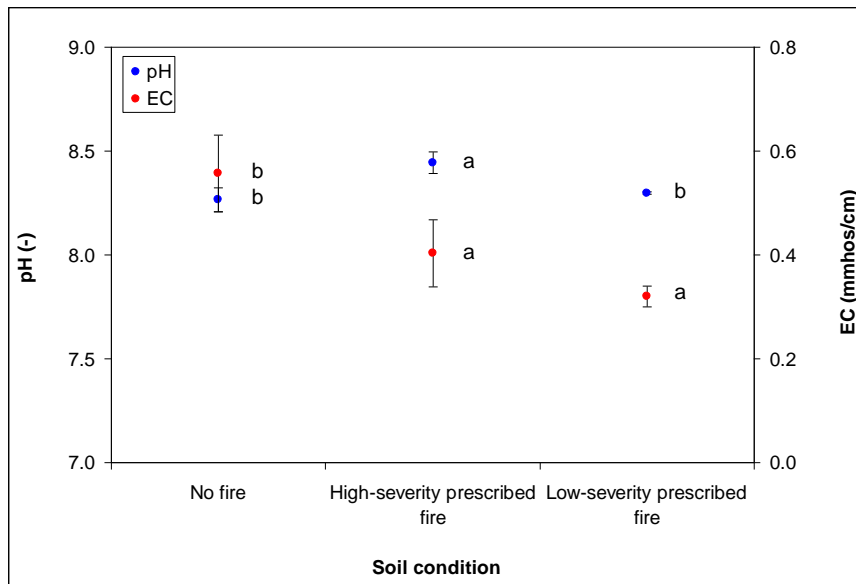
Figure 4 – Soil covers surveyed at two dates in plots under three soil conditions (no fire, high-severity prescribed fire and low-severity prescribed fire) (immediately after fire and one year

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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 $5.47 \pm 0.55\%$, this parameter increased in both fire-affected plots, but the difference was only significant for the soils burned at high severity ($7.25 \pm 0.45\%$) (Figure 5b). TN was $0.28 \pm 0.02\%$ in unburned plots. This parameter increased in soils burned at low severity ($0.36 \pm 0.01\%$) and decreased in soils burned by the fire with high severity ($0.22 \pm 0.01\%$). 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).

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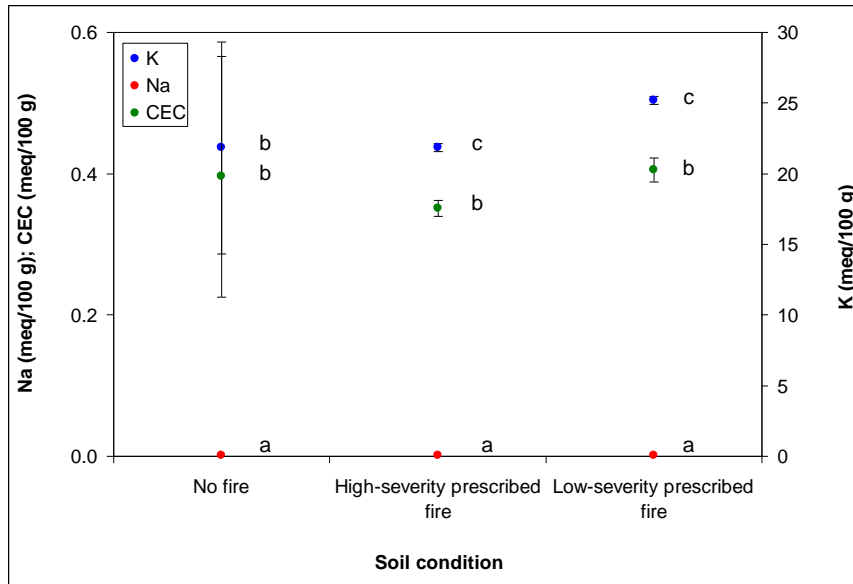


Figure 5 – Main physico-chemical properties of soils under three conditions (no fire, high-severity prescribed fire, and low-severity prescribed fire) immediately after burning (16 October 2019) in La Moraleja forest (Castilla La Mancha, Spain): pH and electrical conductivity (EC) (a); organic carbon (OC), carbon/nitrogen (C/N) ratio, total nitrogen (TN), and phosphorous (P) (b); and potassium (K^{\pm}), sodium (Na^{\pm}), 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^{\pm} , 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 θ_{MOC} , 0.902, and TN, 0.814, and negative for EC, -0.676), while the PC3 was associated with high loadings to K^{\pm} (-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

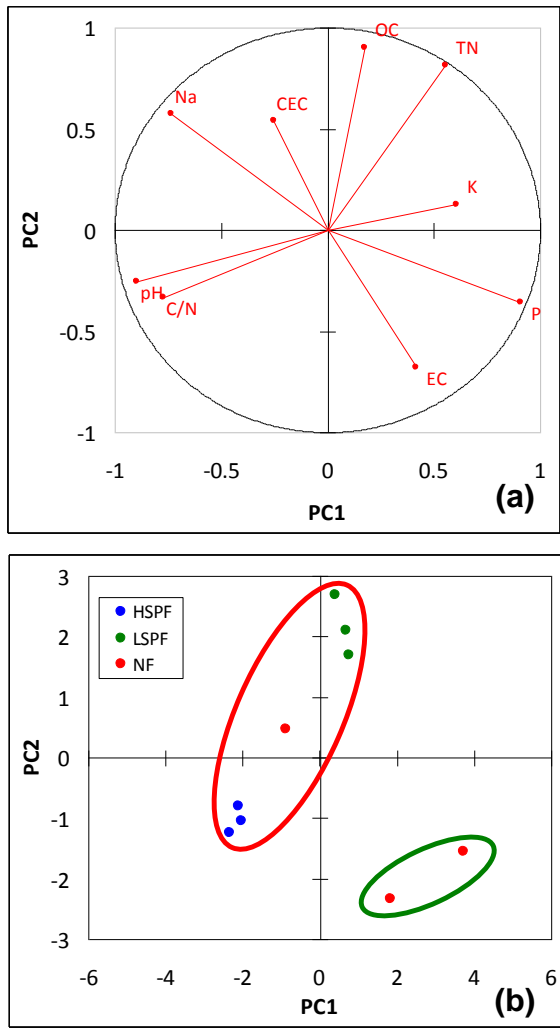


Figure 6 – Loadings of the original variables (a, physico-chemical properties of soil), and scores with relevant clusters (b) on the first two Principal Components (PC1 and PC2) provided by the Principal Component Analysis coupled by Analytical Hierarchical Cluster Analysis applied to soil samples under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

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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 was 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](#); [Cawson et al., 2012](#); [Moody et al., 2013](#); [Zema, 2021](#)). 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., [Carrà et al., 2022](#); [Cawson et al., 2016](#); [Lucas-Borja et al., 2021](#); [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/m²-yr) was noticeably under the low end of the tolerance range of 0.3-1.1 kg/m²-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

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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 (Carrà et al., 2021b; 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; ~~Zema et al., 2022~~), 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., ~~Agbeshie et al., 2022~~; Alcañiz et al.,

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8 534 ~~2018~~2016; Valkó et al., 2016), while increases are common when the burn severity is high, as
9 535 found in this study. In this case, soil pH increase is due to denaturation of organic acids
10 536 (Certini, 2005) and the increase of sodium and potassium oxides, carbonates and hydroxides
11 537 from heating (Pereira et al., 2018; Ulery et al., 1993).
12
13 538 The ~~electrical conductivity~~EC significantly decreased in burned soils, regardless of burn
14 539 severity. This result is unexpected, since an increase in EC is reported by many authors
15 540 (Alcañiz et al., 2020; Granged et al., 2011; Scharenbroch et al., 2012). The reasons of
16 541 previously reported EC increases after fire are the incorporation of ash (Fonseca et al., 2017;
17 542 Scharenbroch et al., 2012; Úbeda and Outeiro, 2009), release of soluble ions during the
18 543 combustion of organic matter (Alcañiz et al., ~~2018~~2016; ~~Certini, 2005~~), and formation of
19 544 black carbon (Alcañiz et al., 2020; ~~Certini, 2005~~). In contrast, other studies show that EC can
20 545 decrease, especially after fires with low intensity (Alcañiz et al., 2020). Accordingly, we
21 546 ascribe the decrease in EC measured in this study to the absence of leaching effect of ions
22 547 from ash into the soil, due to the lack of rainfall after the fire, and the very short time of
23 548 sampling after fire (two days against some time after appreciable precipitations of other
24 549 studies). This explanation is in close accordance with ~~Neary et al. (1999)~~Zavala et al. (2014),
25 550 who state that salts are quickly leached or transported by runoff after burning. Direct
26 551 measurements of the ion contents in the soil should corroborate this hypothesis.
27
28 552 The fate of ~~organic carbon~~OC was different between low- and high-intensity fires. The
29 553 significant increase detected after low-intensity fires may be due to partially pyrolyzed plant
30 554 residues (Agbeshie et al., 2022; Caon et al., 2014), incomplete combustion of the organic
31 555 matter (Alcañiz et al., 2020; Soto and Diaz-Fierros, 1993; Úbeda et al., 2005) and to forest
32 556 floor decomposition (Scharenbroch et al., 2012). It is possible that litter combustion in
33 557 addition to forest floor decomposition could have increased the ~~organic carbon~~OC content of
34 558 the soil. According to some studies (e.g., ~~Alcañiz et al., 2018~~; Scharenbroch et al., 2012; Soto
35 559 and Diaz-Fierros, 1993), OC increases in soils burned at low severity compared to unburned
36 560 areas. In contrast, after the high-severity prescribed fire of this study, the OC was not different
37 561 in comparison to the unburned plots. In general, fires with high severity determine the almost
38 562 total combustion of OC with its mineralization, volatilization, and solubilisation (~~Agbeshie et~~
39 563 ~~al., 2022~~; Rodriguez-Cardona et al., 2020), due to the very high temperature of fire. Soil
40 564 heating at high temperatures generally reduces the amount and quality of OC (Merino et al.,
41 565 2018), since severe wildfires are able to induce volatilization of high amounts of carbon and
42 566 nitrogen, which start to vaporize at about 200 °C (Pereira et al., 2018), and are totally
43 567 consumed lost over 550 °C (Gray and Dighton, 2006). However, in our study, the expected

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8 568 loss of OC due to soil heating could have been balanced by the supply of partially burned
9 569 residues and charred leaves, falling on forest ground immediately after fire. Presumably, the
10 570 total content of OC did not change, but it may be possible that the type of organic compounds
11 571 did, although the relevant determinations were not made in this investigation.

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13 572 Fires also induced noticeable changes in the nutrient content of soils, with significant
14 573 decreases in [total nitrogen-TN](#) and [phosphorous-P](#) after the high-severity fire. The low-severity
15 574 fire resulted in an increase in TN and a decrease in P compared to the unburned conditions,
16 575 and the plots burned at high severity had a decrease in TN and an even greater decrease in P
17 576 than what observed in no fire condition. After burning, organic [nitrogen-N](#) decreases due to
18 577 volatilisation (Binkley and Fisher, 2019; [Certini, 2005](#); Turner et al., 2007), due to the soil
19 578 heating. With low-severity fires, noticeable amounts of organic [nitrogen-N](#) can remain in the
20 579 soil, but in different form than before the fire. In line with some authors (Giovannini et al.,
21 580 1988; Grogan et al., 2000; Rivas et al., 2012; Smithwick et al., 2005; [Zavala et al., 2014](#)), the
22 581 increase in TN detected in this study in soils burned by the low-intensity fire is probably due
23 582 to two factors: (i) the addition of partially pyrolyzed materials containing [nitrogen-N](#) (as
24 583 explained earlier in the case of the OC) and (ii) the release of [nitrogen-N](#) in dead roots and
25 584 compounds. Regarding the [phosphorous-P](#) dynamics, the reductions measured at both fire
26 585 severities are ascribed to volatilisation due to high temperatures (Certini, 2005). The reduction
27 586 in P contrasts some earlier studies, which reported that fires result in an enrichment of
28 587 available [phosphorous-P](#) ([Certini, 2005](#); [Macadam, 1987](#); Serrasolsas and Khanna, 1995),
29 588 which then rapidly declines. The increases in P after low intensity fires is generally ascribed
30 589 to the release of basic cations from the organic matter, ash formation and its incorporation
31 590 into the soil ([Aleaniz et al., 2018](#); Kennard and Gholz, 2001).

32 591 The measurements of cation contents of the burned soils in this study did not show significant
33 592 changes compared to the unburned plots. Only slight increases of K^+ , Na^+ and CEC were
34 593 detected in soils affected by the fire at low severity. Increases in available cations, such as
35 594 [sodium- \$Na^+\$](#) and [potassium- \$K^+\$](#) , are common in soils burned by low-severity prescribed fires
36 595 (e.g., [Aleaniz et al., 2018](#); Arocena and Opio, 2003; Kennard and Gholz, 2001; Scharenbroch
37 596 et al., 2012). In our soils burned by prescribed fires at high severity, the contents of these
38 597 cations varied compared to the unburned soils: the CEC decreased, no difference in K^+ , and
39 598 increased Na^+ . These slight changes contrast several previous studies that showed more
40 599 significant increases (e.g., [Certini, 2005](#); Elliott et al., 2013; Khanna and Raison, 1986;
41 600 Shrestha and Chen, 2010). As with the EC results above, the lack of cation response in the
42 601 plots burned by prescribed fires at high severity may have been due to the immobilization of

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602 these compounds into ashes (Pereira et al., 2018) that were not yet leached into the burned
603 soils (Alcañiz et al., 2020; Cawson et al., 2012). This lack of response is relevant to the
604 cations studied, but this could have been also observed because major cations were not
605 analysed. Declines in CEC are mainly due to the combustion of soil organic matter and the
606 transformation of clay minerals, especially at very high temperatures (Zavala et al., 2014), and
607 this explains what we observed in this study after high-severity prescribed fires.
608 The combined analysis of the physico-chemical properties of the soil through PCA shows an
609 evident mismatching between the dynamics of OC and TN (associated with the PC1) and the
610 other elements or compounds, such as P, K⁺ and Na⁺ (linked to the other two PCs). Moreover,
611 the PCA coupled to AHCA reveals a clear discrimination between burned soils, regardless of
612 burn severity, and all but one unburned area. This demonstrates that fire can change the
613 physico-chemical properties of soils, but these changes are often not so noticeable to create a
614 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

~~This study has evaluated the rainsplash erosion and changes in the main physico-chemical properties of soil burned by prescribed fires with low and high severity in a Mediterranean forest. Immediately after fire, no rainsplash erosion was measured in both fire conditions. Some weeks after fire, the high severity fires gave higher rainsplash erosion after 75% of the observed rainfalls compared to the other soil conditions.~~

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635 Replying to the first research question, the study has shown that rainsplash erosion in [forest](#)
636 soils burned by prescribed fires with high severity [under Mediterranean conditions](#) may be on
637 average higher by 160% and 95% compared to the unburned plots and areas affected by
638 prescribed fires with low severity, respectively. Regarding the second research question, the
639 study has highlighted that high-severity prescribed fires can change some important soil
640 properties (e.g., pH, EC, TN and P), but some changes are not always significant (e.g., OC
641 and cations) compared to the unburned soils. Also, low-severity prescribed fires can
642 significantly change some chemical properties of soils (e.g., EC, OC and TN), while, for other
643 soil parameters, the changes are negligible (e.g., pH and cations) in comparison to unburned
644 soils. ~~The multivariate analysis using the PCA and AHCA demonstrated that fire is able to~~
645 ~~discriminate unburned and burned soils, especially in OC and TN dynamics.~~ However, the
646 differences in post-fire soil changes were limited, but those in soil temperatures during
647 burning were large between the high- and low-severity prescribed fires. This discrimination
648 was not always sharp compared to the unburned sites.

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

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1 **Figures**

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

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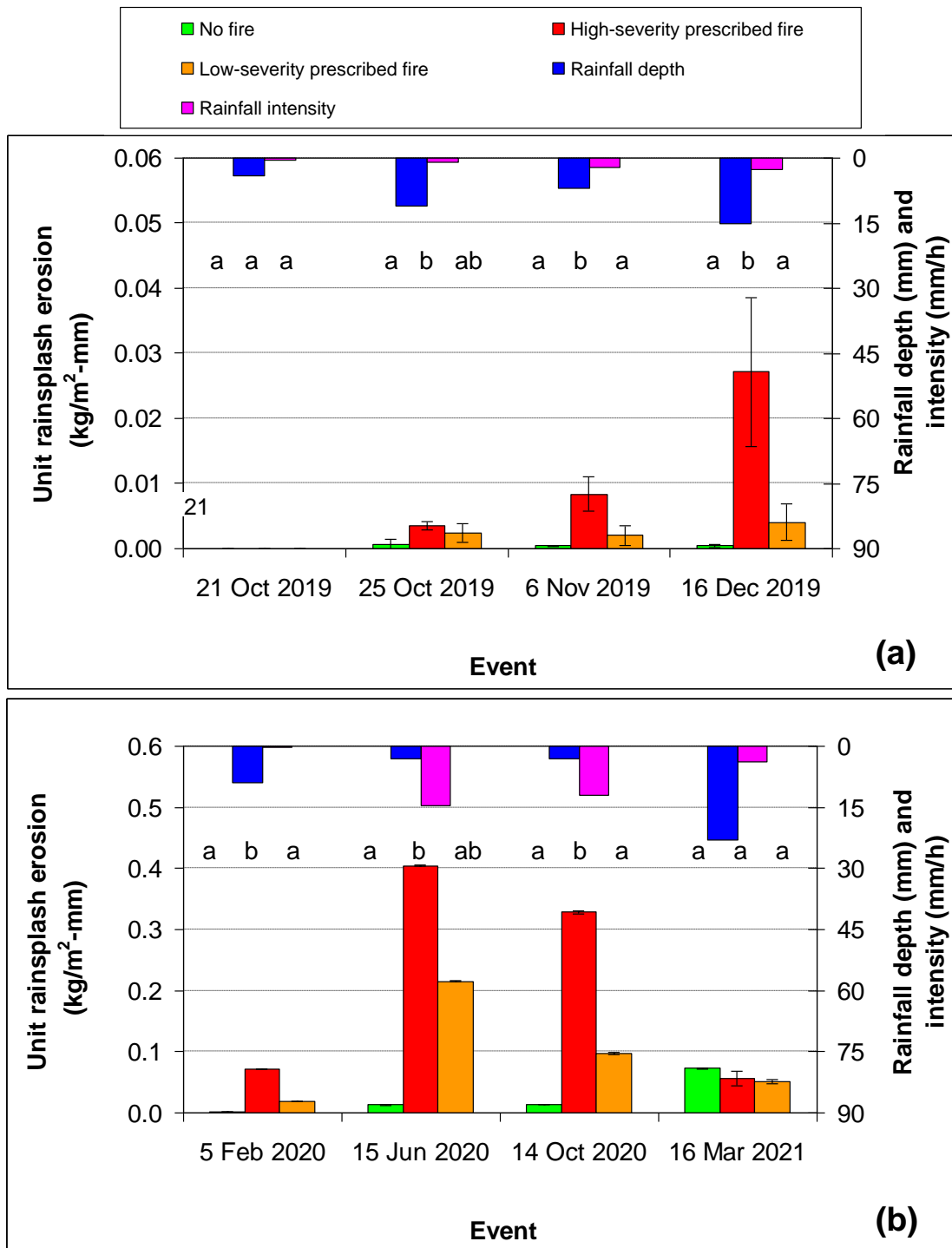
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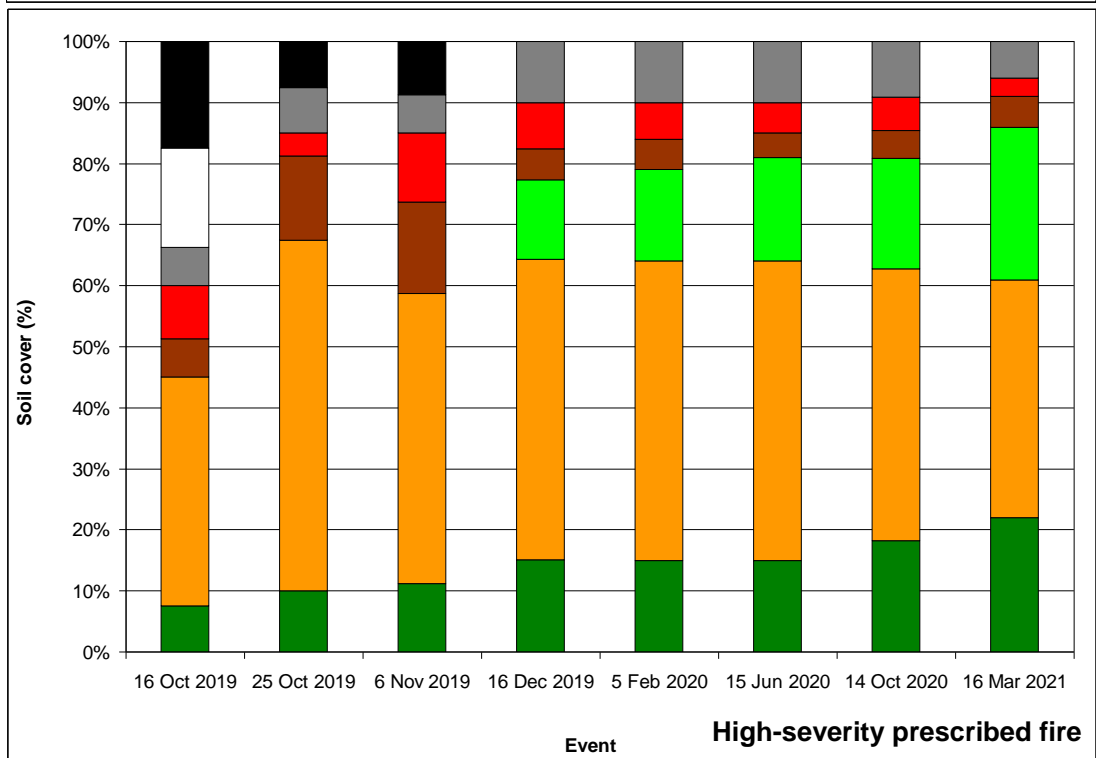
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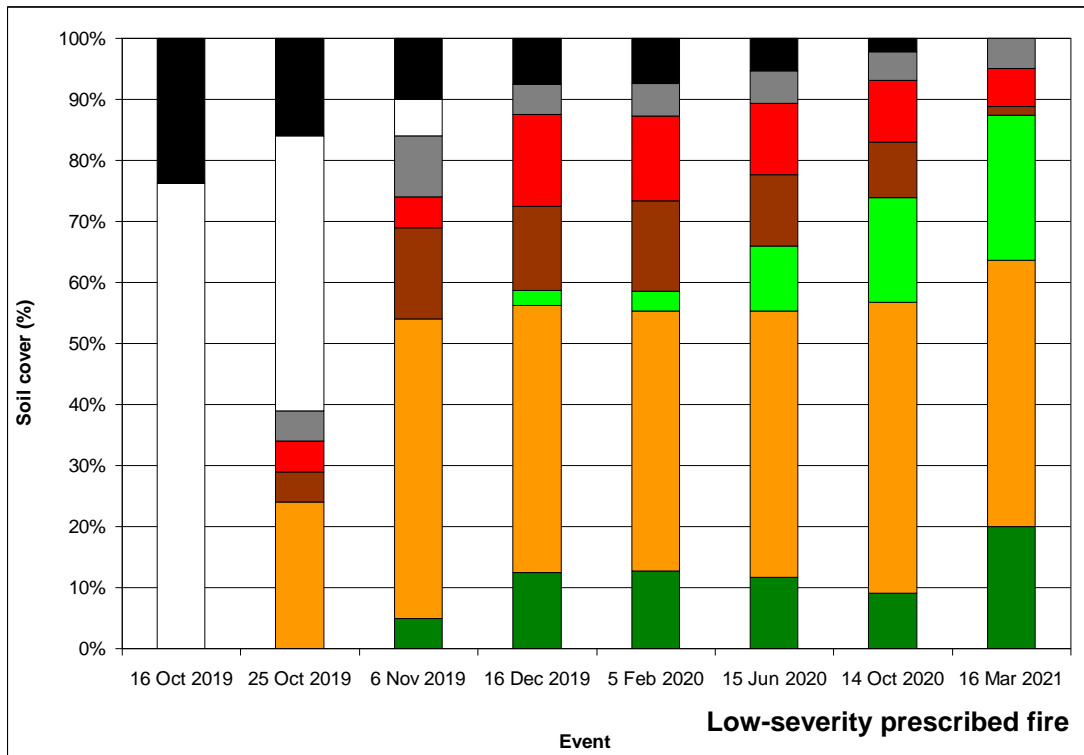
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 24 Figure 2 – Unit rainsplash erosion measured at the plot scale under three soil conditions
 25 (no fire, high-severity prescribed fire and low-severity prescribed fire) after eight
 26 precipitation events in La Moraleja forest (Castilla La Mancha,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

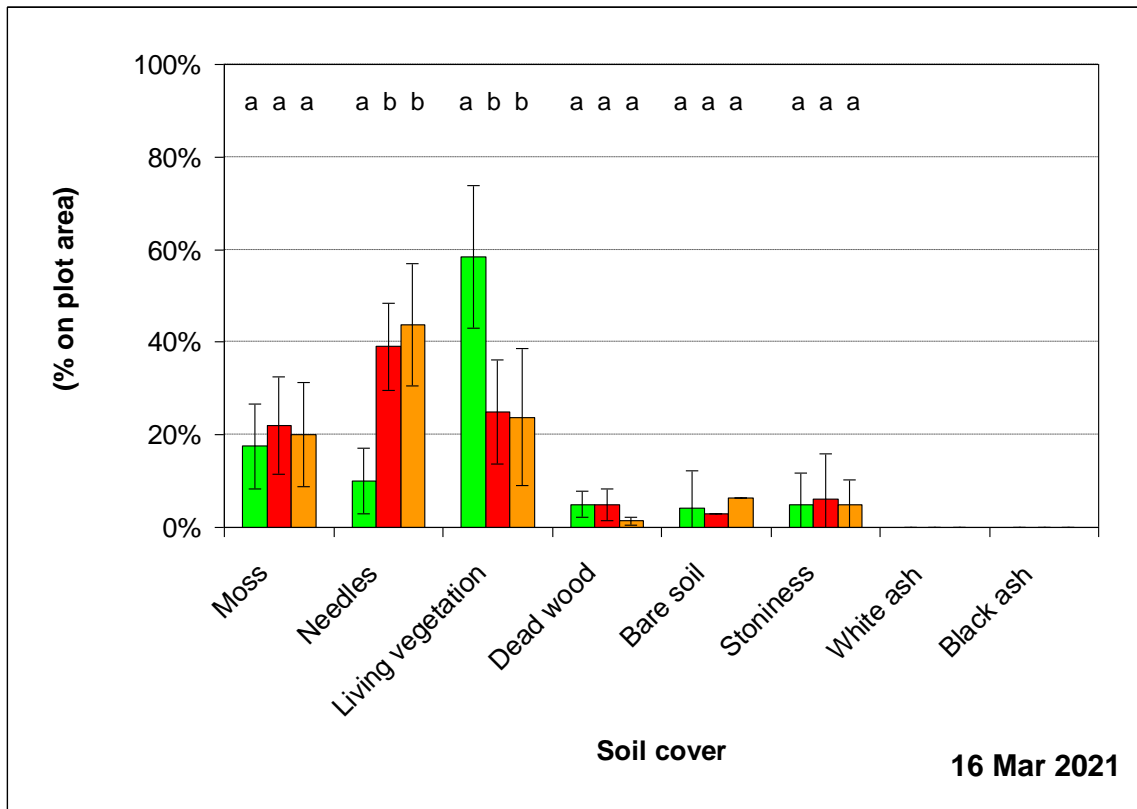
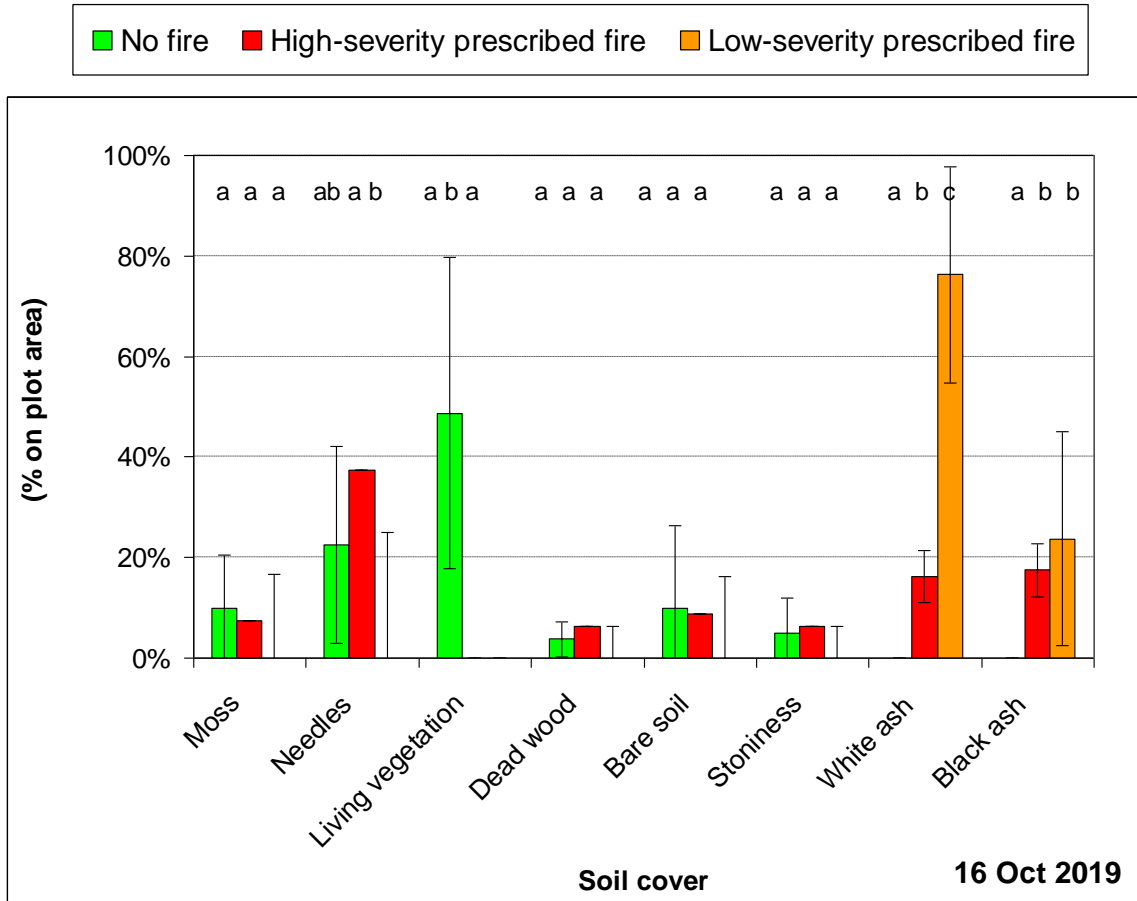




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32 Figure 3 – Evolution of the soil covers in plots under three soil conditions (no fire (a),
 33 high-severity prescribed fire (b) and low-severity prescribed fire (c)) after the prescribed
 34 fire and eight precipitation events (excluding the first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

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

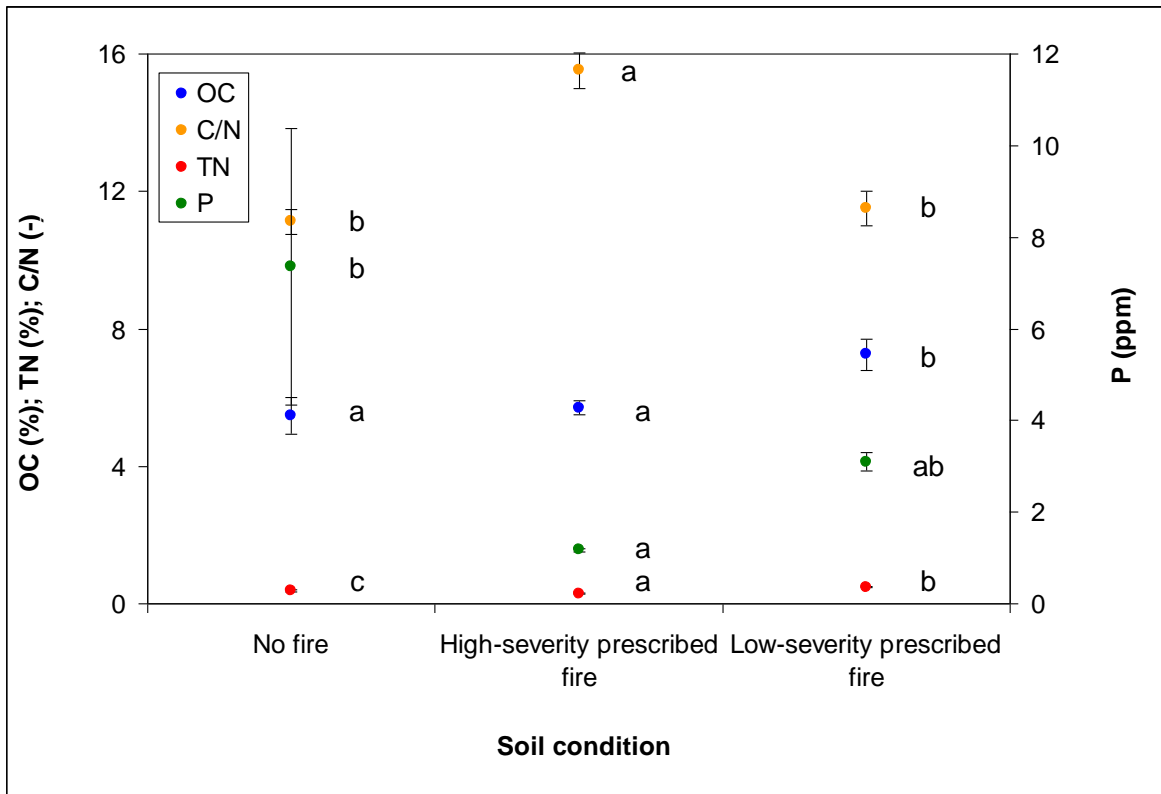
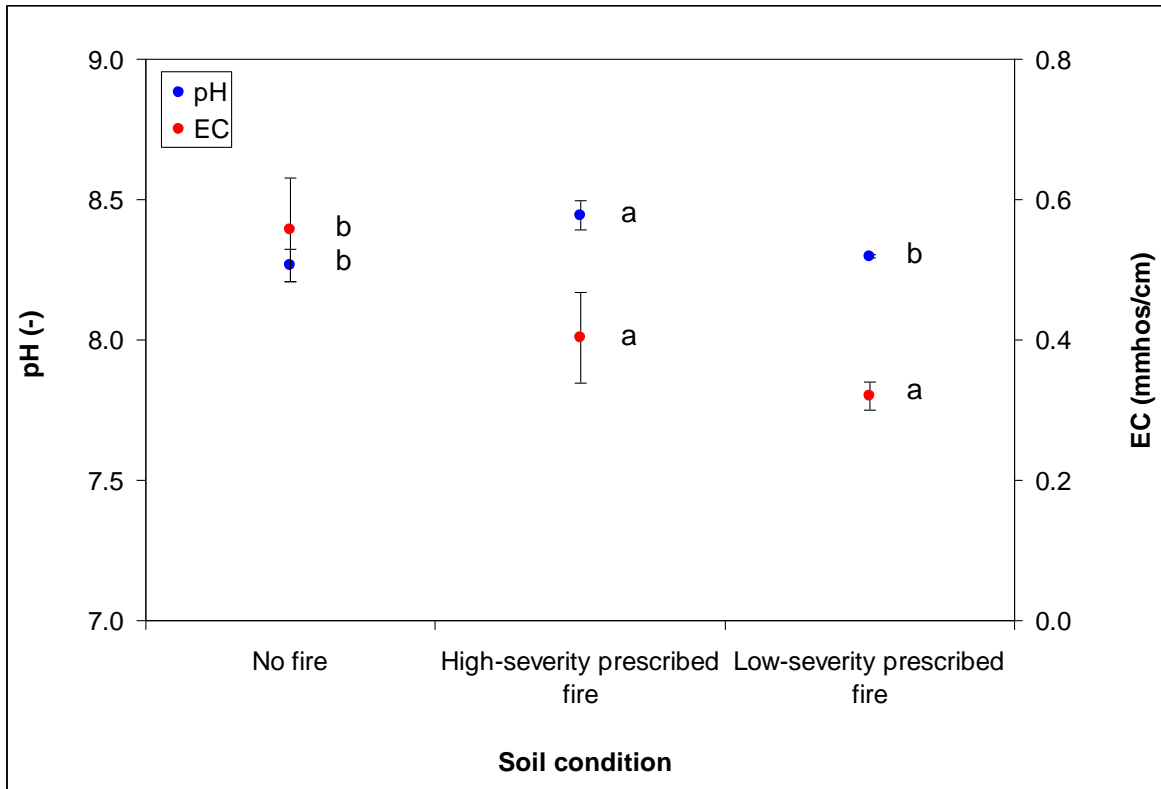
40 and one year and a half after) in La Moraleja forest (Castilla La Mancha, Spain).

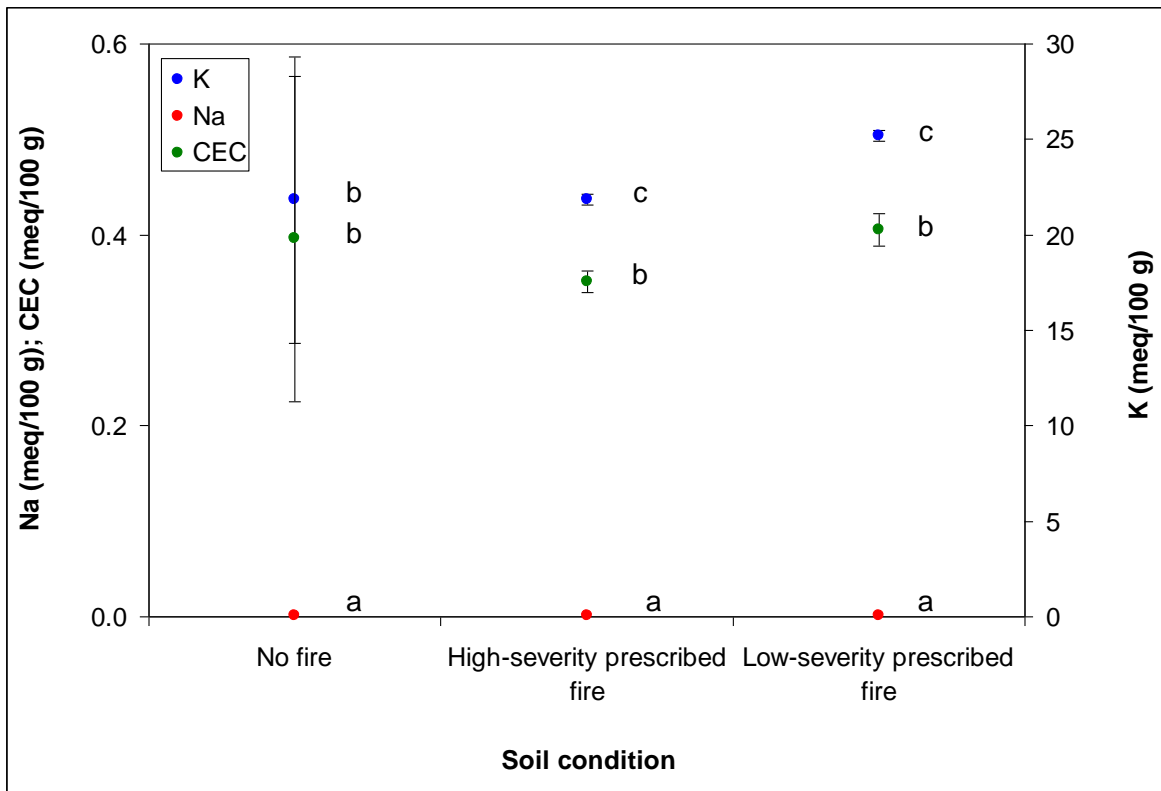
41 Different letters indicate significantly different cover among the soil conditions.

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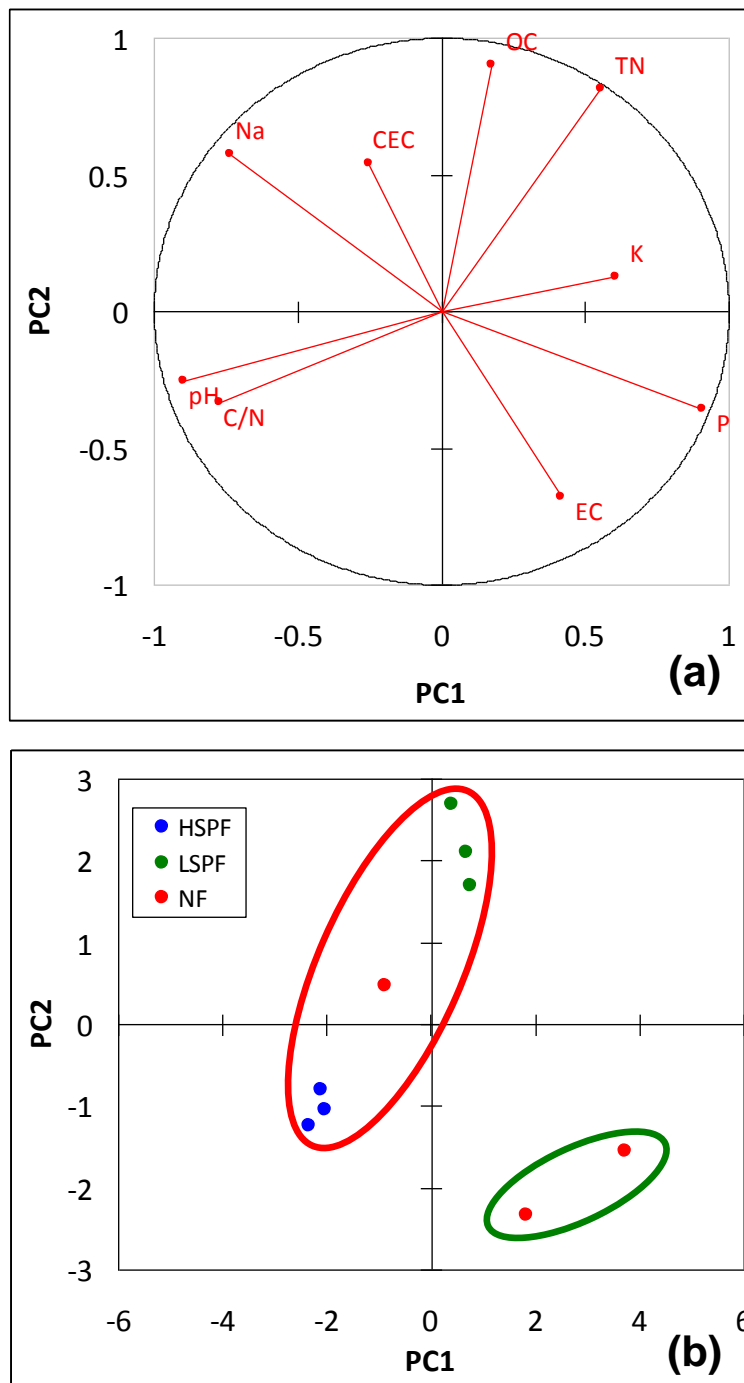
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 47 Figure 5 – Main physico-chemical properties of soils under three conditions (no fire,
 48 high-severity prescribed fire, and low-severity prescribed fire) immediately after
 49 burning (16 October 2019) in La Moraleja forest (Castilla La Mancha,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

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64 Figure 6 – Loadings of the original variables (a, physico-chemical properties of soil),
 65 and scores with relevant clusters (b) on the first two Principal Components (PC1 and
 66 PC2) provided by the Principal Component Analysis coupled by Analytical Hierarchical
 67 Cluster Analysis applied to soil samples under three soil conditions (no fire, NF; high-
 68 severity prescribed fire, HSF; low-severity prescribed fire, LSF) in the study area (La
 69 Moraleja forest, Castilla La Mancha, Spain). Notes: EC = electrical conductivity; OC =
 70 organic carbon; TN = total nitrogen; C/N = carbon to nitrogen ratio; P = phosphorous;
 71 K = potassium; Na = sodium; CEC = cation exchange capacity.

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) | |
|-------------------------------|---------------------|------------|--------------------------------|------------|------------------------------|------------|
| | <i>Max</i> | <i>Min</i> | <i>Max</i> | <i>Min</i> | <i>Max</i> | <i>Min</i> |
| 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 |

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

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Comparison of short-term effects of prescribed fires with different severity on rainsplash erosion and physico-chemical properties of soils in Mediterranean forests

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