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Effects of wildfire and post-fire salvage logging on rainsplash erosion in a semi-arid pine forest of Central Eastern Spain

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Effects of wildfire and post-fire salvage logging on rainsplash erosion in a semi-arid pine forest of Central Eastern Spain / De Pagter, Tijs; Lucas-Borja, Manuel Esteban; Navidi, Mehdi; Carra, Bruno Gianmarco; Baartman, Jantiene; Zema, Demetrio Antonio. - In: JOURNAL OF ENVIRONMENTAL MANAGEMENT. - ISSN 1095-8630. - 329:117059(2023), pp. 1-9. [10.1016/j.jenvman.2022.117059]

*Availability:*

This version is available at: <https://hdl.handle.net/20.500.12318/141559> since: 2024-11-22T10:35:06Z

*Published*

DOI: <http://doi.org/10.1016/j.jenvman.2022.117059>

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3 **de Pagter, T., Lucas-Borja, M.E., Navidi, M., Carra, B.G., Baartman, J., Zema, D.A. 2023.**  
4 ***Effects of wildfire and post-fire salvage logging on rainsplash erosion in a semi-arid pine***  
5 ***forest of Central Eastern Spain. Journal of Environmental Management (Elsevier), 329,***  
6 ***117059,***

7  
8 *which has been published in final doi*

9  
10 10.1016/j.jenvman.2022.117059

11  
12 (<https://www.sciencedirect.com/science/article/pii/S0301479722026329>)

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16 **Effects of wildfire and post-fire salvage logging on rainsplash erosion in a semi-arid pine**  
17 **forest of Central Eastern Spain**

18  
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21  
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31  
32 **Abstract**

33  
34 Rainsplash erosion on forested hillslopes can be increased by both wildfires and post-fire salvage  
35 logging, especially under semi-arid Mediterranean conditions. However, few studies have  
36 compared rainsplash erosion among forest sites impacted by logging to other forest areas. To fill  
37 this gap, this study has evaluated surface runoff and soil erosion in a burnt and logged (manually  
38 or mechanically) pine forest of Central-Eastern Spain under simulated rainfall and compared it to  
39 unlogged and unburnt plots. Compared to the unburnt plots, surface runoff significantly  
40 increased (over 150%) in logged areas, with a peak of 220% on the areas directly subjected to  
41 logging machinery. Peak runoff was substantially increased by fire (+130%) and less by logging  
42 (+8. Soil loss due to rainsplash erosion was about 235% (manual logging) to 750% (mechanical  
43 logging) higher compared to the unburnt plots. Wildfire exerted a much higher soil disturbance  
44 compared to salvage logging, with a soil hydrological response that can be up to an order of  
45 magnitude higher. The increased runoff and erosion rates in response to wildfire and logging  
46 were ascribed to soil compaction, which increased on average 60% on logged plots as well as to  
47 the removal of vegetation cover (-80%), whereas soil roughness played a minor role. From these  
48 results, we suggest using lightweight machinery in burnt soils, to reduce surface runoff and

49 erosion. The possibility of building contour felled log debris using the burnt wood may also be  
50 considered, in order to retain the eroded sediments.

51  
52 **Keywords:** compaction; soil scarification; surface roughness; lightweight machinery; manual  
53 logging; mechanical logging.

## 54 55 **1. Introduction**

56  
57 Wildfires tend to increase surface runoff and soil erosion in forests, but these effects strongly  
58 depend on burn severity. High-severity fires almost totally remove the tree cover, understory  
59 vegetation and litter, leaving the soil bare, and substantially changing soil physico-chemical  
60 properties that drive the hydrological and erosive response to precipitation (Pereira et al., 2018;  
61 Shakesby, 2011; Zema, 2021). Some post-fire management operations, such as salvage logging,  
62 may further disturb soil after wildfire, thus increasing runoff and erosion.

63 In general, soil disturbances due to salvage logging on forest ecosystems have been poorly  
64 studied in Mediterranean countries (Moya et al., 2020; Thorn et al., 2018). Some studies report  
65 economic (linked to wood sale) and environmental (due to fire occurrence) benefits of logging  
66 (e.g., Lindenmayer et al., 2012; Lindenmayer and Noss, 2006). Other studies highlight negative  
67 impacts, such as the use of heavy machinery to extract the charred logs (Fernández and Vega,  
68 2016; Wittenberg et al., 2020), and the disturbance of the vegetation cover (Wagenbrenner et al.,  
69 2016; Wittenberg et al., 2020). Salvage logging compacts forest soils, increasing bulk density  
70 with consequent reduction in soil hydraulic conductivity (García-Orenes et al., 2017; Nazari et  
71 al., 2021). Moreover, tree removal through salvage logging reduces the canopy cover, which  
72 increases the net precipitation and enhances splash erosion on the forest soil (Fernández-Raga et  
73 al., 2017; Olsen et al., 2021). Salvage logging can also decrease the organic matter content of  
74 soil, resulting in decreased aggregate stability and therefore soil porosity (Abiven et al., 2009;  
75 García-Orenes et al., 2017).

76 Due to its impacts on soil and vegetation, salvage logging has the potential to exacerbate post-  
77 wildfire soil erosion over an area many times the extent of the original disturbance (Beschta et  
78 al., 2004; Olsen, 2016; Robichaud et al., 2020a). Some authors report that soil compaction  
79 increases runoff and erosion up to two orders of magnitude (e.g., Lucas-Borja et al., 2019;  
80 Malvar et al., 2017; Olsen, 2016; Robichaud et al., 2020a; Wagenbrenner et al., 2015), whereas  
81 other studies report a decrease in soil erosion (e.g., Fernández et al., 2021; James and Krumland,  
82 2018). These contrasting results demonstrate how the literature on the hydrological effects of

83 post-fire salvage logging is not exhaustive (Prats et al., 2021). Therefore, more research is  
84 needed in specific environments to better understand the effects of this management operation on  
85 burnt forest soils, especially in the semi-arid Mediterranean forests that are more exposed to  
86 erosion due to their specific soil and weather characteristics.

87 Rainsplash erosion is considered an essential process driving the overall soil loss from burned or  
88 disturbed forest hillslopes, since, as being the first stage of erosion, it detaches a large share of  
89 soil particles that can be entrained by overland flow and transported downstream. Much attention  
90 has been paid to rainsplash erosion in forests affected by wildfires (e.g., Fernández-Raga et al.,  
91 2021; Lucas-Borja et al., 2022; Zavala et al., 2009). In contrast, few studies have evaluated the  
92 differences in rainsplash erosion between logged, and undisturbed forest areas, where soil  
93 compaction and vegetation loss are lower. Although the network of forest roads, including skid  
94 tracks, haul roads and landings, is a very small portion of the forest surface (Lucas-Borja and  
95 Zema, 2021; Olsen et al., 2021), large water and sediment flows come from these areas (Prats et  
96 al., 2021), feeding runoff and erosion at the catchment scale, even in unburnt forestland (Jordán-  
97 López et al., 2009; Sheridan et al., 2008).

98 To fill this research gap, this study has evaluated the effects of post-fire salvage logging on the  
99 hydrological and erosive response of a burnt pine forest of Central Eastern Spain under semi-arid  
100 Mediterranean conditions. More specifically, surface runoff and soil loss as well as some key  
101 soil properties were measured during rainfall simulations under four soil conditions: (i) burnt  
102 soils subjected to manual salvage logging; (ii) burnt soils, where logging was carried out using  
103 heavy machinery; (iii) unlogged burnt soils; (iv) soils not disturbed by fire or logging. This study  
104 aims to reply to the following research questions: (i) does post-fire salvage logging modify the  
105 hydrological and erosive response of burnt and unburnt forest soils? (ii) does the logging  
106 technique influence the impacts of this management operation? (iii) which soil disturbance,  
107 wildfire or salvage logging, has greater impacts on soil hydrology and erosion? (iv) which soil  
108 properties drive the soil response at burnt and logged sites? By answering to these research  
109 questions, this study can help forest managers to minimize the impacts of logging on burnt forest  
110 soils, ensuring the sustainability of forest ecosystems. Although only one rainfall simulation  
111 representative of a worst-case scenario of hydrological and erosive response for the study area  
112 was conducted, this work provides practical information to forest managers on how to limit  
113 runoff and erosion in burnt forests if logging operations are planned.

114

## 115 2. Materials and methods

116

### 117 2.1. Study area

118

119 The study area is a forest close to Liétor (province of Albacete, region of Castilla-La Mancha,  
120 Spain, 38°30'40.79" N; 1°56'35.02" W, Figure 1), at an elevation between 520 and 770 m above  
121 mean sea level. The semi-arid climate is of BSk type - "Cold semi-arid" - (Köppen classification,  
122 Kotték et al., 2006). The mean annual temperature and precipitation over the last 20 years were  
123 16.6 °C and 321 mm, respectively, according to data of the Spanish Meteorological Agency.

124 The study area consists of forestland with pine and other minor species, e.g., *Pistacia lentiscus*  
125 L. and *Juniperus oxycedrus* (60%), as well as shrubs and pasture (40%) (Spanish Institute of  
126 Statistics, 2021). The dominant overstory vegetation in the forestland consists of Aleppo pine  
127 (*Pinus halepensis* Mill.) with a shrub layer of kermes oak (*Quercus cocciferae*) (Peinado et al.,  
128 2008). Before the wildfire, the stand density ranged from 500 to 650 trees/ha, the tree height  
129 from 7 to 14 m and the tree diameter from 25 to 35 cm. The tree canopy cover was between 60  
130 and 70%. The understory vegetation included *Rosmarinus officinalis* L., *Brachypodium retusum*  
131 (Pers.) Beauv., *Cistus clusii* Dunal, *Lavandula latifolia* Medik., *Thymus vulgaris* L., *Helichrysum*  
132 *stoechas* L., *Stipa tenacissima* L., *Quercus coccifera* L. and *Plantago albicans* L. (Table 1). The  
133 economic value of the understory species decreased in the mid of the 20<sup>th</sup> century, and this led to  
134 agricultural abandonment and reforestation by Aleppo pines of natural origin. Therefore, a  
135 mixture of natural pine (not affected by wildfire in the last 100 years) and reforested stands of  
136 Aleppo pine, of about 60-70 years old, were present in the study area.

137 In July 2021, a wildfire burned a large part of the forestland. The wildfire resulted in soil burn  
138 severities from low to high, according to the soil burn severity classification proposed by Vega et  
139 al. (2013) (Figure 1), which is based on indicators, e.g., vegetation burning level, charring,  
140 ground colour), as described by Parson et al. (2010).

141 One week after the wildfire, a study site subjected to crown fire at high severity led to 100% tree  
142 mortality (Figure 1). This site had a north-west aspect and a mean slope angle of 15 to 25%.  
143 Soils were classified as Calcic Aridisols (Nachtergaele, 2001) with a sandy loam texture (on  
144 average, 46% of sand, 32% of silt, and 21% of clay).

145 In March 2022, nine months after the wildfire, part of the study site was subjected to manual  
146 salvage logging carried out by a three-person felling crew, i.e., chainsaw operator, helper, and  
147 guide, as described in the work of Lucas-Borja et al. (2020), whereas the other part was  
148 subjected to mechanical logging carried out with heavy machinery, an operation that lasted for

149 five days. In the latter case, a skidder (weight equal to 10800 kg, ground pressure 40-50 kPa) and  
150 autoloader (weight equal to 17700 kg, ground pressure 52-60 kPa) were used.

151

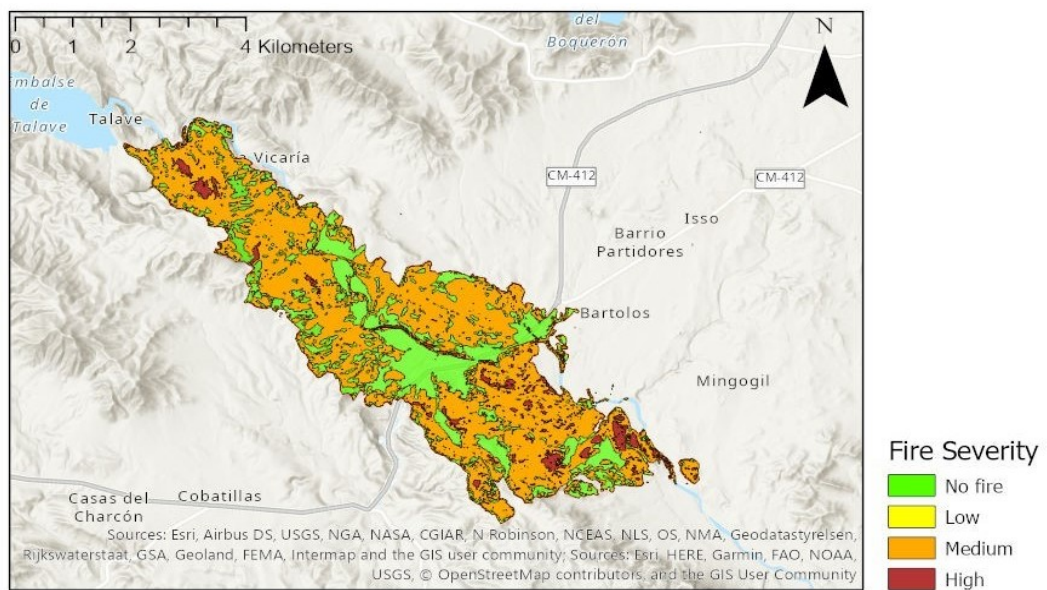


152

153

154

(a)



155

156

(b)

157 Figure 1 – Geographical location (a) and fire severity map (b) of the study area (Liétor, Castilla  
158 La Mancha, Spain).

159

160

161 Table 1 – Main topographic and forest characteristics of the study site (Liétor, Castilla La  
 162 Mancha, Spain).

163

Characteristics	Value or range
Elevation (m)	520-770
Slope (%)	15-20
Aspect	W-SW and N
Tree density (ha <sup>-1</sup> )	500-650
Tree height (m)	7-14
Tree diameter (cm)	25-35
Tree canopy cover (%)	60-70
Tree species composition	<i>Pinus halepensis</i> Mill.
Shrub/herb species	<i>Rosmarinus officinalis</i> L., <i>Brachypodium retusum</i> (Pers.) Beauv., <i>Cistus clusii</i> Dunal, <i>Lavandula latifolia</i> Medik., <i>Thymus vulgaris</i> L., <i>Helichrysum stoechas</i> (L.) Moench, <i>Macrochloa tenacissima</i> (L.) Kunth, <i>Quercus coccifera</i> L. and <i>Plantago albicans</i> L.

164

165

## 166 2.2. Experimental design

167

168 Twenty-two plots were installed within the study area, 4 in an unburnt site and 18 in burnt sites,  
 169 to carry out the experiments and collect soil samples. Of the 18 plots installed in the burnt area, 6  
 170 plots were installed on areas subjected to mechanical logging (hereafter referred to as “ML”), 6  
 171 plots were installed in manually-logged sites (“HL”, “hand-logging”) and another 6 plots in not  
 172 logged sites (NL). The HL plots, located outside of the machine tracks, were subjected to tree  
 173 falling and dragging as well as to the movement of the three workers in the timber yard. The four  
 174 plots that were installed in the unburnt area (NB) were not logged, to serve as control. Hence, the  
 175 experimental design consisted of four soil conditions: (i) burnt and mechanically-logged soils  
 176 (ML); (ii) burnt and manually-logged soils (HL); (iii) burnt but unlogged soils (NL); and (iv)  
 177 unburnt soils (NB).

### 178 2.3. *Rainfall simulations*

179

180 In each of the 22 experimental plots, artificial rainfall was produced using an Eijkelkamp®  
181 rainfall simulator (Hlavčová et al., 2019; Iserloh et al., 2013). One rainfall simulation per plot  
182 was carried out. Both rainfall simulations and surface runoff measurements were done according  
183 to the methodology proposed by Bombino et al. (2019) and Carrà et al. (2021). These previous  
184 authors have used the same portable simulator and a similar experimental setup to carry out  
185 rainfall simulations for analysing the hydrological response of soils.

186 Prior to the rainfall simulations, the pressure head of the sprinkler that controls the intensity of  
187 the rainfall, was adjusted, and the same was done for the tubing of the capillaries of the sprinkler,  
188 so that the drop diameter was 5.9 mm. The simulator was previously calibrated in the laboratory  
189 to ensure that the defined rainfall conditions were effectively achieved.

190 The simulator was carefully placed over the ground on a surface area of 0.3 m x 0.3 m, avoiding  
191 disturbance on soil and its cover. Each rainfall simulation lasted for 5 minutes, amounting to a  
192 total of 36 mm of rain. The intensity of the simulated rainfall was 432 mm/h, and the falling  
193 height was 40 cm. This extreme rainfall intensity has a return period of more than 100 years in  
194 the studied area. The rainfall depth that gives this intensity is close to the total annual  
195 precipitation in the area and was concentrated in one hour, to simulate an extremely erosive  
196 event, producing a noticeable soil particle detachment, as representative of a worst-case scenario  
197 for the study area.

198 On the simulation plot, a hole was dug to fit a small bucket used to collect runoff water and  
199 sediments. The frame of the rainfall simulator, which covers a net area receiving rainfall of  
200  $0.0625 \text{ m}^2$ , was then installed upslope of the hole, ensuring that there was no lateral outflow. A  
201 gutter was installed downslope of the frame, leading any runoff into the hole and the measuring  
202 bucket. Then, the support for the sprinkler was installed, making sure that this support was  
203 perpendicular with the hillslope. After the installation of the frame, the sprinkler was filled with  
204 2200 mL of water, and placed on top of the frame, so that the rainfall simulator was ready to be  
205 used.

206 During the rainfall simulation, the runoff volume was measured at every 30 s with a meterstick.  
207 The experiment ended, when no more runoff was coming through the gutter. Then, the runoff  
208 hydrograph was built, reporting the flow rate over time. This allowed the identification of the  
209 runoff rate, peak runoff and time to peak.

210 After the rainfall simulation, the mixture of water and sediments in the bucket was transported to  
211 the laboratory, and then oven dried at 104 °C for 24 h. Finally, the dried sediments were

212 weighed, and sediment concentration (in milligrams per litre) was determined to further calculate  
213 the soil loss (in tons per hectare).

214

#### 215 *2.4. Soil cover measurement*

216

217 The cover percentage of living vegetation, rock, dead wood, natural mulch (i.e., pine needles and  
218 litter), and bare soil in each plot were measured before the rainfall simulations, as described by  
219 Keizer et al. (2018). Following the methodology of the previous authors (Keizer et al., 2018), a  
220 metal frame with eight ropes that cross from one side of the frame to the other, divided into  
221 several squares, was placed over the plot and a picture was taken. Then, the soil cover was  
222 assigned as follows: each intersection between the ropes was considered one sampling point,  
223 resulting in a total of 16 sampling points. At each point, the type of soil cover was assigned.  
224 When the cover of all sample points was estimated, the number of sample points with a certain  
225 cover type was divided by the total number of sample points to determine the percentage of each  
226 cover type.

227

#### 228 *2.5. Soil analysis*

229

230 Prior to the rainfall simulations, soil samples were collected in three randomly-chosen points at  
231 each plot, to determine bulk density and surface roughness. These variables were selected based  
232 on other studies focusing on soil hydrology after wildfire and salvage logging (García-Orenes et  
233 al., 2017; Nazari et al., 2021; Wagenbrenner et al., 2015). Bulk density was determined using a  
234 soil ring with a volume of 98.1 cm<sup>3</sup>, a diameter of 5 cm, and a height of 5 cm. The sampled soil  
235 was oven-dried (at 104 °C for 24 h), and weighed. Soil roughness was determined using the  
236 chain method proposed by Jester and Klik (2005). According to this method, a chain with a  
237 length of one meter was placed on the soil surface, and the horizontal distance between the two  
238 end points of the chain was measured. This length was then divided by the original length of the  
239 chain, to calculate soil roughness. The smaller the chain length the higher the soil roughness.

240

#### 241 *2.6. Statistical analysis*

242

243 A one-way ANOVA was separately applied to the observations of surface runoff, sediment  
244 concentration and soil loss, as well as to soil properties (bulk density and surface roughness) and  
245 soil cover, to evaluate statistically significant differences among the four soil conditions.

246 Whenever significant differences were identified for a given variable, a Tukey's test (at  $p < 0.05$ )  
247 was used to identify which treatments were different. Prior to the ANOVAs, normality and  
248 homogeneity of variance were evaluated by Shapiro-Wilk's and Levene's tests, respectively.  
249 When the tests were not satisfied, the data were square root-transformed prior to re-running the  
250 ANOVAs.

251 Moreover, a Pearson's correlation analysis was carried out among the simulated variables (runoff  
252 volume and soil loss) and the soil properties measured in the present study.

253 All statistical analyses were carried out using the XLSTAT 2019 software (Addinsoft, Paris,  
254 France).

255

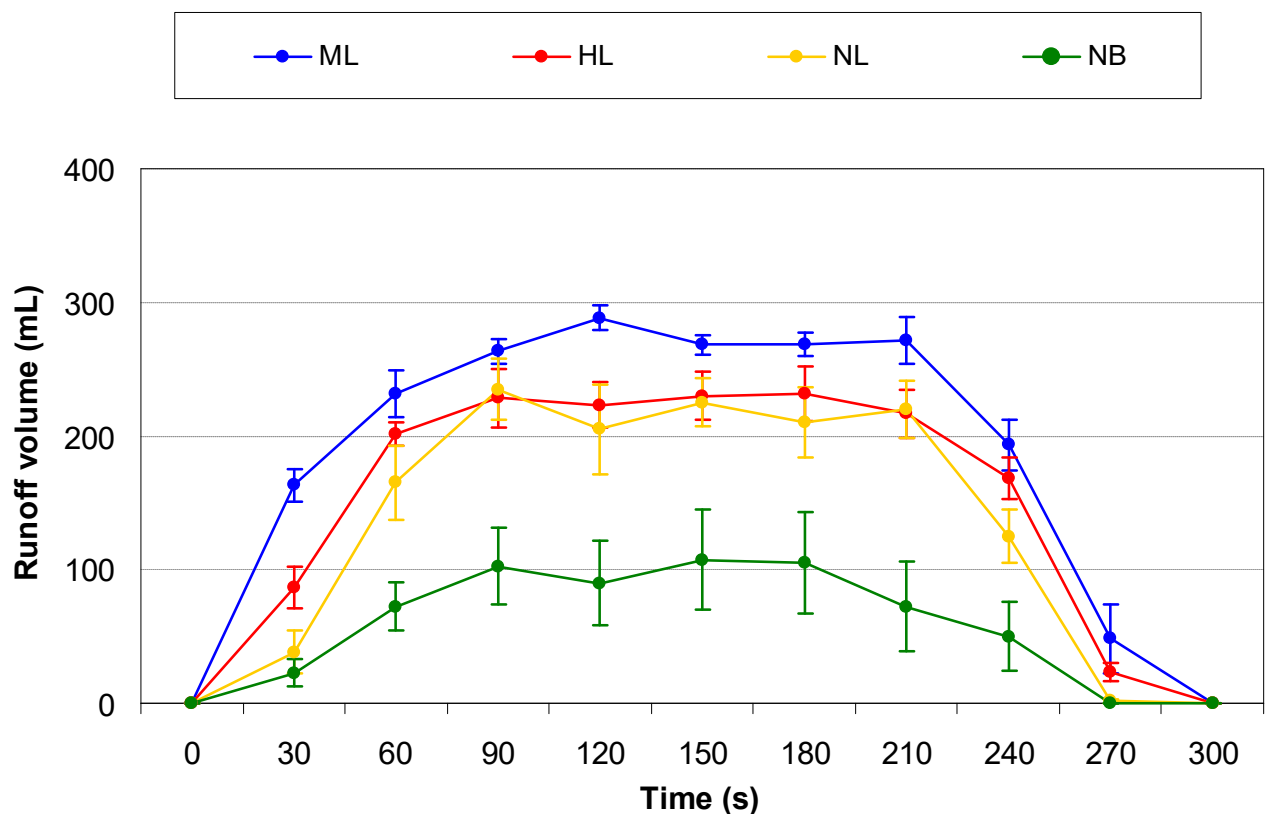
### 256 3. Results

257

258 The hydrographs recorded during the rainfall simulations had a similar shape among the four  
259 experimental conditions, but the peak values were different (Figure 2).

260

261



262

263 Figure 2 – Mean ( $\pm$  standard error) runoff volumes over time for each experimental condition.

264 ML - mechanically-logged soil; HL - manually-logged soil; NL - unlogged soil; NB - unburnt

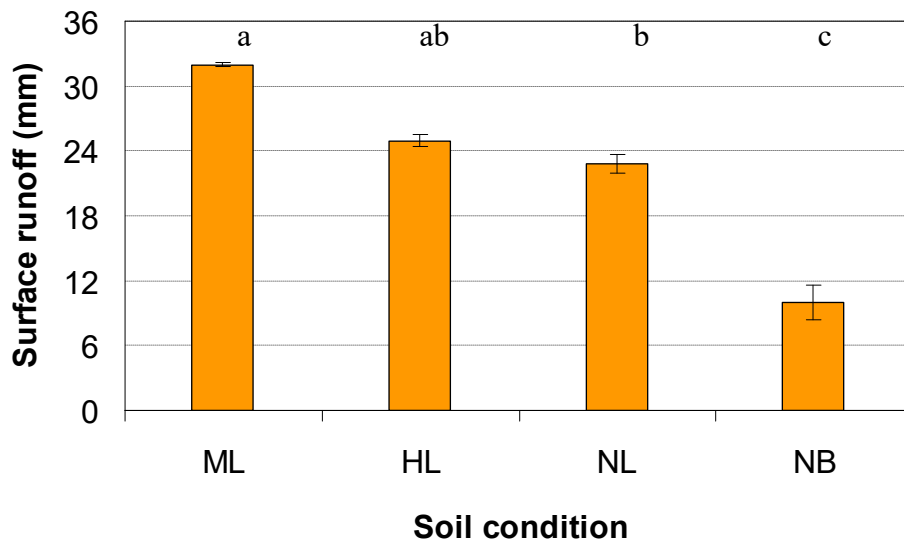
265 soil.

266

267

268 The runoff volume was higher in the burnt and logged plots (ML and HL) compared to the NL  
269 ( $22.8 \pm 0.83$  mm, significantly only for ML plots) and NB ( $10 \pm 1.58$  mm) plots. Among the  
270 logged plots, the runoff was higher in ML plots ( $31.9 \pm 0.19$  mm) and lower in the HL plots ( $25$   
271  $\pm 0.51$  mm), although not significantly (Figure 3a).

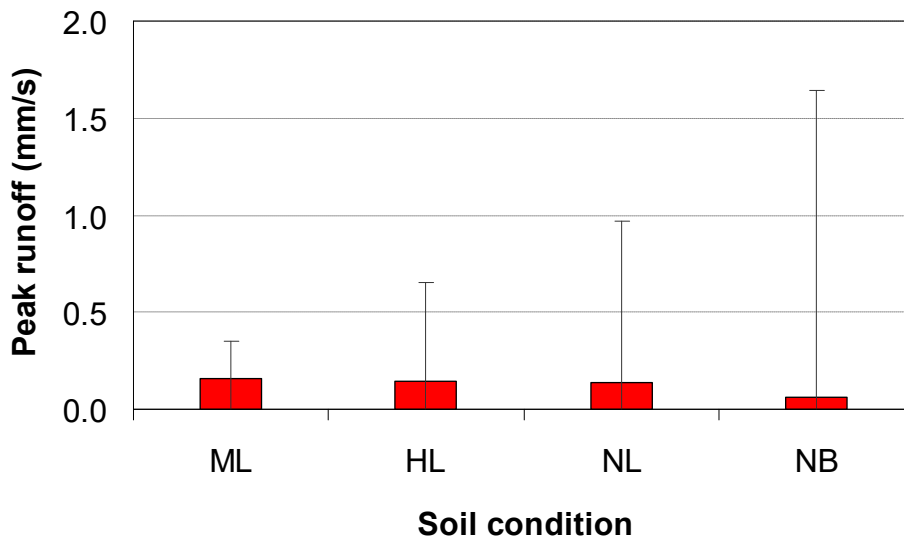
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273

274

(a)

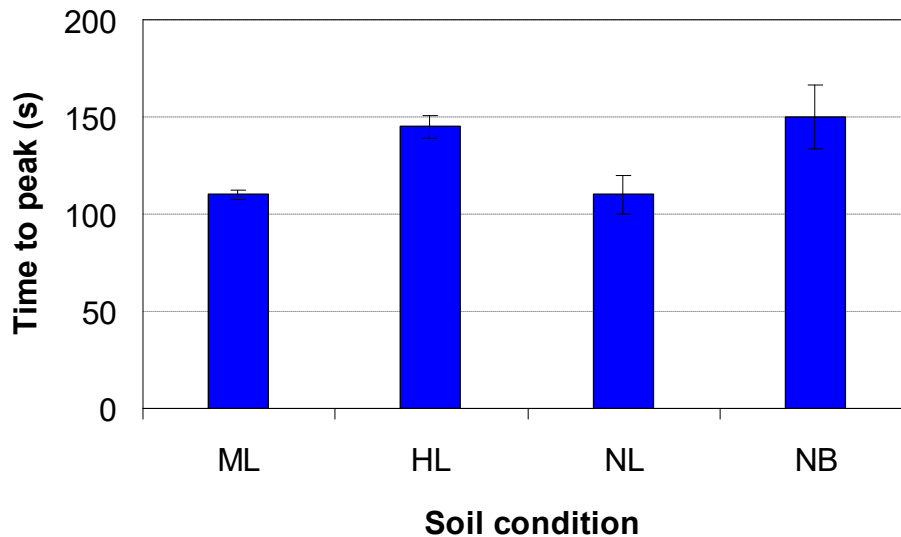


275

276

277

(b)



(c)

278  
 279  
 280 Figure 3 – Mean ( $\pm$  standard error) cumulative surface runoff (a), peak runoff (b), and time to  
 281 peak (c) for each experimental condition. ML - mechanically-logged soil; HL - manually-logged  
 282 soil; NL - unlogged soil; NB - unburnt soil. Different letters indicate significant differences at  $p$   
 283  $< 0.05$ .

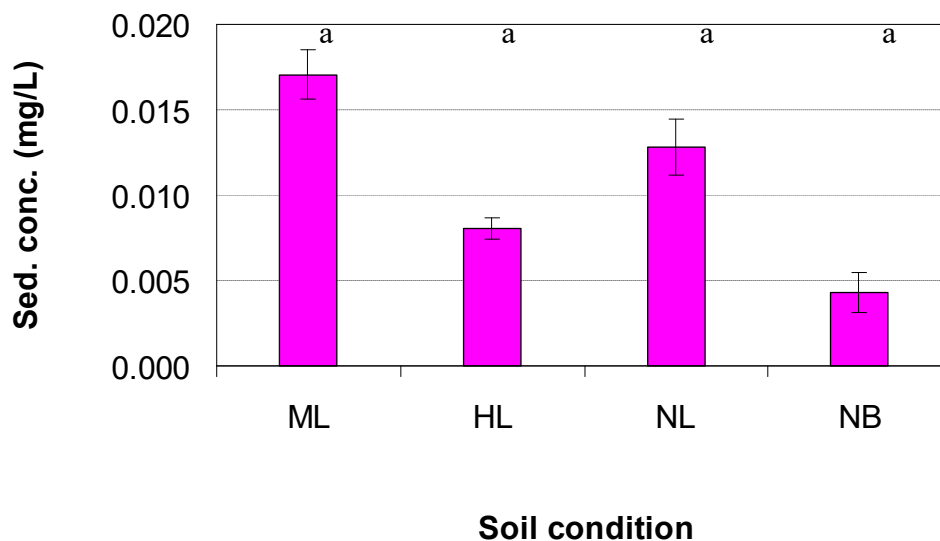
284  
 285  
 286 The highest runoff peak was observed in the ML plots ( $0.16 \pm 0.001$  mm/s). In the other logged  
 287 conditions, the runoff peak was lower ( $0.14 \pm 0.003$  mm/s for the HL plots, and  $0.14 \pm 0.005$   
 288 mm/s for the NL plots), with the NB plots recording the lowest value ( $0.06 \pm 0.009$  mm/s)  
 289 (Figure 3b). However, large variations were found among measurements, as indicated by the  
 290 large error bars, especially for the NB plots. The analysis of the hydrographs built for the four  
 291 soil conditions highlights that reaching the peak runoff in burnt areas (logged or not) takes longer  
 292 compared to the NB plots ( $150 \pm 12.2$  s). Among the logged plots, the quickest peak was reached  
 293 in the ML ( $110 \pm 2.58$  s) and NL ( $110 \pm 4.08$  s) plots, whereas the HL plots showed a similar  
 294 time to peak as the NB plots ( $145 \pm 8.01$  s) (Figure 3c).

295 Regarding erosion, the sediment concentrations measured in the runoff samples from the ML  
 296 plots ( $0.017 \pm 0.001$  mg/L) were higher than those of the HL ( $0.008 \pm 0.001$  mg/L) and NL  
 297 ( $0.013 \pm 0.002$  mg/L) plots. The lowest sediment concentrations were observed at the NB plots  
 298 ( $0.004 \pm 0.001$  mg/L). Still no significant differences in sediment concentrations were found  
 299 among the different soil conditions (Figure 4a).

300 The highest soil losses were measured at the ML plots ( $5.44 \pm 0.44$  tons/ha), while the lowest  
 301 erosion values were measured at the NB plots ( $0.64 \pm 0.26$  tons/ha), with the HL ( $2.13 \pm 0.19$

302 tons/ha) and NL ( $3.14 \pm 0.47$  tons/ha) plots showing intermediate soil losses. Significant  
303 differences were only found between the ML and NB plots (Figure 4b).

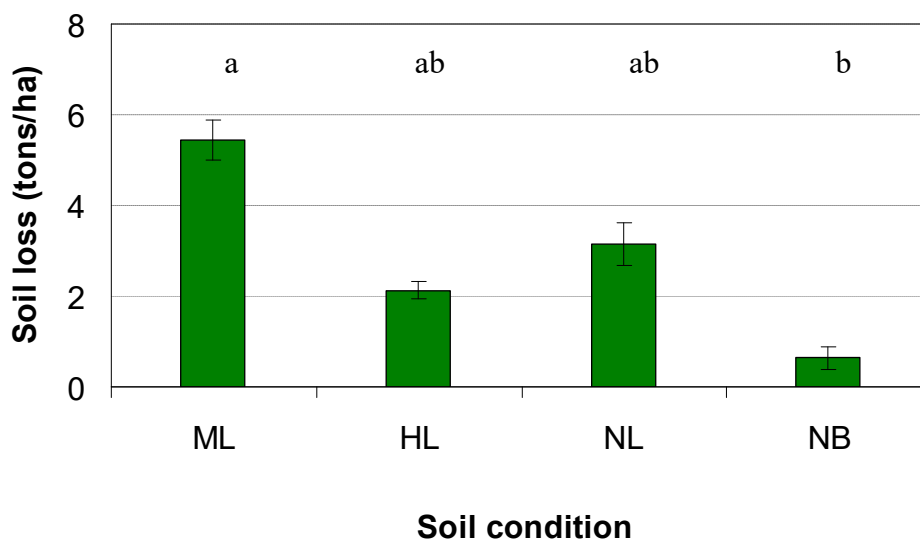
304



305

306

(a)



307

308

(b)

309 Figure 4 – Mean ( $\pm$  standard error) sediment concentrations (a) and soil loss (b) for each  
310 experimental condition. ML - mechanically-logged soil; HL - manually-logged soil; NL -  
311 unlogged soil; NB - unburnt soil. Different letters indicate significant differences at  $p < 0.05$ .

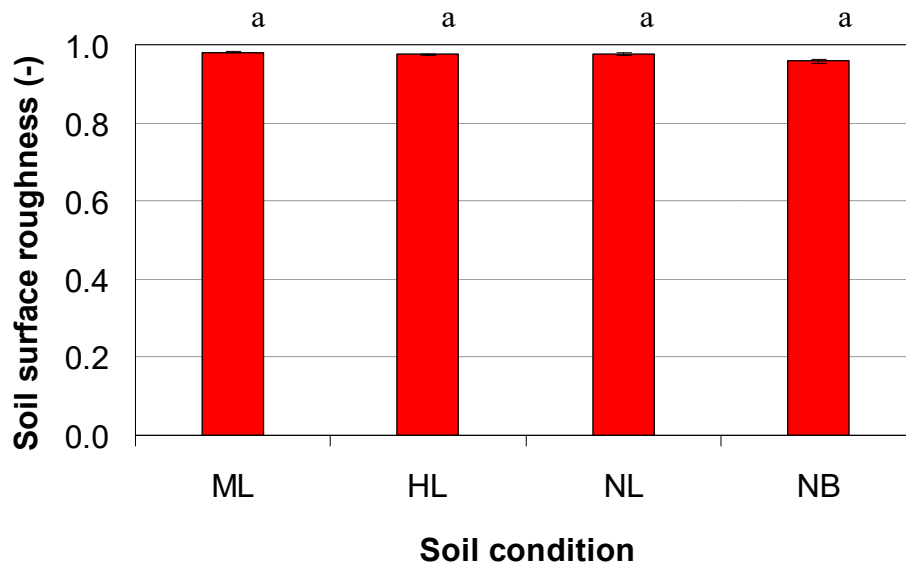
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313

314 Surface roughness was very similar among the four soil conditions, with a maximum value of  
315  $0.98 \pm 0.002$  in the ML soils and minimum of  $0.95 \pm 0.006$  in the NB soils (Figure 5a). In  
316 contrast, noticeable and significant differences were detected for bulk density. The logged and

317 burnt soils showed significantly higher bulk density ( $1.15 \pm 0.03 \text{ g/cm}^3$  for the ML and  $0.99 \pm$   
318  $0.03 \text{ g/cm}^3$  for the HL soils) than the unlogged burnt ( $0.86 \pm 0.01 \text{ g/cm}^3$ ) and unburnt ( $0.68 \pm$   
319  $0.05 \text{ g/cm}^3$ ) soils (Figure 5b).

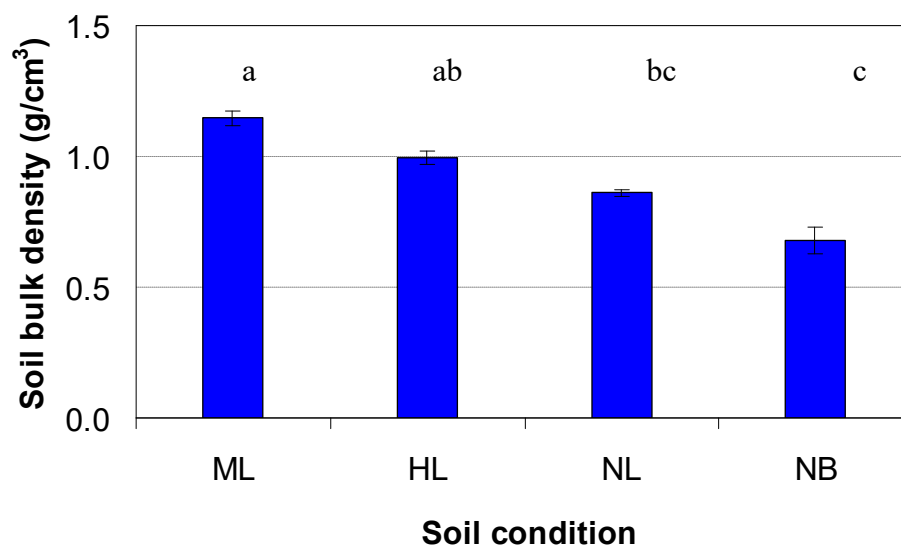
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321

322

(a)



323

324

(b)

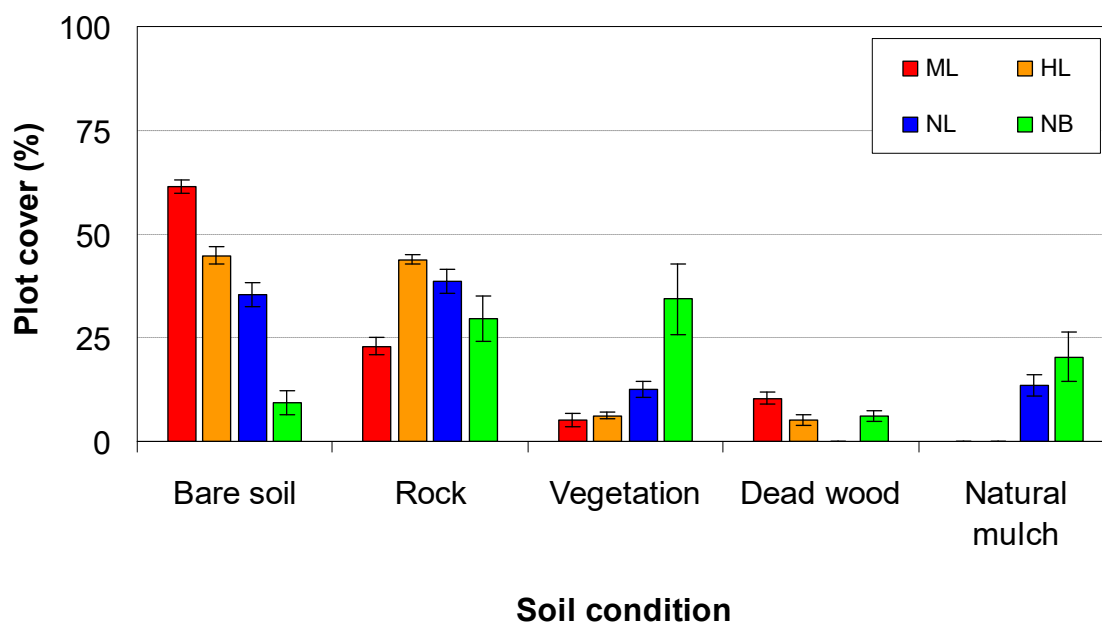
325 Figure 5 – Mean ( $\pm$  standard error) surface roughness (a) and bulk density (b) for each  
326 experimental condition. ML - mechanically-logged soil; HL - manually-logged soil; NL -  
327 unlogged soil; NB - unburnt soil. Different letters indicate significant differences at  $p < 0.05$ .

328

329

330 Regarding soil cover, the ML plots showed the highest percentage of bare soil ( $61.5 \pm 1.53\%$ )  
 331 and the lowest percentage of rocks ( $22.9 \pm 2.15\%$ ) and vegetation ( $5.2 \pm 1.67\%$ ), while the  
 332 opposite was found for the NB plots ( $-9.4 \pm 2.99\%$  of bare soil,  $29.7 \pm 5.47\%$  of rocks, and  $34.4$   
 333  $\pm 8.51\%$  of vegetation cover). However, no significant differences were found in vegetation  
 334 cover among the four soil conditions. Decreasing (ML > HL > NL > NB) and increasing (ML <  
 335 HL < NL < NB) gradients among plots were detected for bare soil and vegetation covers,  
 336 respectively. The presence of rocks was higher in the HL ( $43.8 \pm 1.14\%$ ) and NL ( $38.5 \pm 2.98\%$ )  
 337 plots compared to the other plots. No presence of dead wood was noticed in the NL plots,  
 338 whereas values of  $10.4 \pm 1.42\%$  (ML),  $5.2 \pm 1.22\%$  (HL) and  $6.3 \pm 1.28\%$  (NB) were found in  
 339 the other experimental plots. Finally, natural mulch was only observed in the NL ( $13.5 \pm 2.67\%$ )  
 340 and NB ( $20.3 \pm 5.9\%$ ) plots (Figure 6).

341



342

343 Figure 6 – Mean ( $\pm$  standard error) cover percentage of bare soil, rock, vegetation, dead wood  
 344 and natural mulch for each experimental condition. ML - mechanically-logged soil; HL -  
 345 manually-logged soil; NL - unlogged soil; NB - unburnt soil.

346

347

348 Significant correlations were found among the studied variables. Surface runoff was significantly  
 349 correlated with sediment concentration ( $r = 0.59$ ), bulk density ( $r = 0.75$ ), bare soil ( $r = 0.85$ ),  
 350 vegetation cover ( $r = -0.57$ ) and natural mulch cover ( $r = -0.57$ ). The correlations between soil  
 351 loss and the other variables were not significant, except for sediment concentration ( $r = 0.63$ )  
 352 (Table 2).

353

354

355 Table 2 – Correlation matrix among the different hydrological and erosive variables, as well as  
 356 soil properties measured under the different experimental conditions.

357

Soil properties	R	SC	SL	BD	SR	BS	RC	VC	DWC	NMC
<b>R</b>	<b>1</b>	<b>0.59</b>	0.42	<b>0.75</b>	0.37	<b>0.85</b>	-0.06	<b>-0.57</b>	0.20	<b>-0.57</b>
<b>SC</b>		<b>1</b>	<b>0.63</b>	0.49	-0.24	0.46	-0.28	-0.34	0.28	-0.08
<b>SL</b>			<b>1</b>	0.36	-0.34	0.35	-0.16	-0.23	0.10	-0.09
<b>BD</b>				<b>1</b>	0.30	<b>0.56</b>	0.11	<b>-0.68</b>	<b>0.53</b>	-0.35
<b>SR</b>					<b>1</b>	0.41	0.28	-0.48	-0.05	-0.29
<b>BS</b>						<b>1</b>	-0.27	<b>-0.59</b>	0.17	<b>-0.51</b>
<b>RC</b>							<b>1</b>	-0.35	-0.11	-0.22
<b>VC</b>								<b>1</b>	-0.25	0.12
<b>DWC</b>									<b>1</b>	-0.30
<b>NMC</b>										<b>1</b>

358 R - runoff; SC - sediment concentration; SL - soil loss; BD - bulk density; SR - surface roughness; BS - bare soil;  
 359 RC - rock cover; VC - vegetation cover; DWC - dead wood cover; NMC - natural mulch cover. Numbers in bold  
 360 indicate significant correlations at  $p < 0.05$ .

361

#### 362 4. Discussion

363

364 Wildfires severely alter the hydrological response of forest soils, especially in Mediterranean  
 365 semi-arid conditions, so additional disturbances, such as salvage logging, can further increase  
 366 surface runoff and erosion rates (Lucas-Borja et al., 2019; Robichaud et al., 2020).

367 Compared to the unburnt plots, surface runoff increased up to 220% in burnt areas that were  
 368 mechanically logged, whereas the burnt areas subjected to manual logging showed an increase of  
 369 about 150% in runoff. These findings are in accordance with other studies carried out in burnt  
 370 and logged areas. In two forest sites of North America, Wagenbrenner et al. (2016) found higher  
 371 runoff rates in plots logged using tracked and wheeled skidders/forwarders than in their  
 372 respective controls. These authors ascribed this increase in runoff to equipment traffic, which  
 373 lowers infiltration due to soil compaction (Ares et al., 2005; Horn et al., 2004). Also in  
 374 California, Prats et al. (2019a; 2019b) demonstrated that surface runoff in logged areas may be  
 375 20% to 50% higher compared to undisturbed soils, mainly due to the significantly lower

376 infiltration, but also due to leaching in the compacted plots because of a decrease in  
377 microporosity (Ares et al., 2005; Schäffer et al., 2007). In contrast, in pine forests of Central  
378 Eastern Spain, Lucas-Borja et al. (2019) reported that, in the period after salvage logging, runoff  
379 did not differ between logged and unlogged burnt plots.

380 In our study, the burnt and logged plots not only produced substantially higher runoff than in the  
381 burnt unlogged and unburnt plots, but also increased peak runoff (by 140% when averaging the  
382 ML and HL plots), and anticipated the peak of runoff. Peak flow and time to peak are important  
383 factors in soil hydrology, since they determine the flood occurrence at catchment scale (Neary et  
384 al., 1999; Shakesby, 2011; Cawson et al., 2012; Bombino et al., 2019). Higher runoff at the  
385 logged sites is a direct consequence of the reduced infiltration, as also demonstrated by other  
386 studies (e.g., Carrà et al., 2021; Lucas-Borja et al., 2022). The decrease in time to peak was  
387 likely a consequence of the combined effects of the lack of vegetation as well as reduction in  
388 water travelling times, which reduces water infiltration (Zhao et al., 2016). These changes in the  
389 hydrological response indicate that both wildfire and salvage logging can aggravate the flood  
390 risk in forest-dominated catchments.

391 The fact that surface runoff was significantly correlated with bulk density, bare soil and  
392 vegetation cover in the present study seems to corroborate the idea that a more compacted soil  
393 with lower vegetation cover reduces water infiltration and consequently increases overland flow  
394 velocities, thereby increasing peak flows and sheetwash (e.g., McGuire et al., 2013; Shakesby  
395 and Doerr, 2006; Wagenbrenner et al., 2015; Wagenbrenner and Robichaud, 2014). Soil bulk  
396 density was considerably higher in the burnt and logged plots, showing increases by 69%  
397 (mechanical logging) and 46% (manual logging) compared to the unburnt soils. This effect was  
398 due to the soil compaction, resulting from the weight of machinery and of the logs dragged over  
399 soils. The higher bulk density observed in the logged plots was expected, since many authors  
400 state that ground-based logging equipment increases soil compaction both in unburnt (e.g., Horn  
401 et al., 2004; Page-Dumroese et al., 2006; Wagenbrenner et al., 2015) and burnt forests  
402 (Wagenbrenner et al., 2015). For example, Prats et al. (2021) demonstrated that logging  
403 equipment significantly increased bulk density by 25%, resulting in soil compaction with  
404 consequent reduction in its porosity and infiltration capacity (Prats et al., 2019a; Sheridan et al.,  
405 2008; Sosa-Pérez and MacDonald, 2017).

406 Wildfire coupled to logging noticeably increased rainsplash erosion, resulting in higher sediment  
407 concentrations in the overland flow (from 90% for manual logging to 300% for mechanical  
408 logging). Although some important soil physico-chemical properties were not measured in the  
409 present study (e.g., soil organic matter and aggregate stability), the increase in sediment

410 concentrations in the burnt and logged soils may be due to the well-known effects of wildfire and  
411 logging, such as the decrease in aggregate stability (also linked to the depletion in soil organic  
412 matter), which enhances sediment detachment and therefore erosion (e.g., Francos et al., 2019;  
413 Lucas-Borja et al., 2022). Although the increase in sediment concentrations in the burnt and  
414 logged plots was not significantly different from the unburnt plots, this increment led to higher  
415 (235 to 750%) soil losses due to the higher surface runoff produced. Therefore, the burnt soils  
416 subjected to salvage logging are more erodible, this increased erodibility depending on the  
417 logging technique (mechanical or manual). The noticeably soil loss measured in the ML plots  
418 compared to the HL and NL plots may be also due to the lower percentage of rocks, which are  
419 non-erodible at every rainfall intensity (Bunte and Poesen, 1994; Cochrane et al., 2019). The  
420 areas with bare soil were higher in the burnt and unlogged plots (by about 280%), and even more  
421 (about +330%) in burnt and logged plots when compared to the unburnt plots. Bare areas are the  
422 most exposed to rainfall erosivity, and therefore record the highest erosion rates. The fire burned  
423 about 80% of the vegetation, and logging resulted also in a decrease (-55%) of the plant cover.  
424 The removal of vegetation due to burning makes the soil susceptible to raindrop impact and  
425 sediment entrainment by overland flow (Lucas-Borja et al., 2022; Shakesby and Doerr, 2006).  
426 However, the correlation between erosion and soil cover was not significant, which might be  
427 justified by the fact that, in our study, only rainsplash erosion was directly measured, and other  
428 erosion forms (such as rill and inter-rill erosion) may play a more significant influence on soil  
429 detachment. Other studies, on the other hand, have shown a strong, nonlinear relationship  
430 between the loss of surface cover and increase in the hydrological response of soils, and  
431 especially in surface erosion (e.g., Cerdà and Doerr, 2008; Larsen et al., 2009; Wagenbrenner  
432 and Robichaud, 2014). Likewise, surface cover was the dominant factor for rainsplash and  
433 sediment yield in the study by Prats et al. (2021).

434 The rainfall simulated in this study was representative of an extremely erosive event with return  
435 interval of many decades, which, although being infrequent (3-5 rainstorms per century with  
436 intensity that is comparable to this experiment), may trigger high erosion rates. In the ML plots,  
437 rainsplash erosion was noticeable, and may be of concern when soil losses from more than two  
438 to three very intense events cumulate throughout a year (Rostami et al., 2022). The erosion value  
439 was over the upper limit of 1.4 tons/ha-yr recommended as the tolerable loss for European soils  
440 (Verheijen et al., 2009), which is of concern because: (i) portable rainfall simulators tend to  
441 underestimate rainsplash erosion, since the kinetic energy of the simulated precipitation is lower  
442 compared to a natural rainfall at equal intensity; and (ii) the effects of particle detachment due to  
443 concentrated runoff are not evaluated by small devices (Hamed et al., 2002; Loch et al., 2001).

444 Rainsplash is prevalently measured in rainfall simulations, which do not consider soil  
445 detachment by overland flow and thus rill and inter-rill erosion. Therefore, soil losses occurring  
446 at burnt and logged areas on larger spatial scales may be higher than the values measured in this  
447 study. However, at larger spatial scales there are more opportunities for re-infiltration as well as  
448 sediment redeposition and storage on the hillslopes and within the catchment, which may lead to  
449 lower sediment yield compared to measurements from small rainfall simulators (e.g., de Vente  
450 and Poesen, 2005). Therefore, spatial upscaling of small-scale measurements based on simple  
451 extrapolation of data should be done carefully, and measurements at plot scale under natural  
452 rainfall are more reliable (e.g., Wu et al., 2021a, 2021b). Previous works on the effects of  
453 salvage logging in burnt forests (Wagenbrenner et al. 2016) carried out under natural rainfall  
454 regimes also reported sediment yields up to 1900% higher in logged plots than in the unlogged  
455 plots during the year of logging. Likewise, Wagenbrenner et al. (2015) referred that a sediment  
456 production from plots subjected to skidders were up to 100 times higher than the unlogged  
457 controls. In a study by Robichaud et al. (2020), conducted in a burnt forest of North-Western  
458 USA, the skid trails produced 17-fold more sediment than the unlogged control. In the work of  
459 Prats et al. (2019a), plots compacted by logging machinery doubled rainsplash erosion compared  
460 to uncompacted plots, due to the destruction of the soil aggregates resulting from the pressure of  
461 the logging equipment. However, in a subsequent experiment (Prats et al., 2021), the same  
462 authors found that rainsplash erosion was practically unaffected by salvage logging. Similarly,  
463 Lucas-Borja et al. (2019) stated that logging operations carried out three months after wildfire  
464 did not generate higher erosion rates, likely due to the lightweight machinery used in the  
465 operations.

466 In this work, it become obvious that the wildfire exerted a much higher disturbance (up to an  
467 order of magnitude) than salvage logging. In fact, when averaging the runoff and erosion values  
468 of all burnt plots (ML, HL and NL), substantially higher values, respectively of 170% and 460%,  
469 were found than in the unburnt plots. Salvage logging per se only increased surface runoff and  
470 erosion by 25% and 21% (values averaged in ML and HL plots), respectively. It is well known  
471 that wildfires noticeably influence hydrological processes, for example by reducing water  
472 infiltration or shifting runoff generation mechanisms (Inbar et al., 2014; Niemeyer et al., 2020;  
473 Wittenberg et al., 2020). The fire also changes many important soil properties, such as hydraulic  
474 conductivity, water repellency level, soil organic matter, minerals and macro-nutrients contents  
475 (Alcañiz et al., 2018; Shakesby and Doerr, 2006; Zavala et al., 2014).

476 Overall, this study highlights how, in Mediterranean pine forests burnt by wildfires, logging may  
477 aggravate the soil erosion risk, and consequently the off-site impacts of fire. Therefore, manual  
478 logging or lightweight machinery is recommended to limit the disturbance of forest ecosystems.

479

## 480 **5. Conclusions**

481

482 This study aimed at evaluating the changes in surface runoff and soil erosion among  
483 Mediterranean forest plots impacted by manual or mechanical salvage logging compared to  
484 unlogged and unburnt areas. Salvage logging significantly increased surface runoff and erosion  
485 compared to unlogged and unburnt plots with the strongest effects found when heavy machinery  
486 was used for logging. Wildfire impacted on soil disturbance much more than salvage logging,  
487 since the soil hydrological and erosive response was one order of magnitude higher.

488 The soil compaction and the reduction in vegetation cover were the main drivers of the increases  
489 in surface runoff and erosion after wildfire and salvage logging. Therefore, soil compaction and  
490 vegetation cover must be carefully controlled by forest managers when salvage logging is  
491 planned in severely-burnt forests. As a portable rainfall simulator was used in the present study,  
492 rainsplash erosion was likely underestimated, since particle detachment due to overland flow was  
493 not taken into account. Therefore, future studies should include measurements at larger scales  
494 and under natural rainfalls, to consider all erosion forms and to account for the spatial and  
495 temporal variability of erosion processes.

496 Overall, the results of this study highlight the need for limiting the use of heavy machinery in  
497 burnt soils, since these areas are prone to higher surface runoff and erosion compared to unburnt  
498 areas. Therefore, lightweight logging equipment and, when economically feasible, the manual  
499 logging are recommended to forest managers, since these practices exert a lower soil  
500 disturbance. The possibility of leaving the logs on the burnt soils (when its economic value is  
501 low) may be also a good management practice. If the logs are placed along contour lines they  
502 can act as a barrier helping to retain the sediments transported by the overland flow and thus  
503 reduce the sediment yield.

504 Moreover, other chemical (e.g., the dynamics of organic matter and nutrients) and biological  
505 (e.g., enzymatic activity and microbial communities composition) soil properties should also be  
506 monitored in future studies as they can strongly influence the hydrological and erosive response  
507 of burnt and logged soils. Awareness about the effects of wildfire and post-fire land  
508 management, such as salvage logging, could help forest managers towards quicker and more

509 effective restoration and/or rehabilitation actions in fire-affected Mediterranean forest areas,  
510 ensuring the maintenance of ecosystem services.

511

## 512 **Declaration of Competing Interest**

513

514 The authors declare no known competing financial interests.

515

## 516 **Acknowledgement**

517

518 Thanks are due for the financial support from EPyRIS (SOE2/P5/E0811) project, funded by the  
519 European Union through the SUDOE INTERREG Program and the National Natural Science  
520 Foundation of China (NSFC41930755, NSFC41722107).

521

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