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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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31

32 Abstract

33

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

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

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

54

1. Introduction 55

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

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

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

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

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

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

- 2. Materials and methods 115
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2.1. Study area 117

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

The study area consists of forestland with pine and other minor species, e.g., Pistacia lentiscus 124 L. and Juniperus oxycedrus (60%), as well as shrubs and pasture (40%) (Spanish Institute of 125

Statistics, 2021). The dominant overstory vegetation in the forestland consists of Aleppo pine 126 (Pinus halepensis Mill.) with a shrub layer of kermes oak (Querco cocciferae) (Peinado et al., 127 2008). Before the wildfire, the stand density ranged from 500 to 650 trees/ha, the tree height

from 7 to 14 m and the tree diameter from 25 to 35 cm. The tree canopy cover was between 60 129

and 70%. The understory vegetation included Rosmarinus officinalis L., Brachypodium retusum 130

(Pers.) Beauv., Cistus clusii Dunal, Lavandula latifolia Medik., Thymus vulgaris L., Helichrysum 131

stoechas L., Stipa tenacissima L., Quercus coccifera L. and Plantago albicans L. (Table 1). The 132 economic value of the understory species decreased in the mid of the 20th century, and this led to 133 agricultural abandonment and reforestation by Aleppo pines of natural origin. Therefore, a 134 mixture of natural pine (not affected by wildfire in the last 100 years) and reforested stands of 135 Aleppo pine, of about 60-70 years old, were present in the study area. 136

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

One week after the wildfire, a study site subjected to crown fire at high severity led to 100% tree 141

mortality (Figure 1). This site had a north-west aspect and a mean slope angle of 15 to 25%. 142

Soils were classified as Calcic Aridisols (Nachtergaele, 2001) with a sandy loam texture (on 143 average, 46% of sand, 32% of silt, and 21% of clay). 144

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

- five days. In the latter case, a skidder (weight equal to 10800 kg, ground pressure 40-50 kPa) and
 autoloader (weight equal to 17700 kg, ground pressure 52-60 kPa) were used.
- 151



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

- 158 La Mancha, Spain).
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- 160

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

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

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166 2.2. Experimental design

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

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

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

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

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

During the rainfall simulation, the runoff volume was measured at every 30 s with a meterstick.

The experiment ended, when no more runoff was coming through the gutter. Then, the runoff hydrograph was built, reporting the flow rate over time. This allowed the identification of the runoff rate, peak runoff and time to peak.

After the rainfall simulation, the mixture of water and sediments in the bucket was transported to the laboratory, and then oven dried at 104 °C for 24 h. Finally, the dried sediments were weighed, and sediment concentration (in milligrams per litre) was determined to further calculate
the soil loss (in tons per hectare).

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215 2.4. Soil cover measurement

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

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228 2.5. Soil analysis

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Prior to the rainfall simulations, soil samples were collected in three randomly-chosen points at 230 each plot, to determine bulk density and surface roughness. These variables were selected based 231 on other studies focusing on soil hydrology after wildfire and salvage logging (García-Orenes et 232 al., 2017; Nazari et al., 2021; Wagenbrenner et al., 2015). Bulk density was determined using a 233 soil ring with a volume of 98.1 cm³, a diameter of 5 cm, and a heigth of 5 cm. The sampled soil 234 was oven-dried (at 104 °C for 24 h), and weighed. Soil roughness was determined using the 235 chain method proposed by Jester and Klik (2005). According to this method, a chain with a 236 length of one meter was placed on the soil surface, and the horizontal distance between the two 237 end points of the chain was measured. This length was then divided by the original length of the 238 chain, to calculate soil roughness. The smaller the chain length the higher the soil roughness. 239

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241 2.6. Statistical analysis

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A one-way ANOVA was separately applied to the observations of surface runoff, sediment concentration and soil loss, as well as to soil properties (bulk density and surface roughness) and soil cover, to evaluate statistically significant differences among the four soil conditions. Whenever significant differences were identified for a given variable, a Tukey's test (at p < 0.05) was used to identify which treatments were different. Prior to the ANOVAs, normality and homogeneity of variance were evaluated by Shapiro-Wilk's and Levene's tests, respectively. When the tests were not satisfied, the data were square root-transformed prior to re-running the ANOVAs.

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

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

255

256 **3. Results**

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



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Figure 2 – Mean (± standard error) runoff volumes over time for each experimental condition.
ML - mechanically-logged soil; HL - manually-logged soil; NL - unlogged soil; NB - unburnt
soil.

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

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267







2.0 1.5 1.0 0.5 0.0 ML HL NL NB Soil condition

(b)

275 276



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

(c)

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285

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

Regarding erosion, the sediment concentrations measured in the runoff samples from the ML plots $(0.017 \pm 0.001 \text{ mg/L})$ were higher than those of the HL $(0.008 \pm 0.001 \text{ mg/L})$ and NL

 $(0.013 \pm 0.002 \text{ mg/L})$ plots. The lowest sediment concentrations were observed at the NB plots $(0.004 \pm 0.001 \text{ mg/L})$. Still no significant differences in sediment concentrations were found among the different soil conditions (Figure 4a).

The highest soil losses were measured at the ML plots (5.44 ± 0.44 tons/ha), while the lowest erosion values were measured at the NB plots (0.64 ± 0.26 tons/ha), with the HL (2.13 ± 0.19 tons/ha) and NL $(3.14 \pm 0.47 \text{ tons/ha})$ plots showing intermediate soil losses. Significant differences were only found between the ML and NB plots (Figure 4b).





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306



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

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

burnt soils showed significantly higher bulk density (1.15 \pm 0.03 g/cm³ for the ML and 0.99 \pm 317 0.03 g/cm³ for the HL soils) than the unlogged burnt (0.86 \pm 0.01 g/cm³) and unburnt (0.68 \pm 318 0.05 g/cm^3) soils (Figure 5b). 319





321 322



0.5

0.0

ML

324

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

HL

(b)

NL

Soil condition

NB

328

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





Soil condition

342

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

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

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

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

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

362 4. Discussion

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

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

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

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

The fact that surface runoff was significantly correlated with bulk density, bare soil and 391 vegetation cover in the present study seems to corroborate the idea that a more compacted soil 392 with lower vegetation cover reduces water infiltration and consequently increases overland flow 393 velocities, thereby increasing peak flows and sheetwash (e.g., McGuire et al., 2013; Shakesby 394 and Doerr, 2006; Wagenbrenner et al., 2015; Wagenbrenner and Robichaud, 2014). Soil bulk 395 density was considerably higher in the burnt and logged plots, showing increases by 69% 396 (mechanical logging) and 46% (manual logging) compared to the unburnt soils. This effect was 397 due to the soil compaction, resulting from the weight of machinery and of the logs dragged over 398 soils. The higher bulk density observed in the logged plots was expected, since many authors 399 state that ground-based logging equipment increases soil compaction both in unburnt (e.g., Horn 400 et al., 2004; Page-Dumroese et al., 2006; Wagenbrenner et al., 2015) and burnt forests 401 (Wagenbrenner et al., 2015). For example, Prats et al. (2021) demonstrated that logging 402 equipment significantly increased bulk density by 25%, resulting in soil compaction with 403 consequent reduction in its porosity and infiltration capacity (Prats et al., 2019a; Sheridan et al., 4042008; Sosa-Pérez and MacDonald, 2017). 405

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

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

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

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

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

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

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480 **5.** Conclusions

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

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

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

Moreover, other chemical (e.g., the dynamics of organic matter and nutrients) and biological (e.g., enzymatic activity and microbial communities composition) soil properties should also be monitored in future studies as they can strongly influence the hydrological and erosive response of burnt and logged soils. Awareness about the effects of wildfire and post-fire land 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	
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