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

Original

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 0301-4797. - 329:117059(2023), pp. 1-9. [10.1016/j.jenvman.2022.117059]

Published

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

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

10.1016/j.jenvman.2022.117059

(https://www.sciencedirect.com/science/article/pii/S0301479722026329)

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

Tijs de Pagter[1], Manuel Esteban Lucas-Borja[2], Mehdi Navidi[3], Bruno Gianmarco Carra[4], Jantiene Baartman[1], Demetrio Antonio Zema[4,*]

[1] Soil Physics and Land Management group, Wageningen University, PO Box 47, 6700 AA Wageningen, The Netherlands

[2] School of Advanced Agricultural and Forestry Engineering, Campus Universitario s/n, Castilla La Mancha University, E-02071 Albacete, Spain

[3] Faculty of Natural Resources, Urmia University, Iran.

[4] Department AGRARIA, "Mediterranea" University of Reggio Calabria, Località Feo di Vito, I-89122 Reggio Calabria, Italy

* Correspondence: dzema@unirc.it

Abstract

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

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

1. Introduction

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

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

Due to its impacts on soil and vegetation, salvage logging has the potential to exacerbate post-wildfire soil erosion over an area many times the extent of the original disturbance (Beschta et al., 2004; Olsen, 2016; Robichaud et al., 2020a). Some authors report that soil compaction increases runoff and erosion up to two orders of magnitude (e.g., Lucas-Borja et al., 2019; Malvar et al., 2017; Olsen, 2016; Robichaud et al., 2020a; Wagenbrenner et al., 2015), whereas other studies report a decrease in soil erosion (e.g., Fernández et al., 2021; James and Krumland, 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 disturbed forest hillslopes, since, as being the first stage of erosion, it detaches a large share of soil particles that can be entrained by overland flow and transported downstream. Much attention has been paid to rainsplash erosion in forests affected by wildfires (e.g., Fernández-Raga et al., 2021; Lucas-Borja et al., 2022; Zavala et al., 2009). In contrast, few studies have evaluated the differences in rainsplash erosion between logged, and undisturbed forest areas, where soil compaction and vegetation loss are lower. Although the network of forest roads, including skid tracks, haul roads and landings, is a very small portion of the forest surface (Lucas-Borja and Zema, 2021; Olsen et al., 2021), large water and sediment flows come from these areas (Prats et al., 2021), feeding runoff and erosion at the catchment scale, even in unburnt forestland (Jordán-López et al., 2009; Sheridan et al., 2008).

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

2. Materials and methods

2.1. Study area

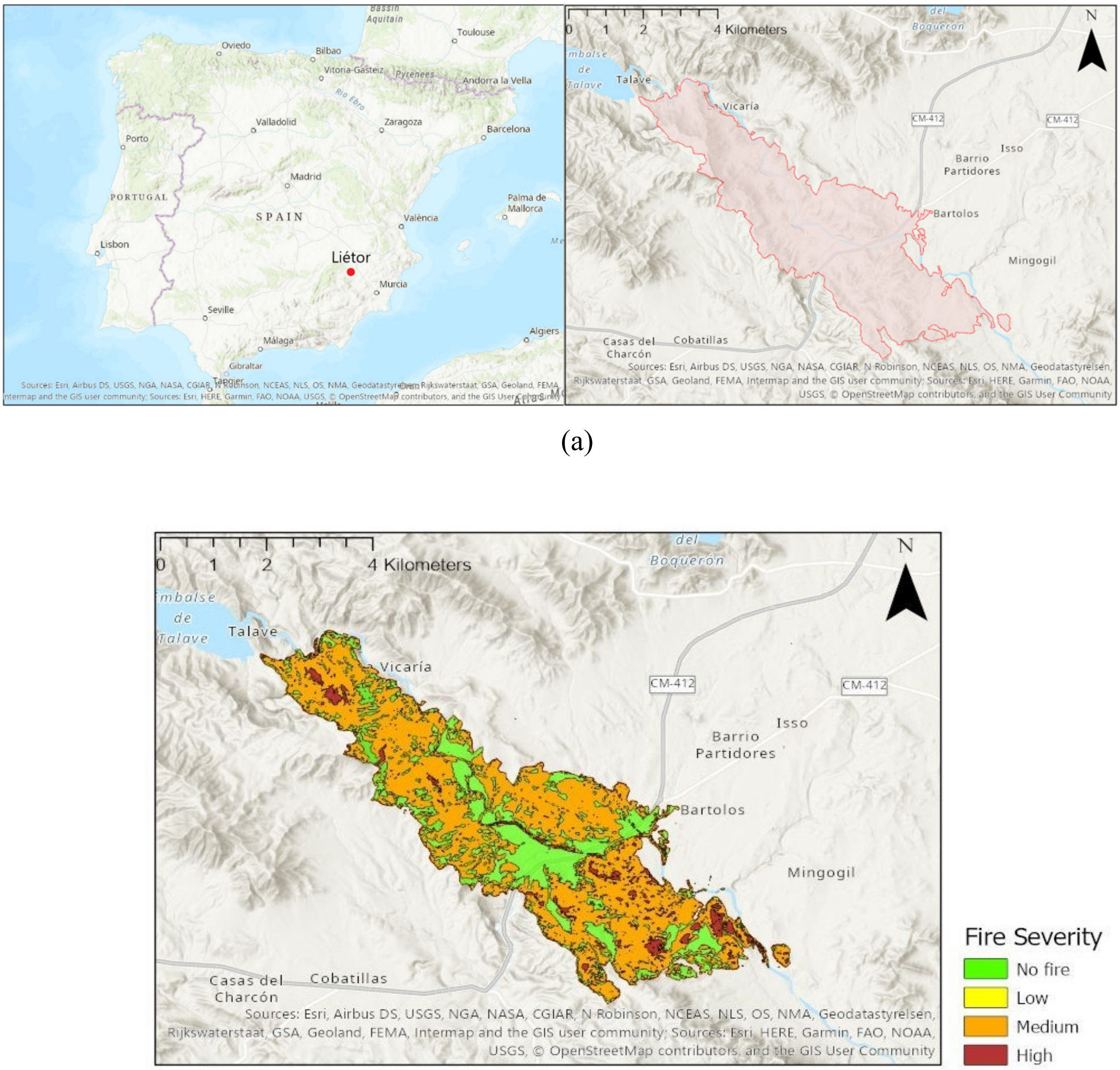
The study area is a forest close to Liétor (province of Albacete, region of Castilla-La Mancha, Spain, 38º30'40.79" N; 1º56'35.02" W, Figure 1), at an elevation between 520 and 770 m above mean sea level. The semi-arid climate is of BSk type - "Cold semi-arid" - (Köppen classification, Kottek et al., 2006). The mean annual temperature and precipitation over the last 20 years were 16.6 °C and 321 mm, respectively, according to data of the Spanish Meteorological Agency.

The study area consists of forestland with pine and other minor species, e.g., *Pistacia lentiscus* L. and *Juniperus oxycedrus* (60%), as well as shrubs and pasture (40%) (Spanish Institute of Statistics, 2021). The dominant overstory vegetation in the forestland consists of Aleppo pine (*Pinus halepensis* Mill.) with a shrub layer of kermes oak (*Querco cocciferae*) (Peinado et al., 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 and 70%. The understory vegetation included *Rosmarinus officinalis* L., *Brachypodium retusum* (Pers.) Beauv., *Cistus clusii* Dunal, *Lavandula latifolia* Medik., *Thymus vulgaris* L., *Helichrysum stoechas* L., *Stipa tenacissima* L., *Quercus coccifera* L. and *Plantago albicans* L. (Table 1). The economic value of the understory species decreased in the mid of the 20th century, and this led to agricultural abandonment and reforestation by Aleppo pines of natural origin. Therefore, a mixture of natural pine (not affected by wildfire in the last 100 years) and reforested stands of Aleppo pine, of about 60-70 years old, were present in the study area.

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

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

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



(a)

(b)

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

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

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 composition	*Pinus halepensis* Mill.
Shrub/herb species	*Rosmarinus officinalis* L., *Brachypodium retusum* (Pers.) Beauv., *Cistus clusii* Dunal, *Lavandula latifolia* Medik., *Thymus vulgaris* L., *Helichrysum stoechas* (L.) Moench, *Macrochloa tenacissima* (L.) Kunth, *Quercus coccifera* L. and *Plantago albicans* L.

2.2. Experimental design

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

2.3. Rainfall simulations

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

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

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).

2.4. Soil cover measurement

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

2.5. Soil analysis

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

2.6. Statistical analysis

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).

3. Results

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

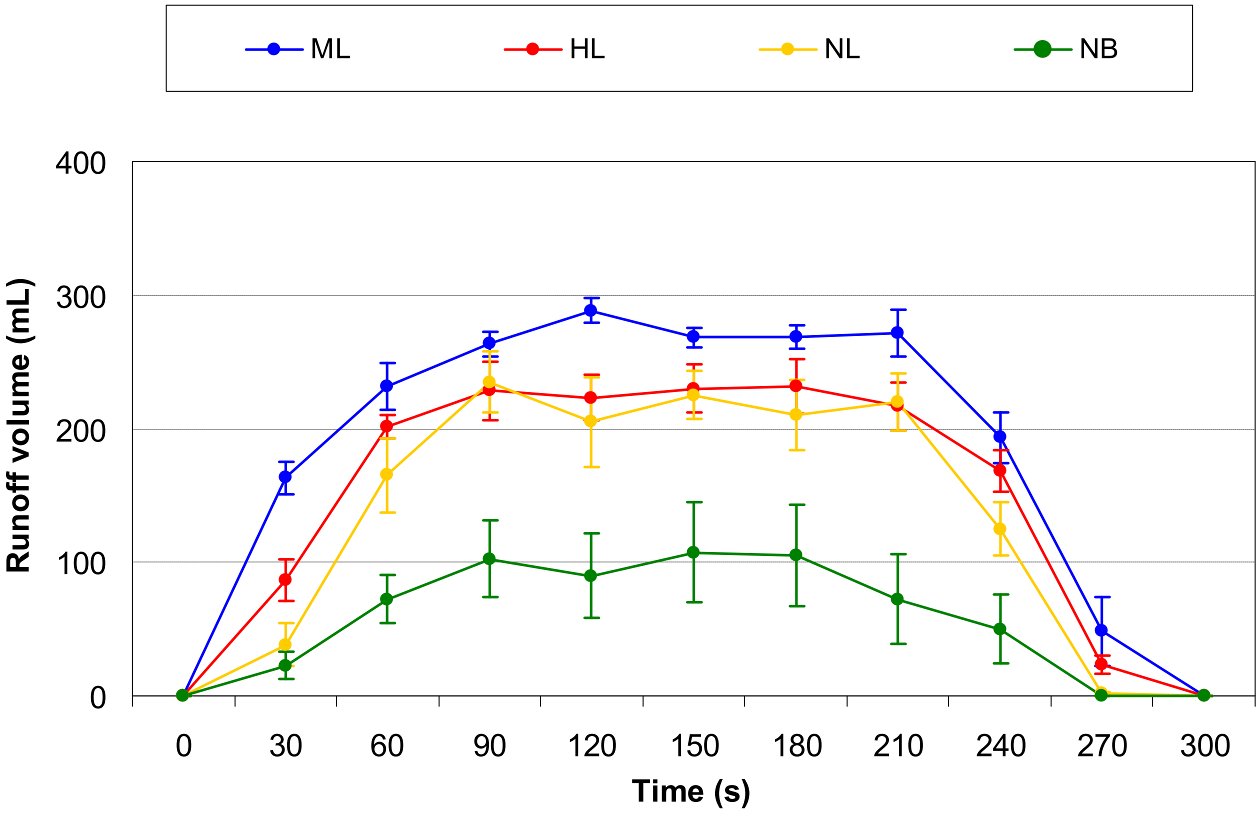
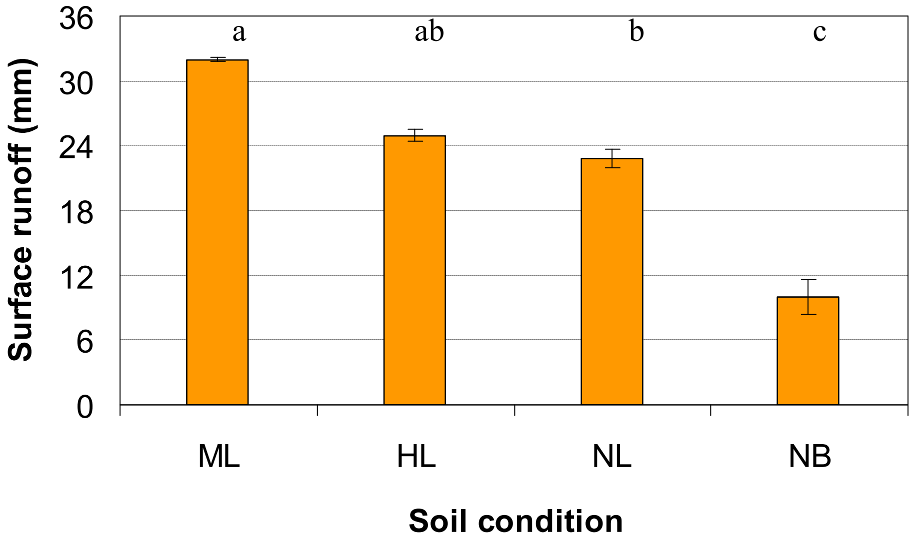
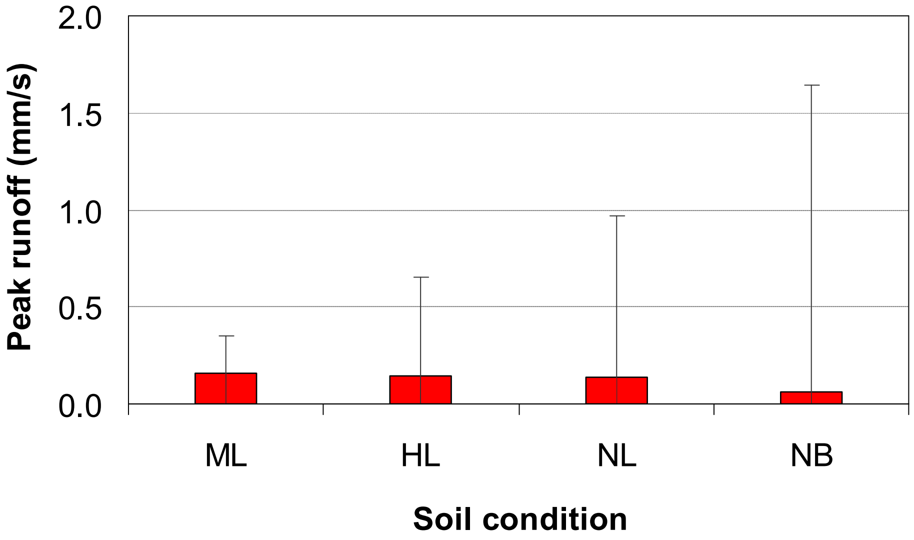


Figure 2 – Mean (± standard error) runoff volumes over time for each experimental condition. ML - mechanically-logged soil; HL - manually-logged soil; NL - unlogged soil; NB - unburnt soil.

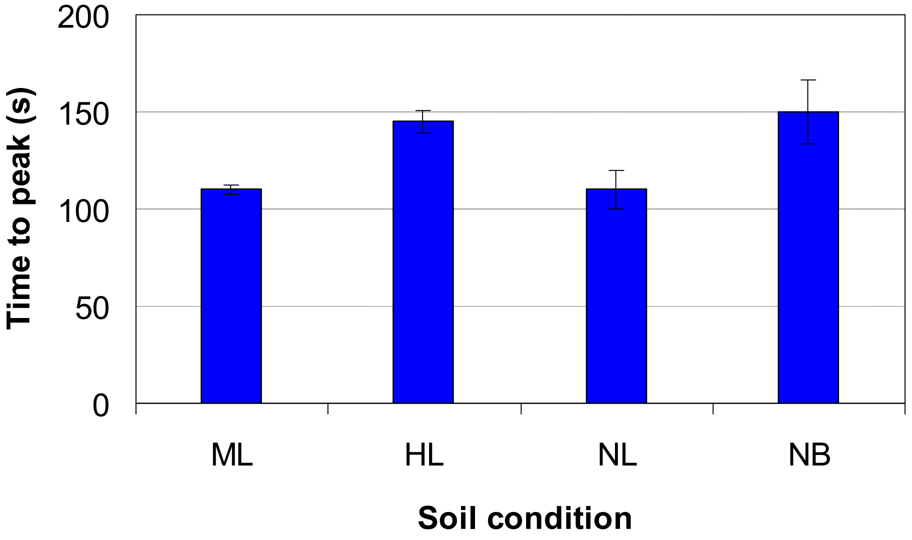
The runoff volume was higher in the burnt and logged plots (ML and HL) compared to the NL (22.8 ± 0.83 mm, significantly only for ML plots) and NB (10 ± 1.58 mm) plots. Among the logged plots, the runoff was higher in ML plots (31.9 ± 0.19 mm) and lower in the HL plots (25 ± 0.51 mm), although not significantly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



(a)



(b)



(c)

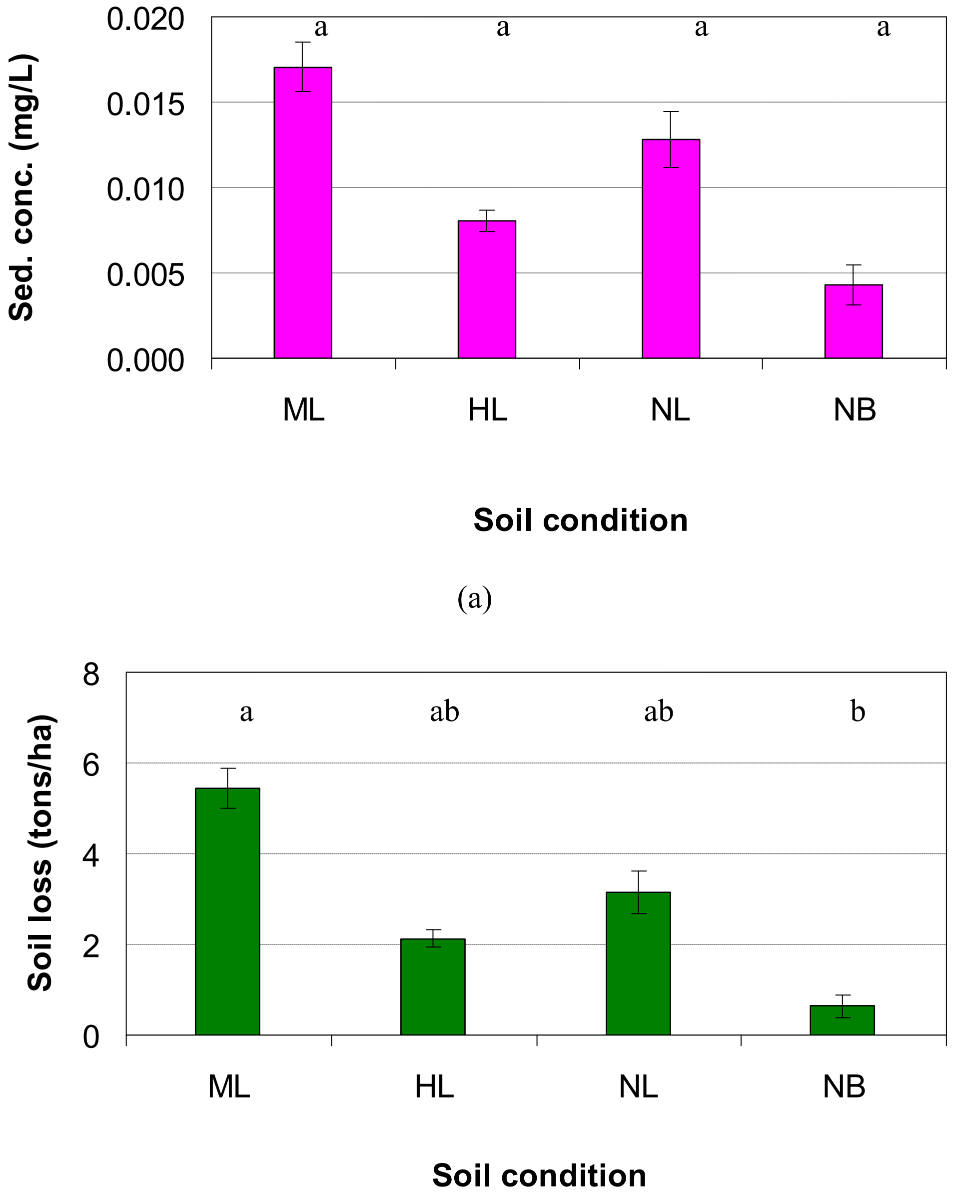
Figure 3 – Mean (± standard error) cumulative surface runoff (a), peak runoff (b), and time to peak (c) for each experimental condition. ML - mechanically-logged soil; HL - manually-logged soil; NL - unlogged soil; NB - unburnt soil. Different letters indicate significant differences at $p < 0.05$.

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

Regarding erosion, the sediment concentrations measured in the runoff samples from the ML plots (0.017 ± 0.001 mg/L) were higher than those of the HL (0.008 ± 0.001 mg/L) and NL (0.013 ± 0.002 mg/L) plots. The lowest sediment concentrations were observed at the NB plots (0.004 ± 0.001 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 ± 0.47 tons/ha) plots showing intermediate soil losses. Significant differences were only found between the ML and NB plots (Figure 4b).

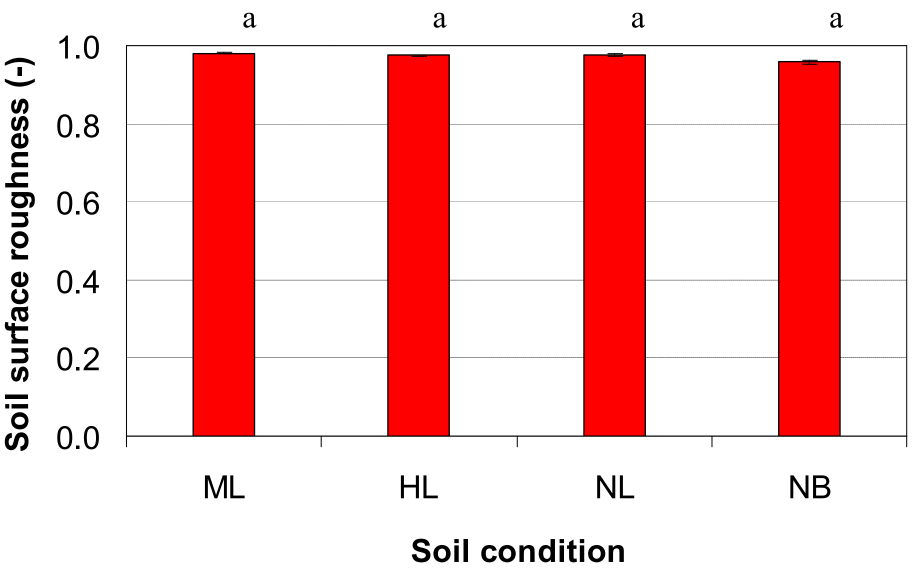


(a)

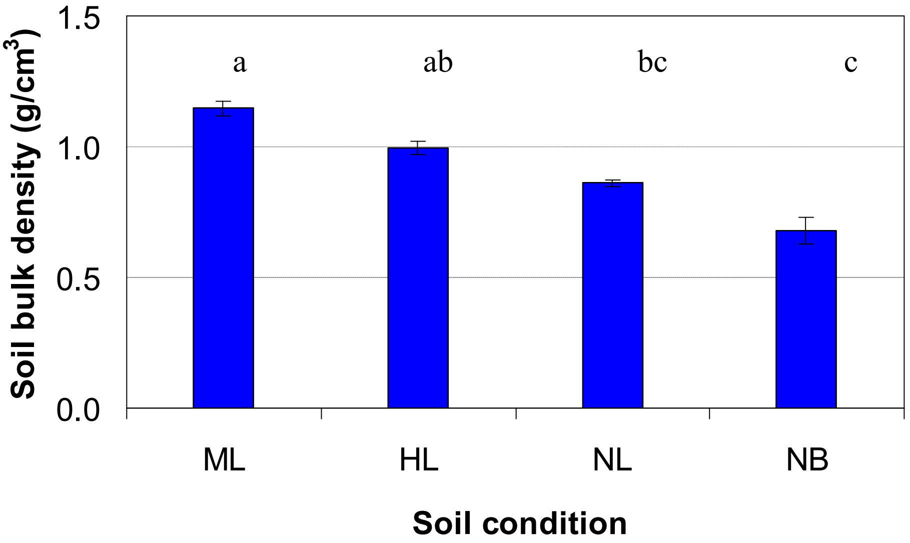
(b)

Figure 4 – Mean (± 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 $p < 0.05$.

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 ± 0.03 g/cm^3 for the ML and 0.99 ± 0.03 g/cm^3 for the HL soils) than the unlogged burnt (0.86 ± 0.01 g/cm^3) and unburnt (0.68 ± 0.05 g/cm^3) soils (Figure 5b).



(a)



(b)

Figure 5 – Mean (± standard error) surface roughness (a) and bulk density (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 $p < 0.05$.

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

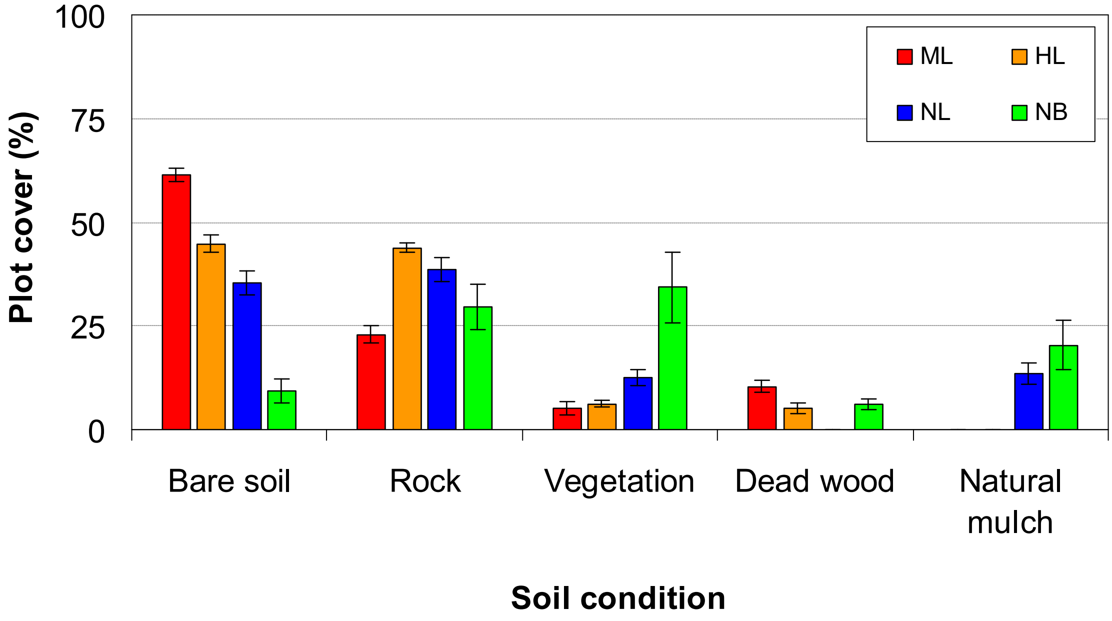


Figure 6 – Mean (± standard error) cover percentage of bare soil, rock, vegetation, dead wood and natural mulch for each experimental condition. ML - mechanically-logged soil; HL - manually-logged soil; NL - unlogged soil; NB - unburnt soil.

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.

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						**1**	-0.27	**-0.59**	0.17	**-0.51**
RC							**1**	-0.35	-0.11	-0.22
VC								**1**	-0.25	0.12
DWC									**1**	-0.30
NMC										**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 $p < 0.05$.

4. Discussion

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 mechanically logged, whereas the burnt areas subjected to manual logging showed an increase of about 150% in runoff. These findings are in accordance with other studies carried out in burnt and logged areas. In two forest sites of North America, Wagenbrenner et al. (2016) found higher runoff rates in plots logged using tracked and wheeled skidders/forwarders than in their respective controls. These authors ascribed this increase in runoff to equipment traffic, which lowers infiltration due to soil compaction (Ares et al., 2005; Horn et al., 2004). Also in California, Prats et al. (2019a; 2019b) demonstrated that surface runoff in logged areas may be 20% to 50% higher compared to undisturbed soils, mainly due to the significantly lower 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 burnt unlogged and unburnt plots, but also increased peak runoff (by 140% when averaging the ML and HL plots), and anticipated the peak of runoff. Peak flow and time to peak are important factors in soil hydrology, since they determine the flood occurrence at catchment scale (Neary et al., 1999; Shakesby, 2011; Cawson et al., 2012; Bombino et al., 2019). Higher runoff at the logged sites is a direct consequence of the reduced infiltration, as also demonstrated by other studies (e.g., Carrà et al., 2021; Lucas-Borja et al., 2022). The decrease in time to peak was likely a consequence of the combined effects of the lack of vegetation as well as reduction in water travelling times, which reduces water infiltration (Zhao et al., 2016). These changes in the hydrological response indicate that both wildfire and salvage logging can aggravate the flood risk in forest-dominated catchments.

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

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

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

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

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

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.

5. Conclusions

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

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

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

Declaration of Competing Interest

The authors declare no known competing financial interests.

Acknowledgement

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

References

Abiven, S., Menasseri, S., Chenu, C., 2009. The effects of organic inputs over time on soil aggregate stability–A literature analysis. Soil Biology and Biochemistry 41, 1–12.

Alcañiz, M., Outeiro, L., Francos, M., Úbeda, X., 2018. Effects of prescribed fires on soil properties: A review. Science of the Total Environment 613, 944–957.

Ares, A., Terry, T.A., Miller, R.E., Anderson, H.W., Flaming, B.L., 2005. Ground - based forest harvesting effects on soil physical properties and Douglas - Fir growth. Soil Science Society of America Journal 69, 1822–1832.

Beschta, R.L., Rhodes, J.J., Kauffman, J.B., Gresswell, R.E., Minshall, G.W., Karr, J.R., Perry, D.A., Hauer, F.R., Frissell, C.A., 2004. Postfire management on forested public lands of the western United States. Conservation Biology 18, 957–967.

Bombino, G., Denisi, P., Gómez, J.A., Zema, D.A., 2019. Water infiltration and surface runoff in steep clayey soils of olive groves under different management practices. Water 11, 240.

Bunte, K., Poesen, J., 1994. Effects of rock fragment size and cover on overland flow hydraulics, local turbulence and sediment yield on an erodible soil surface. Earth Surface Processes and Landforms 19(2), 115-135.

Carrà, B.G., Bombino, G., Denisi, P., Plaza-Àlvarez, P.A., Lucas-Borja, M.E., Zema, D.A., 2021. Water Infiltration after Prescribed Fire and Soil Mulching with Fern in Mediterranean Forests. Hydrology 8, 95.

Cawson, J.G., Sheridan, G.J., Smith, H.G., Lane, P.N.J., 2012. Surface runoff and erosion after prescribed burning and the effect of different fire regimes in forests and shrublands: a review. International Journal of Wildland Fire 21, 857–872.

Cerdà, A., Doerr, S.H., 2008. The effect of ash and needle cover on surface runoff and erosion in the immediate post-fire period. Catena 74, 256–263.

Cochrane, TA., Yoder, D. C., Flanagan, D. C., Dabney, S. M., 2019. Quantifying and modeling sediment yields from interrill erosion under armouring. Soil and Tillage Research 195, 104375.

de Vente, J., Poesen, J., 2005. Predicting soil erosion and sediment yield at the basin scale: Scale issues and semi-quantitative models. Earth-Science Reviews 71, 95–125. https://doi.org/10.1016/j.earscirev.2005.02.002

Fernández, C., Fontúrbel, T., Vega, J.A., 2021. Cumulative effects of salvage logging and slash removal on erosion, soil functioning indicators and vegetation in a severely burned area in NW Spain. Geoderma 393, 115004.

Fernández, C., Vega, J.A., 2016. Are erosion barriers and straw mulching effective for controlling soil erosion after a high severity wildfire in NW Spain? Ecological Engineering 87, 132–138. https://doi.org/10.1016/j.ecoleng.2015.11.047

Fernández-Raga, M., Gutiérrez, E.G., Keesstra, S.D., Tárrega, R., Nunes, J.P., Marcos, E., Rodrigo-Comino, J., 2021. Determining the potential impacts of fire and different land uses on splash erosion in the margins of drylands. Journal of Arid Environments 186, 104419.

Fernández-Raga, M., Palencia, C., Keesstra, S., Jordán, A., Fraile, R., Angulo-Martínez, M., Cerdà, A., 2017. Splash erosion: A review with unanswered questions. Earth-Science Reviews 171, 463–477. https://doi.org/10.1016/j.earscirev.2017.06.009

Francos, M., Úbeda, X., Pereira, P., 2019. Impact of torrential rainfall and salvage logging on post-wildfire soil properties in NE Iberian Peninsula. Catena 177, 210–218.

García-Orenes, F., Arcenegui, V., Chrenková, K., Mataix-Solera, J., Moltó, J., Jara-Navarro, A.B., Torres, M.P., 2017. Effects of salvage logging on soil properties and vegetation recovery in a fire-affected Mediterranean forest: a two year monitoring research. Science of the Total Environment 586, 1057–1065.

Hamed, Y., Albergel, J., Pépin, Y., Asseline, J., Nasri, S., Zante, P., Berndtsson, R., El-Niazy, M., Balah, M., 2002. Comparison between rainfall simulator erosion and observed reservoir sedimentation in an erosion-sensitive semiarid catchment. Catena 50, 1–16.

Hlavčová, K., Danáčová, M., Kohnová, S., Szolgay, J., Valent, P., Výleta, R., 2019. Estimating the effectiveness of crop management on reducing flood risk and sediment transport on hilly agricultural land – A Myjava case study, Slovakia. CATENA 172, 678–690. https://doi.org/10.1016/j.catena.2018.09.027

Horn, R., Vossbrink, J., Becker, S., 2004. Modern forestry vehicles and their impacts on soil physical properties. Soil and Tillage Research 79, 207–219.

Inbar, A., Lado, M., Sternberg, M., Tenau, H., Ben-Hur, M., 2014. Forest fire effects on soil chemical and physicochemical properties, infiltration, runoff, and erosion in a semiarid Mediterranean region. Geoderma 221, 131–138.

Iserloh, T., Ries, J.B., Arnáez, J., Boix-Fayos, C., Butzen, V., Cerdà, A., Echeverría, M.T., Fernández-Gálvez, J., Fister, W., Geißler, C., 2013. European small portable rainfall simulators: A comparison of rainfall characteristics. Catena 110, 100–112.

James, C.E., Krumland, B., 2018. Immediate post–forest fire salvage logging, soil erosion, and sediment delivery. Forest Science 64, 246–267.

Jester, W., Klik, A., 2005. Soil surface roughness measurement—methods, applicability, and surface representation. Catena 64, 174–192.

Jordán-López, A., Martínez-Zavala, L., Bellinfante, N., 2009. Impact of different parts of unpaved forest roads on runoff and sediment yield in a Mediterranean area. Science of the Total Environment 407, 937–944.

Keizer, J.J., Silva, F.C., Vieira, D.C., González-Pelayo, O., Campos, I., Vieira, A.M.D., Valente, S., Prats, S.A., 2018. The effectiveness of two contrasting mulch application rates to reduce post-fire erosion in a Portuguese eucalypt plantation. Catena 169, 21–30.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F., 2006. World map of the Köppen-Geiger climate classification updated.

Larsen, I.J., MacDonald, L.H., Brown, E., Rough, D., Welsh, M.J., Pietraszek, J.H., Libohova, Z., Dios Benavides-Solorio, J., Schaffrath, K., 2009. Causes of Post - Fire Runoff and Erosion: Water Repellency, Cover, or Soil Sealing? Soil Sci. Soc. Am. j. 73, 1393–1407. https://doi.org/10.2136/sssaj2007.0432

Lindenmayer, D.B., Burton, P.J., Franklin, J.F., 2012. Salvage logging and its ecological consequences. Island Press.

Lindenmayer, D.B., Noss, R.F., 2006. Salvage logging, ecosystem processes, and biodiversity conservation. Conservation Biology 20, 949–958.

Loch, R.J., Robotham, B.G., Zeller, L., Masterman, N., Orange, D.N., Bridge, B.J., Sheridan, G., Bourke, J.J., 2001. A multi-purpose rainfall simulator for field infiltration and erosion studies. Soil Research 39, 599–610.

Lucas-Borja, M.E., González-Romero, J., Plaza-Álvarez, P.A., Sagra, J., Gómez, M.E., Moya, D., Cerdà, A., de las Heras, J., 2019. The impact of straw mulching and salvage logging on post-fire runoff and soil erosion generation under Mediterranean climate conditions. Science of The Total Environment 654, 441–451. https://doi.org/10.1016/j.scitotenv.2018.11.161

Lucas-Borja, M.E., Heydari, M., Miralles, I., Zema, D.A., Manso, R., 2020. Effects of Skidding Operations after Tree Harvesting and Soil Scarification by Felled Trees on Initial Seedling Emergence of Spanish Black Pine (Pinus nigra Arn. ssp. s alzmannii). Forests 11, 767.

Lucas-Borja, M.E., Plaza-Àlvarez, P.A., Uddin, S.M., Parhizkar, M., Zema, D.A., 2022. Short-term hydrological response of soil after wildfire in a semi-arid landscape covered by Macrochloa tenacissima (L.) Kunth. Journal of Arid Environments 198, 104702.

Lucas-Borja, M.E., Zema, D.A., 2021. Rill erosion in unpaved and rock-paved roads after wildfire in a mediterranean forest. Geosciences 11, 79.

Malvar, M.C., Silva, F.C., Prats, S.A., Vieira, D.C., Coelho, C.O., Keizer, J.J., 2017. Short-term effects of post-fire salvage logging on runoff and soil erosion. Forest ecology and management 400, 555–567.

McGuire, L.A., Pelletier, J.D., Gómez, J.A., Nearing, M.A., 2013. Controls on the spacing and geometry of rill networks on hillslopes: Rain splash detachment, initial hillslope roughness, and the competition between fluvial and colluvial transport. Journal of Geophysical Research: Earth Surface 118, 241–256.

Moya, D., Sagra, J., Lucas-Borja, M.E., Plaza-Álvarez, P.A., González-Romero, J., De Las Heras, J., Ferrandis, P., 2020. Post-fire recovery of vegetation and diversity patterns in semiarid Pinus halepensis mill. Habitats after salvage logging. Forests 11, 1345.

Nachtergaele, F., 2001. Soil taxonomy—a basic system of soil classification for making and interpreting soil surveys. Geoderma 99, 336–337.

Nazari, M., Eteghadipour, M., Zarebanadkouki, M., Ghorbani, M., Dippold, M.A., Bilyera, N., Zamanian, K., 2021. Impacts of logging-associated compaction on forest soils: A Meta-Analysis. Front. For. Glob. Chang 4, 780074.

Neary, D.G., Klopatek, C.C., DeBano, L.F., Ffolliott, P.F., 1999. Fire effects on belowground sustainability: a review and synthesis. Forest ecology and management 122, 51–71.

Niemeyer, R.J., Bladon, K.D., Woodsmith, R.D., 2020. Long - term hydrologic recovery after wildfire and post - fire forest management in the interior Pacific Northwest. Hydrological Processes 34, 1182–1197.

Olsen, W.H., 2016. Effects of wildfire and post-fire salvage logging on rill networks and sediment delivery in California forests. Michigan Technological University.

Olsen, W.H., Wagenbrenner, J.W., Robichaud, P.R., 2021. Factors affecting connectivity and sediment yields following wildfire and post - fire salvage logging in California's Sierra Nevada. Hydrological Processes 35, e13984.

Page-Dumroese, D.S., Jurgensen, M.F., Tiarks, A.E., Ponder, J., Sanchez, F.G., Fleming, R.L., Kranabetter, J.M., Powers, R.F., Stone, D.M., Elioff, J.D., 2006. Soil physical property changes at the North American Long-Term Soil Productivity study sites: 1 and 5 years after compaction. Canadian Journal of Forest Research 36, 551–564.

Parson, A., Robichaud, P.R., Lewis, S.A., Napper, C., Clark, J.T., 2010. Field guide for mapping post-fire soil burn severity. Gen. Tech. Rep. RMRS-GTR-243. Fort Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Research Station. 49 p. 243.

Pereira, P., Francos, M., Brevik, E.C., Ubeda, X., Bogunovic, I., 2018. Post-fire soil management. Current Opinion in Environmental Science & Health 5, 26–32. https://doi.org/10.1016/j.coesh.2018.04.002

Prats, Sergio A., González - Pelayo, Ó., Silva, F.C., Bokhorst, K.J., Baartman, J.E., Keizer, J.J., 2019. Post - fire soil erosion mitigation at the scale of swales using forest logging residues at a reduced application rate. Earth Surface Processes and Landforms 44, 2837–2848.

Prats, S. A., Malvar, M.C., Coelho, C.O.A., Wagenbrenner, J.W., 2019. Hydrologic and erosion responses to compaction and added surface cover in post-fire logged areas: Isolating splash, interrill and rill erosion. Journal of Hydrology 575, 408–419.

Prats, S.A., Malvar, M.C., Wagenbrenner, J.W., 2021. Compaction and cover effects on runoff and erosion in post - fire salvage logged areas in the Valley Fire, California. Hydrological Processes 35, e13997.

Robichaud, P.R., Lewis, S.A., Brown, R.E., Bone, E.D., Brooks, E.S., 2020a. Evaluating post - wildfire logging - slash cover treatment to reduce hillslope erosion after salvage logging using ground measurements and remote sensing. Hydrological Processes 34, 4431–4445.

Robichaud, P.R., Lewis, S.A., Brown, R.E., Bone, E.D., Brooks, E.S., 2020b. Evaluating post-wildfire logging-slash cover treatment to reduce hillslope erosion after salvage logging using ground measurements and remote sensing. Hydrological Processes 34, 4431–4445. https://doi.org/10.1002/hyp.13882

Rostami, N., Heydari, M., Uddin, S.M., Esteban Lucas-Borja, M., Zema, D.A., 2022. Hydrological Response of Burned Soils in Croplands, and Pine and Oak Forests in Zagros Forest Ecosystem (Western Iran) under Rainfall Simulations at Micro-Plot Scale. Forests 13, 246.

Schäffer, B., Stauber, M., Müller, R., Schulin, R., 2007. Changes in the macro - pore structure of restored soil caused by compaction beneath heavy agricultural machinery: a morphometric study. European Journal of Soil Science 58, 1062–1073.

Shakesby, R.A., 2011. Post-wildfire soil erosion in the Mediterranean: review and future research directions. Earth-Science Reviews 105, 71–100.

Shakesby, R.A., Doerr, S.H., 2006. Wildfire as a hydrological and geomorphological agent. Earth-Science Reviews 74, 269–307.

Sheridan, G.J., Noske, P.J., Lane, P.N., Sherwin, C.B., 2008. Using rainfall simulation and site measurements to predict annual interrill erodibility and phosphorus generation rates from unsealed forest roads: Validation against in-situ erosion measurements. Catena 73, 49–62.

Sosa-Pérez, G., MacDonald, L.H., 2017. Effects of closed roads, traffic, and road decommissioning on infiltration and sediment production: a comparative study using rainfall simulations. Catena 159, 93–105.

Thorn, S., Bässler, C., Brandl, R., Burton, P.J., Cahall, R., Campbell, J.L., Castro, J., Choi, C.-Y., Cobb, T., Donato, D.C., 2018. Impacts of salvage logging on biodiversity: A meta - analysis. Journal of Applied Ecology 55, 279–289.

Verheijen, F.G.A., Jones, R.J.A., Rickson, R.J., Smith, C.J., 2009. Tolerable versus actual soil erosion rates in Europe. Earth-Science Reviews 94, 23–38. https://doi.org/10.1016/j.earscirev.2009.02.003

Wagenbrenner, J.W., MacDonald, L.H., Coats, R.N., Robichaud, P.R., Brown, R.E., 2015. Effects of post-fire salvage logging and a skid trail treatment on ground cover, soils, and sediment production in the interior western United States. Forest Ecology and Management 335, 176–193. https://doi.org/10.1016/j.foreco.2014.09.016

Wagenbrenner, J.W., Robichaud, P.R., 2014. Post - fire bedload sediment delivery across spatial scales in the interior western United States. Earth Surface Processes and Landforms 39, 865–876.

Wagenbrenner, J.W., Robichaud, P.R., Brown, R.E., 2016. Rill erosion in burned and salvage logged western montane forests: Effects of logging equipment type, traffic level, and slash treatment. Journal of Hydrology 541, 889–901. https://doi.org/10.1016/j.jhydrol.2016.07.049

Wittenberg, L., van der Wal, H., Keesstra, S., Tessler, N., 2020. Post-fire management treatment effects on soil properties and burned area restoration in a wildland-urban interface, Haifa Fire case study. Science of The Total Environment 716, 135190.

Wu, J., Baartman, J.E., Nunes, J.P., 2021a. Testing the impacts of wildfire on hydrological and sediment response using the OpenLISEM model. Part 2: Analyzing the effects of storm return period and extreme events. Catena 207, 105620.

Wu, J., Nunes, J.P., Baartman, J.E., Urbina, C.F., 2021b. Testing the impacts of wildfire on hydrological and sediment response using the OpenLISEM model. Part 1: Calibration and evaluation for a burned Mediterranean forest catchment. Catena 207, 105658.

Zavala, L.M., Jordán, A., Gil, J., Bellinfante, N., Pain, C., 2009. Intact ash and charred litter reduces susceptibility to rain splash erosion post - wildfire. Earth Surface Processes and Landforms 34, 1522–1532.

Zavala, L.M.M., de Celis Silvia, R., López, A.J., 2014. How wildfires affect soil properties. A brief review. Cuadernos de investigación geográfica/Geographical Research Letters 311–331.

Zema, D.A., 2021. Postfire management impacts on soil hydrology. Current Opinion in Environmental Science & Health 21, 100252. https://doi.org/10.1016/j.coesh.2021.100252

Zhao, C., Gao, J., Huang, Y., Wang, G., Zhang, M., 2016. Effects of vegetation stems on hydraulics of overland flow under varying water discharges. Land Degradation & Development 27, 748–757.