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Effects of Post-Fire Mulching with *Loranthus europaeus* Jacq. on Surface Runoff and Rainsplash Erosion in a Semi-Arid Pine Forest

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Abstract: To avoid flooding and erosion hazards, post-fire management actions are essential in Mediterranean forests after severe wildfires. In this regard, mulching is the most common action but some mulch materials, such as straw, may lead to adverse impacts in burned forests. The use of yellow mistletoe fruits (*Loranthus europaeus* Jacq., hereafter "LE") for the production of biodegradable mulch and its effectiveness in post-fire hydrology have never been studied. To fill this gap, this study has evaluated surface runoff and rainsplash erosion in a pine forest in Central Eastern Spain burned by a wildfire and mulched by a mixture of LE fruits and straw (with or without adding clay particles) using a portable rainfall simulator. Compared to untreated sites, runoff increased in burned and mulched soils (by 13.6% for the mixture without clay and by 17.2% when clay was added, in the latter case significantly). This increase was mainly due to the compact layer created by mulch application on the soil surface. However, the peak flow and the time to peak were lower in mulched soils (on average by 32.7% and 60.5%, significantly only for the mulch mixture without clay), thus indicating that, in these soils, peak runoff takes longer and its maximum value is lower compared to untreated sites. Soil erosion noticeably and significantly decreased (up to 97%) in mulched areas in comparison to untreated sites without significant differences between the two mixtures. Overall, this study indicates to land managers that soil mulching with a mixture of *Loranthus europaeus* Jacq. and straw is an effective post-fire management action to reduce the soil erosion risk after a wildfire.

Keywords: soil hydrology; post-fire management; overland flow; time to peak; soil loss; rainfall simulation

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1. Introduction

Forest wildfires are an important agent of the alteration of soil's hydrological and erosive responses to rainfalls, since burning generally results in increased surface runoff and erosion rates, often by more than one order of magnitude [1,2]. These undesired effects mainly depend on the severity of the fire [3,4], but other site-specific characteristics may also have a heavy influence on the soil's hydrological and erosive response to fire (e.g., weather, soil properties, vegetation type) [2,5,6]. More specifically, in sites burned by high-severity fires, tree cover, understory vegetation and litter are almost completely removed, leaving the soil bare and thus exposed to the erosivity of rainfall and overland flow [7,8]. At the same time, many soil properties are strongly altered, such as pH, electrical conductivity and organic matter and nutrient contents. Moreover, fire induces soil hydrophobicity [9,10], which often results in decreased soil water conductivity. The changes in vegetation cover and soil properties can be long-lasting and the pre-fire properties of soils burned by high-intensity fires may take several years or even decades to recover [11,12]. Therefore, after wildfires, soil hydrology is noticeably altered and this may lead to high hydrogeological hazards in valley areas with consequent floods, debris flows and landslides.

The hydrogeological risks due to wildfires are particularly high in Mediterranean semi-arid areas. Here, soils are usually shallow and poor in organic matter and nutrients (with consequent low aggregate stability) [13] and very intense rainfalls are frequent (with high erosivity) [14,15]. Moreover, in Mediterranean forests, climate change scenarios predict an increase in average temperature and a decrease in precipitation [16], which will undoubtedly exacerbate fire risk and damage. This would result in an aggravation of the soil's hydrological response to fire and rainstorms, with possible damage to civil infrastructures and, in extreme flooding events, loss of human lives.

To avoid the negative impacts of wildfires and post-fire operations on soil hydrology, management actions to protect fire-prone forests and to reduce the hydrogeological risk in fire-affected catchments are essential. Post-fire management techniques are many, showing different levels of effectiveness and functions across the burned environments. Due to the variability of its effects, each technique must be tailored considering the specific climatic, geomorphologic and ecological conditions of the application site [17,18]. Mulching is one of the most common post-fire management techniques and plant residues are often used as mulch material [19,20]. Mulch protects the soil from rainfall and helps restore vegetation [21,22], but the artificial ground cover also prevents sudden changes in soil temperature and moisture [23,24]. The protective effect of mulch is generally attributed to the combined effects of reduced raindrop energy, improved water retention, increased roughness of the soil surface, higher infiltration rate, delayed runoff formation and a reduced amount and energy of runoff [22,25]. Mulching is also able to influence soil temperature thanks to its shadowing effects and to limit water evaporation from the soil, thus increasing the available water for plants [22,26].

The effectiveness of mulching on the hydrological and erosive response of burned soils has been tested in many environments. In this regard, the review of [18] reports an updated state-of-the-art of the hydrological effects of many post-fire management techniques, including mulching. This study shows noticeable reductions in both runoff and erosion in burned and mulched soils compared to burned but untreated soils. For instance, and limiting the analysis to erosion, the reductions in sediment yields in wildfire-affected areas in the USA treated by mulching were demonstrated by [27], and these reductions can be up to 95%, as shown by [28], again in the USA. In Mediterranean environments, Ref. [29] reported a decrease in erosion of up to 80% depending on the forest species. In a Portuguese eucalypt stand, Ref. [30] measured a reduction in soil loss of 85–95% in mulched areas in the first year after a wildfire. In Spain, both Ref. [31] in Galicia and Ref. [32] in Castilla La Mancha found that erosion in mulched areas was less than half the values measured in the untreated and burned sites. More recently, again in Castilla La Mancha, Ref. [17] reported reductions in soil loss of mulched sites of 55% to 90%.

Despite this general agreement about the positive effects of mulches applied in wildfire-affected forests on soil hydrology, some authors reported some undesired effects. For instance, according to [33], soil mulching coupled with seeding was not able to significantly reduce runoff and erosion in shrubland in Galicia, as shown by the small differences in soil loss between treated and untreated sites. Also, Ref. [34] found lower water infiltration in mulched soils compared to untreated sites, particularly in the drier season.

The effectiveness of the many mulch materials in several environments has been also debated in the literature, showing pros and cons for each mulching substrate. Straw is the most common mulch material that is used as post-fire ground cover. However, this mulch can be removed by wind in some areas, thus leaving the soil bare, and accumulate in other zones, thus hampering vegetation regrowth [35,36]. A possible alternative to straw is the use of forest residues, such as wood chips, branches and fresh pieces [19,29]. In any case, forest residues are biodegradable and can be easily incorporated into the soil, thus increasing the organic matter content and improving the physical properties of soil [26,37].

Among the possible mulch materials, the yellow mistletoe fruits (*Loranthus europaeus* Jacq., hereafter simply "LE") can be used in the production of biodegradable mulch thanks to its adhesive properties. Mistletoe is a hemiparasitic flowering plant occurring on different host trees and shrubs. This plant produces its own photosynthetic carbohydrates and obtains water and mineral nutrients from its host plants, due to its semiparasitic behavior [38]. LE species are considered tree pests in forests and plantations [39,40], since they disturb the water and nutrient balances and reduce photosynthesis and respiration, thus debilitating infected trees [41,42]. However, the LE fruits spread on soils may act as an adhesive binding for soil particles, which may reduce their detachment from the original sites, therefore lowering soil erodibility. This is particularly important in burned soils, where erosion rates are increased by the fire effects and therefore a natural agent that can reduce soil erosion may be beneficial for soil conservation purposes. However, to the authors' best knowledge, no previous studies have evaluated the viability of LE fruits as mulching material in wildfire-affected forests and therefore its effectiveness as a post-fire mulching material is currently unknown.

Rainsplash detachment of soil, which is the first stage of erosion, removes soil particles that can be transported downstream by overland flow and thus is an essential process driving the overall soil loss from burned or disturbed forest hillslopes. However, in spite of the great attention paid to rainsplash erosion in wildfire-affected forests (e.g., [12,43,44]), little research exists on the differences in rainsplash erosion between mulched and untreated burned forest sites, and no studies have explored the effects in soils mulched with LE.

To fill this gap, this study has evaluated soil temperature and water content as well as surface runoff and rainsplash erosion in a pine forest in Central Eastern Spain burned by a wildfire and mulched by LE fruits, using a portable rainfall simulator. We hypothesized that the application of this mulch material would be able to reduce the hydrological and erosive responses of soils following a forest wildfire in the short term. The response to this research hypothesis could provide insight for forest managers about a viable and cheap mulch material for post-fire management of burned forests under Mediterranean semi-arid conditions.

2. Materials and Methods

2.1. Study Area

In July 2021, a high-severity fire burned approximately 2500 ha in a pine forest of the municipality of Liétor (Castilla La Mancha, Spain, 38°30′41′ N; 1°56′35′ W) (Figure 1), identified as the study area. This soil burn severity derives from the classification proposed by [45], based on visual indicators (e.g., vegetation burning level, charring, ground color), as described by [46].

The climate of the area is semi-arid, "BSk" type, according to the Koppen classification [47]. The mean annual temperature and precipitation are 17 °C and 320 mm, respectively, according to the most recent 20-year records of the Spanish Meteorological Agency at the weather station of Hellín (about 20 km far from Liétor).

The prevalent overstory vegetation species are Aleppo pine (*Pinus halepensis* Mill.) and kermes oak (*Quercus coccifera* L.). Before the wildfire, the stand density was 500 to 650 trees/ha and the tree height was in the range of 7 to 14 m. The understory vegetation includes *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. The soils are Calcic Aridisols [48] with sandy loamy texture. The study sites have an elevation between 520 and 770 m above the mean sea level, a northwest aspect (with exposure to dominant winds from the north) and a mean slope of between 15 and 25%.

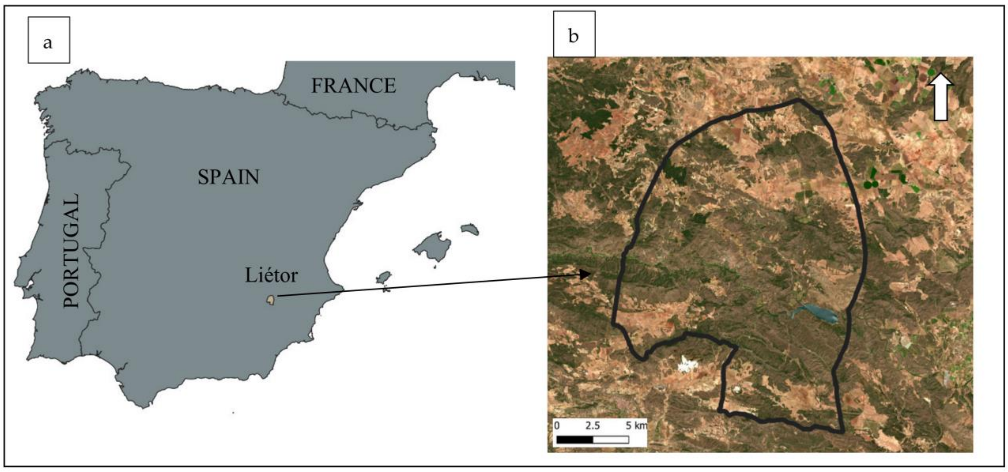


Figure 1. Geographical location (**a**) and aerial map (**b**) of the study area (Liétor, Castilla La Mancha, Spain).

2.2. Experimental Design

A total of 15 plots were installed in a burned site of the study area in order to measure surface runoff and soil loss during rainfall simulations. More specifically, five plots were burned and not treated ("B"). Of the remaining ten plots, five were mulched with a mixture of LE and wheat straw ("LS") and the other five were mulched with the same mixture while also adding clay particles ("LSC"). Since in the laboratory pre-tests, the LS mixture had a relatively soft surface against pressure, clay was used as an additive in order to increase the strength of the mulch layer. Therefore, the experimental design consisted of three soil conditions (B, LS and LSC) with five replicated plots for each condition. All plots were located at a reciprocal distance higher than 300 m to avoid pseudo-replications.

The LE fruits were collected in late autumn from a forest close to the study site. In the laboratory of the University of Castilla La Mancha, after drying in the open air, these fruits were crushed in a blender and water was added (Figure 2a). Then, the two mixtures for soil mulching were prepared as follows (Figure 2b):

- LS: 3 L of water + 600 g of LE + 150 g of straw (total 3750 g per square meter of plot area)
- LSC: 3 L of water + 600 g of LE + 150 g of straw + 150 g of clay particles (total 3900 g per m^2).

(**a**) (**b**)

Figure 2. Blend of water and *Loranthus europaeus* Jacq. fruits (**a**); mixtures of water, LE and straw (**left**) and water, LE, straw and clay particles (**right**) (**b**), used for soil mulching (Liétor, Castilla La Mancha, Spain).

The main characteristics of the mulch additives (straw and clay particles) were the following:

- Straw: length 0.5–3 cm; width 0.25–1 cm; thickness 0.1–0.7 cm; specific weight 80–100 g/dm^3
- Clay particles: smaller than 0.075 mm.

2.3. Rainfall Simulations and Measurement of Runoff and Soil Loss

Each plot was subjected to one simulation of an artificial rainfall using an Eijkelkamp® rainfall simulator [49,50] following the methodology proposed by [51], where more detail can be found. To summarize, after calibration in a laboratory, the simulator was carefully placed over the ground. A rainfall of 36 mm was produced for a time of 5 min on a surface area of 0.3 m $\times$ 0.3 m (net area receiving rainfall of 0.0625 m^2, intensity of 432 mm/h and falling height of 40 cm). This extreme rainfall intensity has a return period of more than 100 years in the studied area [51].

During the rainfall simulation, the runoff volume ("SR") was measured every 30 s with a meterstick and water and sediments were collected into a small bucket until runoff ended. Then, the runoff hydrograph was built, reporting the flow rate over time. This allowed the identification of the runoff rate, time to peak (the time of maximum runoff rate, TP) and peak flow (the maximum runoff rate, PF). The bucket collecting water and sediments was transported to the laboratory and then oven-dried at 104 °C for 24 h. The dried sediments were weighed and the sediment concentration ("SC") was determined to further calculate the soil loss ("SL").

2.4. Measurement of Soil Temperature and Water Content

Before each rainfall simulation, the soil temperature (hereafter "ST") was measured using a 6000-09TC thermocouple probe connected to a portable photosynthesis system (LI-COR 6400, LI-COR Inc. Lincoln, NEB, USA). At the same time, the volumetric soil water content ("SWC") was determined using an MP406 portable moisture probe (ICT International, Armidale, NSW, Australia).

2.5. Statistical Analysis

The measured values of surface runoff, sediment concentration and soil loss were statistically processed using a one-way ANOVA to identify statistically significant differences in these response variables among the three soil conditions (independent factors). If significant differences were found for a variable, a Tukey test (at $p < 0.05$) was used to determine which treatments were different. Before, the ANOVAs, normality and homogeneity of variance were checked with the Shapiro-Wilk test and Levene's test, respectively. If the tests were not satisfactory, the data were square-root transformed before running the ANOVAs again.

Then, a multivariate statistical analysis was carried out based on the studied variables. More specifically, the principal components analysis (PCA) was applied to identify representative derivative variables (principal components, PCs) from the original dataset of observations. First, the original variables (expressed by different measuring units) were standardized and Pearson's method was used to compute the correlation matrix. The first two PCs, explaining at least 75% of the variance of the original variables, were considered. Finally, the observations were grouped in clusters using the Agglomerative Hierarchical Cluster Analysis (AHCA), a distribution-free ordination technique to group samples with similar characteristics by considering an original group of variables. Euclidean distance was used as the similarity—dissimilarity measure.

Finally, reciprocal correlations between pairs of variables (SC vs. SR, SL vs. SR or SL vs. SC) were set up using a linear regression analysis after checking the data fitting with other functions (e.g., logarithmic, power, polynomial, exponential).

The statistical analysis was carried out using the XLSTAT release 19.1 (Addinsoft, Paris, France) software.

3. Results

3.1. Variability of ST and SWC with Soil Condition

The one-way ANOVA showed that ST was significantly different among the three soil conditions (F = 50.493, $p < 0.0001$). The highest value was measured in B plots (31.1 ± 0.89 °C) and the lowest in LS plots (20.5 ± 0.73 °C), with LSC plots showing an intermediate ST (20.5 ± 0.73 °C) (Figure 3).

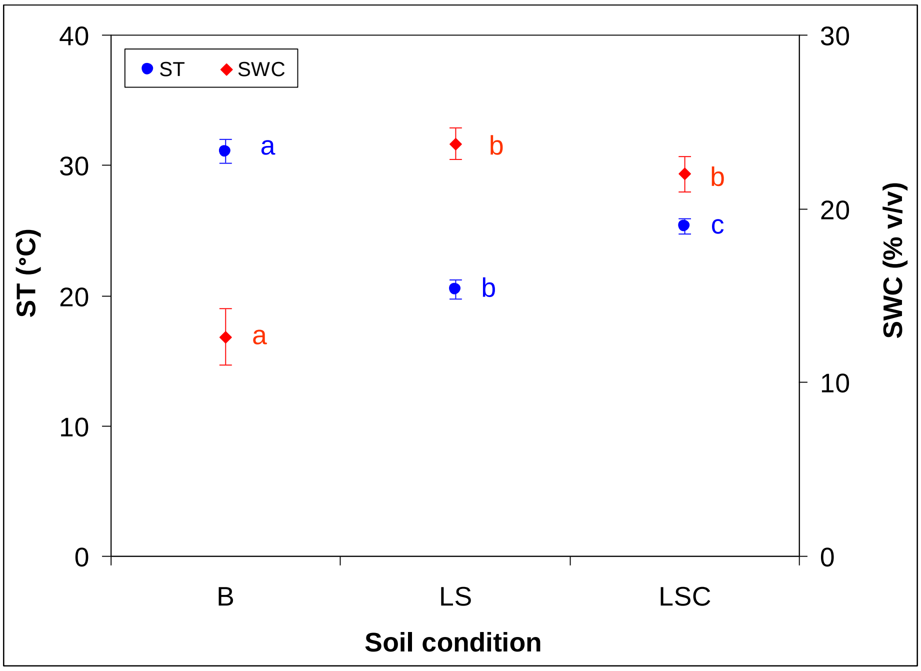


Figure 3. Mean ± standard error of soil temperature (ST) and water content (SWC) measured under three soil conditions—burned and untreated (B), burned and mulched with Loranthus europaeus Jacq. and straw (LS) and burned and mulched with Loranthus europaeus Jacq., straw and clay particles (LSC)—in the experimental plots (Liétor, Castilla La Mancha, Spain). Different letters indicate significant differences after Tukey's test ($p < 0.05$).

For SWC, significant differences were found only between untreated (B) and mulched (LS and LSC) soils (F = 23.799, $p < 0.0001$). B plots showed a significantly higher SWC (12.6 ± 1.62%) compared to LS (23.7 ± 0.91%) and LSC (22.0 ± 1.03%) plots (Figure 3).

3.2. Variability of Runoff and Erosion with Soil Condition

Figure 4 reports the cumulated runoff volume and runoff rate over time for the three soil conditions. The related hydrographs show evident differences in these hydrological variables between burned and untreated and burned and mulched plots, while these differences between soils treated with the two mulches are much lower.

The soil condition factor significantly explained the variability of surface runoff (F = 6.075, $p < 0.05$). The lowest surface runoff was measured in B plots (24.5 ± 1.39 mm) and this value was significantly different from the runoff in LSC plots (28.7 ± 0.41 mm) but not from the value of LS plots (27.8 ± 0.56 mm) (Figure 5). Moreover, the soil condition significantly influenced both peak flow and times to peak (F = 3.984; $p < 0.05$ and F = 5.207, $p < 0.05$, respectively). Although the total runoff was higher, the mulched plots showed lower PF (94.4 ± 18.5 mm/h, LS and 106 ± 3.78 mm/h, LSC) and higher TP (198 ± 29 s, LS and 168 ± 7 s, LSC) compared to the untreated sites (149 ± 16.1 mm/h and 114 ± 11 s). The differences in PF and TP were significant only between LS and B plots (Figure 5).

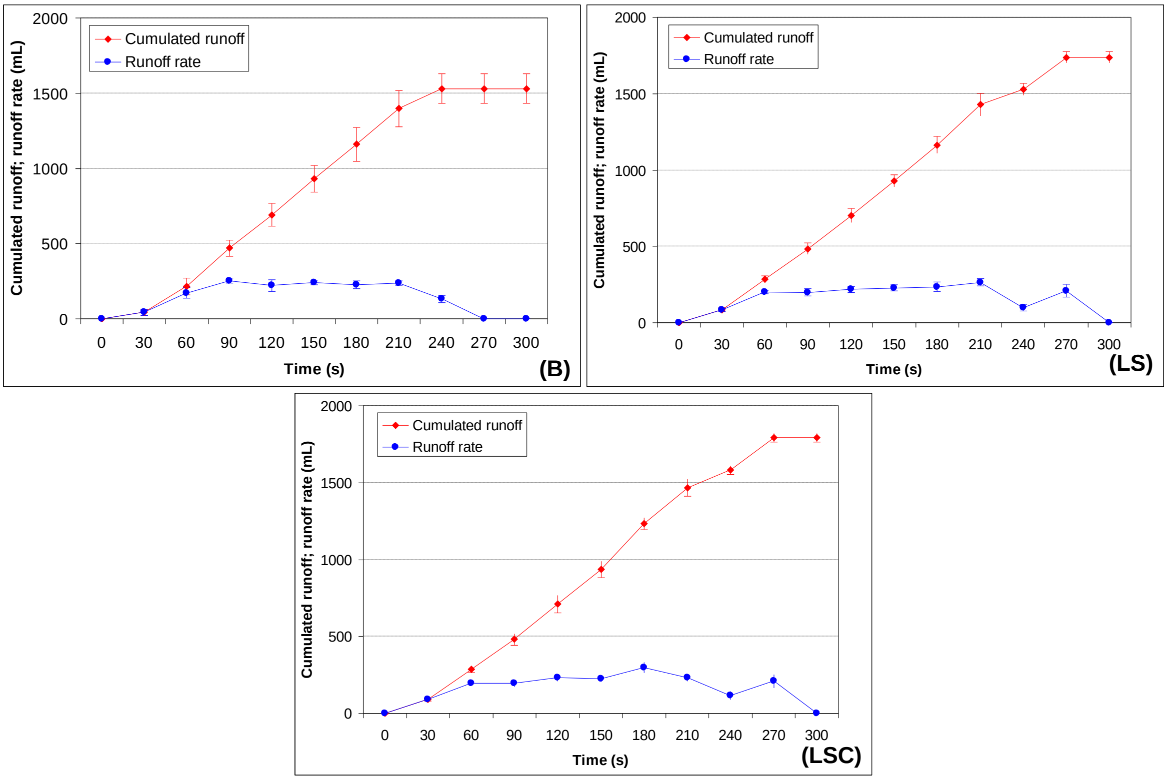


Figure 4. Cumulated runoff volume and runoff rate over time measured under three soil conditions—burned and untreated (B), burned and mulched with *Loranthus europaeus* Jacq. and straw (LS) and burned and mulched with Loranthus europaeus Jacq., straw and clay particles (LSC)—in the experimental plots (Liétor, Castilla La Mancha, Spain).

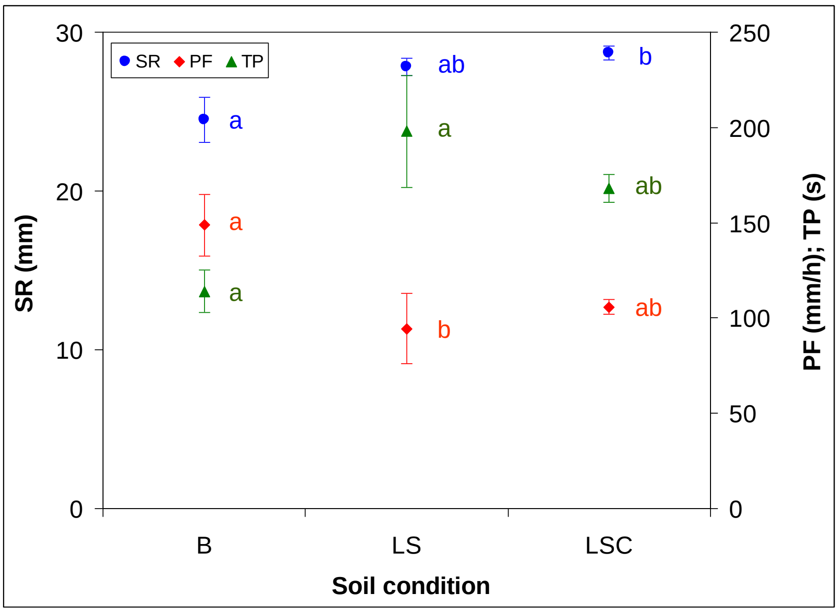


Figure 5. Mean ± standard error of surface runoff (SR), peak flow (PF) and time to peak (TP) measured under three soil conditions—burned and untreated (B), burned and mulched with *Loranthus europaeus* Jacq. and straw (LS) and burned and mulched with *Loranthus europaeus* Jacq., straw and clay particles (LSC)—in the experimental plots (Liétor, Castilla La Mancha, Spain). Different letters indicate significant differences after Tukey's test ($p < 0.05$).

According to the ANOVA, sediment concentration (F = 7.290, $p < 0.01$) and soil loss (F = 7.348, $p < 0.01$) were significantly influenced by the soil condition. The sediment concentration pattern was equal to surface runoff, with B plots showing the highest values (15.3 ± 5.52 g/L). This sediment concentration was significantly different compared to the values measured in both LS (0.28 ± 0.04 g/L) and LSC (0.47 ± 0.05 g/L) plots (Figure 6). The differences in soil loss between the mulched plots were not significant for neither soil loss nor sediment concentration. B plots produced the highest soil loss (3.60 ± 1.29 tons/ha) and this value was significantly higher compared to the erosion measured in both LS (0.08 ± 0.01 tons/ha) and LSC (0.13 ± 0.01 tons/ha) plots (Figure 6).

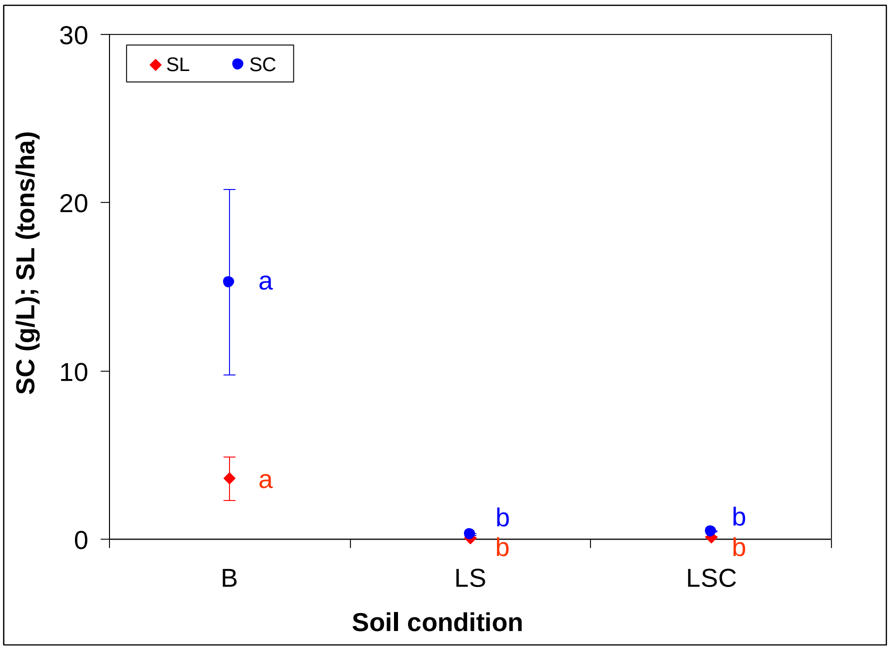
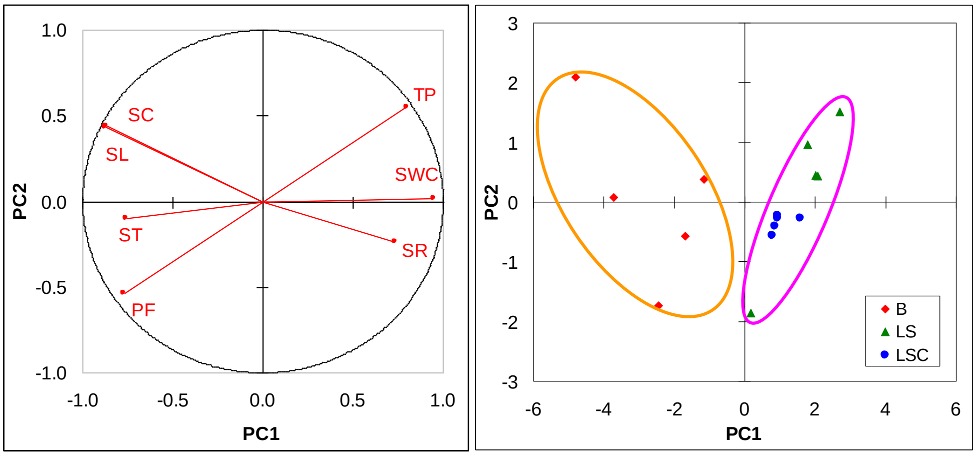


Figure 6. Mean ± standard error of sediment concentration (SC) and soil loss (SL) measured under three soil conditions—burned and untreated (B), burned and mulched with Loranthus europaeus Jacq. and straw (LS) and burned and mulched with Loranthus europaeus Jacq., straw and clay particles (LSC)—in the experimental plots (Liétor, Castilla La Mancha, Spain). Different letters indicate significant differences after Tukey's test ($p < 0.05$).

3.3. Multivariate Statistical Analysis

The PCA gave two derivative variables (PCs), which explained together 83% of the variance of the original variables (68.2% for PC1 and 14.9% for PC2). The first PC was significantly influenced by all the original variables (absolute value of loadings >0.731), while only PF significantly weighed on the second PC (loading of −0.534). It is worth noting that higher values of PC1 were associated with higher SWC (loading of 0.946), SR (0.731) and TP (0.797), while PC1 decreased with ST (loading of −0.763), PF (−0.771), SC (−0.880) and SL (−0.870) (Figure 7a).

According to the AHCA, the observations were clustered into two different groups: a first cluster including the values of variables measured in LS and LSC plots and a second cluster consisting of only observations at B plots, also showing a noticeable scattering among points. The first group (regardless of the mixture used) was associated with lower values of PC1 (and therefore with high SC, SL, ST and PF), while the second cluster was characterized by high PC1 (and therefore high TP, SWC and SR) (Figure 7b).



(**a**) (**b**)

Figure 7. Loadings of the original variables (**a**)—soil temperature (ST), soil water content (SWC), surface runoff (SR), sediment concentration (SC) and soil loss (SL)—and scores with relevant clusters (**b**) on the first two principal components (PC1 and PC2) provided by the principal component analysis coupled with analytical hierarchical cluster analysis applied to observations made under three soil conditions—burned and untreated (B), burned and mulched with *Loranthus europaeus* Jacq. and straw (LS) and burned and mulched with *Loranthus europaeus* Jacq., straw and clay particles (LSC)—in the experimental plots (Liétor, Castilla La Mancha, Spain).

3.4. Regression Analysis

For all plots, sediment concentration and soil loss were not linearly correlated with surface runoff ($r^2 < 0.36$ and 0.46, respectively). In contrast, a very high coefficient of determination ($r^2 > 0.97$) was found between soil loss and sediment concentration under all soil conditions (Figure 8). Moreover, SWC was well and inversely correlated with ST ($r^2 = 0.67$). Finally, low coefficients of determination were found between ST and SWC on one side and SR on the other side ($r^2 < 0.31$).

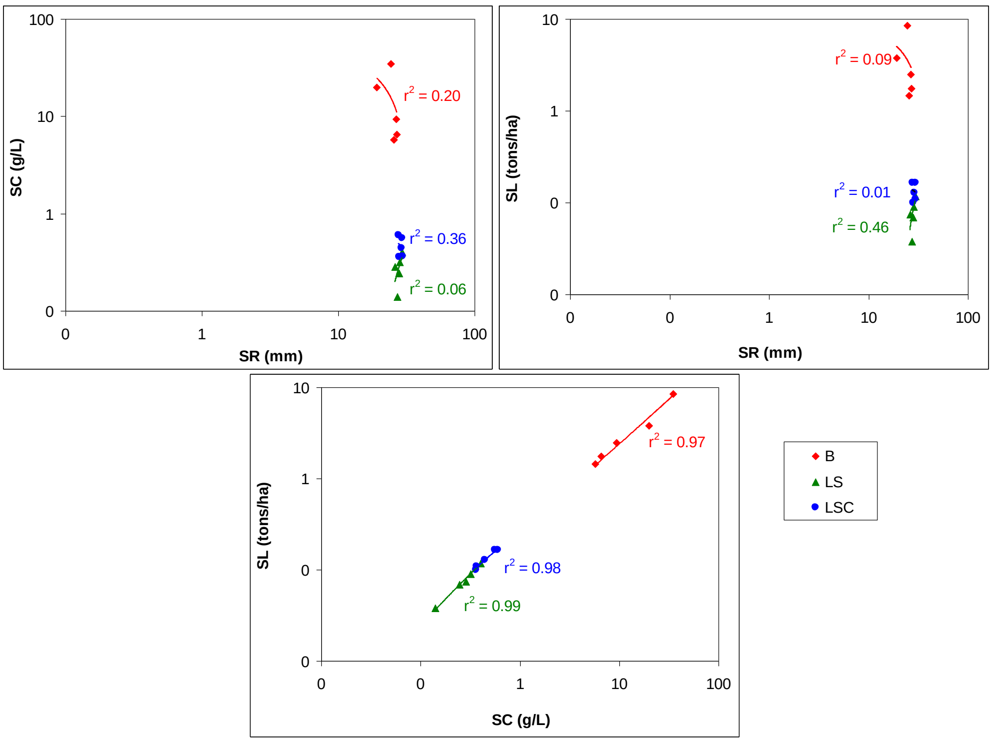


Figure 8. Linear regressions between pairs of measurements (SR, surface runoff; SC, sediment

concentration; SL, soil loss) using a rainfall simulator under three soil conditions—burned and untreated (B), burned and mulched with *Loranthus europaeus* Jacq. and straw (LS) and burned and mulched with *Loranthus europaeus* Jacq., straw and clay particles (LSC)—in the experimental plots (Liétor, Castilla La Mancha, Spain).

4. Discussion

4.1. Effects of Mulching on Soil Temperature and Water Content

Mulching with both mixtures decreased soil temperature in burned soils compared to burned and untreated plots. This decrease was significantly higher (−34%) in soils treated with the LS mixture, about two-fold, compared to the variation measured in plots treated with LSC mulch (−18.6%). SWC was also significantly reduced in mulched soils, regardless of the mixture type. These variations were very noticeable, with the maximum reduction (−88%) measured in soils mulched with the LS mixture. A decrease of 74.3% was detected in soils covered by LSC mulch, but the difference between the two mulches was not significant (−7.3%). These reductions in ST and SWC are expected in mulched soils (e.g., [22]), since mulch application over ground reduces the sunlight supply in comparison to untreated soils. In mulched sites, water losses due to evapotranspiration decrease, thus increasing the SWC and therefore the water storage in soil. These effects are beneficial in semi-arid soils, where the evapotranspiration rates are high and the organic matter content (which retains water by absorption [52]) is low. Therefore, a lower ST and a higher SWC due to mulching support seed germination and seedling growth after fire [53,54], with consequent vegetation recruitment. This allows the overcoming of an important limiting factor for vegetal species restoration, such as water storage. However, [34] warns that, in comparison to untreated soils, it is true that straw maintains higher temperatures and water contents in mulched plots, but this mulch can reduce the unsaturated hydraulic conductivity, particularly in the drier season.

4.2. Effects of Mulching on Surface Runoff and Time to Peak

Surface runoff significantly increased in burned and mulched soils—both under treatment with LS (+13.6%) and LSC (+17.2%) mixtures—compared to burned plots without treatments. The reasons for this noticeable increase in surface runoff due to mulching could be due to the fact that mulch supply to soil creates a compact layer on its surface, which is less pervious to water compared to the untreated soils (Figure 9). Therefore, water infiltration is reduced due to the decrease in soil hydraulic conductivity, which increases the portion of rainwater that turns to overland flow [55,56]. Moreover, the soils mulched with the LSC mixture showed a slightly higher but non-significant runoff generation capacity compared to the sites treated with LS (+3.2%). This increase may be due to the higher fraction of finer particles in the soil, which further raises up the runoff response of burned and mulched soils due to the lower soil hydraulic conductivity. However, in comparison to untreated sites, peak flow (−36.5% and −28.9% for LS and LSC mulches, respectively, and significantly only for LS plots) and time to peak were lower (with reductions of 47.4%, LSC and 73.7%, LS, significant in the latter case) in mulched soils, but the differences between these two variables were not significant (+12.1% for peak flow and −15.1% for time to peak in LSC soils compared to LS sites). This means that, in mulched soils, peak runoff takes longer and its maximum value is lower compared to the untreated sites with runoff hydrographs that are flatter and wider. The time lag of surface runoff in mulched soils may be due to the higher surface roughness that slows down the overland flow compared to untreated soils, but this statement would require the direct measurement of this soil parameter.

When compared to the results of this study, most researchers reported significant decreases in surface runoff in mulched sites compared to untreated areas affected by wildfire (e.g., [4,18]). Concerning the Mediterranean forests, other relevant investigations show that soil mulching with straw and wood chips decreases runoff coefficients compared to untreated areas in pine forests in Central-Eastern Spain [17], but this decrease is not significant. Also Ref. [33] found a lack of significance in runoff between mulched and non-mulched sites in burned shrublands of Northern Spain after an experimental fire and rainfall simulations. This experience is an example of soil mulching with low effectiveness on runoff. In contrast, Ref. [32] reported decreases of 12% in surface runoff from mulched sites of pine stands in Central Eastern Spain, in spite of the disturbance exerted by salvage logging.

Figure 9. A portion of the surface layer cut from soils mulched with mixtures of *Loranthus europaeus* Jacq. and straw (with or without addition of clay particles) in the experimental site.

Peak flow and time to peak are important factors in soil hydrology at the catchment level, since these parameters govern the timing of floods [35]. The delayed response in runoff found in mulched sites is beneficial, since water stream travels slower on the soil surface and therefore flood formation takes longer compared to untreated catchments, resulting in a lower hazard for valley areas [57]. In contrast, in the burned areas without any post-fire treatments, the time to peak is shorter and the peak flow is higher [17], as a direct consequence of the reduced infiltration and vegetation removal due to burning [58].

4.3. Effects of Mulching on Soil Loss

Soil erosion noticeably and significantly decreased in mulched areas in comparison to untreated sites, with reductions of 96% (LSC mixture) to 98% (LS) for both mulches and without significant differences between the two mixtures (71.4%). Since the runoff volumes were higher in mulched soils compared to soil in the absence of treatments, these reductions should be essentially ascribed to the reduced sediment concentration in the overland flow, as also demonstrated by the low correlation between soil loss and surface runoff. More specifically, the sediment load in the water stream generated by the simulated precipitation significantly decreased by 98.2% and 96.9% in the soils treated with the LS and LSC mixtures, without any significant differences between these two mulches (67.6%). This led to a consequent reduction in the total soil loss in comparison to untreated sites. The main reason for the decrease in soil loss in mulched sites is the reduced rainsplash detachment, which noticeably lowers sediment concentrations in the generated runoff. In other words, the higher the sediment concentration, the higher the soil loss, as shown by the high correlation between these pairs of variables. The mixture of LE and straw (with or without the clay addition) binds the soil particles, which exerts a high resistance to detachment from their original position due to the kinetic energy of rainfall. However, the creation of a compact layer in the mulched sites requires attention from an ecological point of view, since soil compaction may lead to adverse effects on post-fire regeneration of plants, and this requires direct investigations [59,60]. For instance, soil compaction reduces soil infiltration, which in turn may decrease the groundwater recharge and increase the runoff response of soil.

Comparisons of the results of this study with relevant literature show general and noticeable decreases in soil erosion due to post-fire mulching in forests burned by wildfires [4,6,18]. In Mediterranean forests, Ref. [17] report significantly lower soil loss in plots treated with wood chips and mainly straw as mulch materials. These authors recorded maximum reductions in soil loss of 90–95% in the steeper soils, while the decrease in erosion measured by [32] was on average 40% compared to untreated soils.

The maximum soil loss measured in the burned site, which is equal to 3.6 tons/ha, is due to an extremely intense precipitation and is far from the tolerance limit for erosion in agricultural areas suggested by [61,62] (approx. 10–12 tons/ha per year). However, it should be borne in mind that portable rainfall simulators, such as those used in this study, only measure rainsplash erosion, while other erosion forms (sheet flow and rill erosion) are not considered and therefore presumably underestimated [63]. Ref. [44] found higher differences in erosion rates among different soil conditions compared to the corresponding differences detected for runoff. This study is in line with those results and we think that soil loss occurring at larger spatial scales (plots or hillslopes or even catchments) may be higher than the values measured in this investigation at the microplot scale. This opinion requires deeper investigation in the field by upscaled experiments. Moreover, the kinetic energy of simulated rainfalls is generally lower under artificial conditions, which leads to an underestimation of rainsplash erosion in comparison to natural precipitation. Therefore, the high difference between the tolerance limits mentioned above and the experimental values of this study may be lower than the measured value. This also requires careful attention from land managers, especially in those areas that are more exposed to erosion risk (e.g., sites with low vegetal cover and high steepness) and that may be noticeably eroded by extreme rainfalls following high-severity fires, as often happens in forests in the Mediterranean environment [64].

4.4. Changes in Hydrological and Erosive Response among Mulched and Untreated Soils

PCA provided an individual indicator (the first principal component) that summarizes the soil response to extreme rainstorms. In other words, the lower the PC1, the lower the peak flow and sediment concentration and therefore erosion, strongly correlated to sediment concentration. In contrast, the higher the first PC, the higher the runoff generation and the shorter the concentration time of a possible flood. Also, other authors found that post-fire management techniques clearly discriminate between burned and undisturbed soils from burned and treated sites [8,65,66].

Strong correlations between sediment concentration and soil loss after a wildfire in areas with a Mediterranean climate, as in the present study, have been reported by [67] in burned forests of Northern Iran and by [44] in semi-arid burned shrublands of Central-Eastern Spain, although no further attention has been paid to the effects of mulching on these relationships.

Moreover, the analytical treatment of the hydrological and erosive variables by PCA and AHCA revealed that soil hydrology was noticeably influenced by post-fire treatments. More specifically, mulching discriminates the runoff and erosion response to rainfall between burned soils—showing higher erosion and lower runoff (associated with lower values of PC1)—and mulched soils, which evidence a lower aptitude to mobilize sediments but higher runoff generation capacity and times to peak (associated with higher PC1). This means that the erosion risk is higher in burned and untreated soils, while higher flooding hazards are possible in burned and mulched sites. However, these areas are characterized by higher concentration times, which allow for an early warning to avoid damage to people and infrastructures [68,69].

5. Conclusions

This study has demonstrated that, in pine forest in Central Eastern Spain burned by a high-severity fire and in comparison to burned and untreated sites, post-fire mulching of soil with mixtures of *Loranthus europaeus* Jacq. and straw (with or without the addition of clay particles): (i) significantly reduced soil temperature and mainly water content; (ii) increased runoff (significantly in the plots where clay was added to the mulch mixture); (iii) reduced the peak flow and time to peak (significantly for the mulch mixture without clay); (iv) noticeably and significantly reduced soil erosion (but without significant differences between the two mixtures). Thanks to these results, the working hypothesis that the application of this mulch material can reduce the hydrological and erosive responses of soils following a forest wildfire in the short term should be rejected for surface runoff and accepted for soil erosion.

This study indicates to land managers that soil mulching with a mixture of *Loranthus europaeus* Jacq. and straw is an effective post-fire management action to reduce the soil erosion risk after a wildfire. However, the runoff response in mulched sites is higher compared to untreated areas and, in this regard, the addition of clay particles is discouraged, since this may aggravate this response. In spite of the increased runoff generation due to mulching, the flooding risk is not higher compared with the non-mulched areas, due to the increase in concentration times and reductions in peak flow.

Overall, more research is suggested in order to explore the hydrological and erosive effects of these mulch materials on larger scales and to quantify the cheapness of this management strategy compared to the other post-fire techniques.

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