

# Ecological Engineering

## Effects of post-fire mulching with straw and wood chips on soil hydrology in pine forests under Mediterranean conditions

--Manuscript Draft--

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<b>Abstract:</b>	<p>Mulching is one of the most common post-fire management techniques, which has been widely studied at the global scale. However, more research is needed on the hydrological effects of mulching in forest ecosystems under Mediterranean semi-arid conditions. This study has evaluated water infiltration, surface runoff and soil loss using a portable rainfall simulator in Central-Eastern Spain after post-fire treatments. In this area, a large wildfire recently affected a pine forest, and the burned soil was mulched using wheat straw (dose of 0.3 kg/m<sup>2</sup>) or wood chips (2 kg/m<sup>2</sup>) on plots with two different slopes (about 30%, lower slope, and 50%, higher slope). The study has shown that the soil condition (burned control vs. soils mulched with straw or wood chips) and slope (lower vs. higher) did not significantly influence the water infiltration. However, the mean infiltration of the soils mulched with straw were higher (+40% and +17%, respectively) compared to both the control and the plots mulched with wood chips. Moreover, lower surface runoff (-23%) was measured in the mulched soils compared to the control plots. The soil mulching with straw was more effective at decreasing the runoff coefficient (-31%) compared to plots treated with wood chips (-18%) and the control areas. Soil loss was significantly lower in plots treated using straw (-87% compared to the burned and not treated soils) compared to wood chips (-54%). Peaks of 90-95% of reduction in the soil loss were even recorded in the steeper soils. Finally, we suggest the application of wheat straw rather than wood chips, since the wheat straw mulch material provides a higher soil cover (on average 73% against 48% of wood chips) and therefore is more indicated to reduce the hydrological response in burned soils, as confirmed by the lower runoff (in the average -16%) and erosion (-73%) measured in this experiment on both gentler and steeper soils.</p>
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Professor Jan Vymazal  
Editor-in-Chief  
of Ecological Engineering

**Cover letter**

Dear Prof. Jan Vymazal,

Ample and eminent literature has evaluated the effects of several post-fire management strategies, including soil mulching with vegetal residues. However, the effectiveness of these eco-engineering techniques may be variable site by site, depending on the specific climatic, geomorphological and ecological conditions of the burned sites. About soil mulching, contrasting results have been highlighted by some studies in burned forests under Mediterranean conditions. This suggests the need of more research on soil mulching using different vegetal materials, which may indicate the effectiveness of this technique at mitigating the erosion risk in these delicate environments.

To this aim, we propose for possible publication on “Ecological Engineering” a study that has evaluated water infiltration, surface runoff and soil loss using a portable rainfall simulator in a burned forest of Central-Eastern Spain. In this environment, after a high-severity wildfire, burned plots with two different slopes were mulched using wheat straw or wood chips.

To summarize the main results of this study, neither the soil condition (burning vs. burning and mulching with two materials) or the slope significantly influenced water infiltration. However, the mean infiltration of the soils mulched with straw were higher (+40% and +17%, respectively) compared to both the untreated soils and the plots mulched with wood chips. Moreover, lower surface runoff (-23%) was measured in the mulched soils compared to the burned and not treated plots. The soil mulching with straw was more effective at decreasing the runoff coefficient (-31%) compared to the application of wood chips (-18%) in comparison to the burned and not treated areas. The decrease in runoff was more pronounced in soils with lower slopes. The soil treatments were particularly effective in reducing the erosion from burned forests. Soil loss was significantly lower in plots treated using straw (-87% compared to the burned and not treated soils) compared to wood chips (-54%), and peaks of 90-95% of reduction in the soil loss were even recorded in the steeper soils. Finally, we suggest the application of wheat straw rather than wood chips, since the wheat straw mulch material provides a higher soil cover and therefore is more indicated to reduce the hydrological response in burned soils, as confirmed by the lower runoff (in the average -16%) and erosion (-73%) measured in this experiment on both gentler and steeper soils.

In our opinion, this study provides a useful contribution for a broader use of effective eco-engineering techniques towards the restoration of burned forests under semi-arid conditions. As such, we think that the paper may give landscape planners insight on the effectiveness of soil mulching against the flood and erosion risks in the Mediterranean forests. For these reasons, we think that the paper may be of interest for the readers of “Ecological Engineering”. Finally, we thank You in advance for the attention You will pay to our paper.

Kind regards.

*Demetrio Antonio Zema*  
(on behalf of the co-authors)



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## **HIGHLIGHTS**

- Rainfall was simulated on burned forest soils mulched with straw and wood chips.
- Straw was more effective than wood chips at decreasing surface runoff coefficient.
- This reduction was more evident in soils with lower slopes.
- Soil loss decreased by 87% on straw-mulched soils and by 54% using wood chips.
- Straw mulch provides a higher soil cover than wood chips and is thus more advisable.

## **AUTHORS' REPLIES TO THE EDITOR**

Dear Prof. Vymazal,

Thank You for the possibility to revise our manuscript. Since we have addressed all the major and minor issues raised by the two Reviewers, we think that the paper is now improved. We would be grateful if You could reconsider the revised manuscript for publication in *Ecological Engineering*. Thank you again for your attention.

Kind regards.

## **AUTHORS' REPLIES TO THE ASSOCIATE EDITOR**

Dear Associate Editor,

We deeply appreciate the work of both Reviewers, since all their comments greatly helped to improve our paper.

You will find below the revision notes and our replies to each of the reviewer comments. As required, all changes are reported in the tracked submission. We have also uploaded a clean and updated version with the exact content.

Finally, thank you again for your attention to our paper.

Kind regards.

## **AUTHORS' REPLIES TO THE COMMENTS OF THE REVIEWER #1**

### **Comment**

The manuscript addresses an experimental study on the effects of straw and wood chips mulching on infiltration, runoff coefficient and soil losses, by using rainfall simulations. The study has demonstrated the effectiveness of this post-fire mitigation measure in decreasing runoff coefficient and soil erosion. The subject is very interesting and would provide significant advances in the state-of-the art of soil protection after wildfires, especially in semi-arid ecosystems, for which new measures are urgently needed. The manuscript is very well written and the key results clearly discussed. Therefore, I would recommend its publication in *Ecological Engineering*, providing that the Authors can address some minor issues, as suggested below.

### **Reply**

Dear Prof./Dr., thanks a lot for Your revision work that we have considered very useful to improve our MS. We are glad that You have appreciated the paper. In the following text, You will find our replies to all Your comments. However, we address You to the file containing the revised paper and attached to the resubmission.

### **Comment**

-Highlights are requested, as they are mandatory in this Journal. It is also suggested to provide a Graphical Abstract.

### **Reply**

Thanks for the suggestions. We have added to the MS the highlights and a graphical abstract.

**Comment**

-Abstract: The abstract could be substantially shortened.

**Reply**

We have shortened the abstract accordingly.

**Comment**

-[line 32] It is not clear that "burning vs. burning and mulching with tow material" refers to different treatments. It is suggested to replace with "control vs. mulched". Consider the same suggestion throughout the document.

**Reply**

According to the Reviewer's suggestion, we have changed "burning vs. burning and mulching with two material" to "burned control vs. soils mulched with straw or wood chips". We think that under this form it is more concise and clear.

**Comment**

-[lines 64-65]: Citations. Although the Journal allows authors to choose their citation style, it is recommended to harmonize citations. For example: Certino, 2005; Zavala et al., 2014, and not L.M. Zavala et al., 2014. Consi

**Reply**

We used an automatic reference manager (Zotero®) and these mistakes derive from this. However, we have manually checked all references and changed when necessary, according to the journal style.

**Comment**

-[line 69]: Replace "decade" with "decades". Consider the same suggestion throughout the document.

**Reply**

Done, thanks.

**Comment**

-Section 2.2. Experimental design. It is suggested to explain why different application rates (0.3 vs. 2 kg/m<sup>2</sup>) of mulch were tested. Is it because of different material densities? It is also suggested to better describe the plots configuration, were they bounded?

**Reply**

These doses are those suggested by forest services of the Iberian Peninsula, and widely used in literature (e.g., Girona-García et al., 2021; Kim et al., 2008; Lucas-Borja et al., 2019). Information added in the revised text (see lines 206-209).

**Comment**

-[line 179]. Replace "was" with "were".

**Reply**

Done.

**Comment**

-[line 185]. Replace "ration" with "ratio".

**Reply**

Done.

**Comment**

-[line 208]. Replace "root-transformation" with "root-transformed".

**Reply**

Done.

**Comment**

-[lines 252-255]. "Only the soil loss of the burned soil with higher slope was significantly different from the values detected in the burned and not treated and soils mulched with wheat straw as well as in the soils covered with wood chips at the lower slope (Figure 4)." The subject of this sentence is not clear, it is suggested to rewrite it to clarify the observation.

**Reply**

Rewritten accordingly.

**Comment**

-Figure 4: It is not clear what "all plots" series refers to or how it was calculated. If "all plots" is a mean/average between lower slope and higher slope plots, it does not make sense that its values are lower than both lower and higher plots. Please clarify.

**Reply**

Thanks for the suggestion. Yes, "all plots" refer to the mean/average between lower slope and higher slope plots, but, after a careful check, we have realised that there was a mistake in one row of the Excel data that we have corrected. Moreover, we have specified in the figure what "all plots" stands for.

**Comment**

-[lines 292-293]: "(...) neither the soil condition either the slope or both (...)". Rewrite the sentence with correct grammar.

**Reply**

Corrected.

**Comment**

-Section 4. Discussion. At the end of the discussion, it would be advisable to provide some recommendations for post-fire management in steep slopes.

**Reply**

In the Conclusions (also following the suggestions given by the other Reviewer), we have added some indications sourcing from the results of the study for land managers charged with tasks of post-fire management (see lines 544-549).

## **AUTHORS' REPLIES TO THE COMMENTS OF THE REVIEWER #2**

### **Comment**

Dear authors, This article investigates the effects of post-fire mulching (wheat straw and wood chip) on plots with two different slopes on water infiltration, surface runoff and soil loss using a portable rainfall simulator in Central-Eastern Spain. The study design is robust and the topic fits well to the scope of the journal. The manuscript is generally clearly designed, written and illustrated. Although, some concerns arise about the novelty of this manuscript, in the WORD FILE I share some questions and suggestions for changes which I would like the authors and the editor to concern before it could be considered for publication in the journal.

Best regards

### **Reply**

Dear Prof./Dr., thanks a lot for Your revision work that we have considered very useful to improve our MS. In the following text, You will find our replies to all Your comments. However, we address You to the file containing the revised paper and attached to the resubmission.

### **Comment**

Line 28. It should be shortened.

### **Reply**

We have shortened the abstract.

### **Comment**

Line 31. Please be specify about the treatment and slope classes.

### **Reply**

We have added more information about the treatment and slope classes.

### **Comment**

Line 39. Which slope?

### **Reply**

We don't understand this question, since we have specified above that we are studying two slope classes (lower vs. higher slope).

### **Comment**

Line 44. Was the percentage of soil cover covered by mulch also calculated?

### **Reply**

Yes, we have reported this percentage in Figure 4 of the original MS and mentioned it in the abstract, as required.

### **Comment**

Line 46. The results of the research should be expressed more quantitatively. Rewrite.

### **Reply**



We have added more data about the results. However, please consider that You and the other Reviewer have suggested shortening the abstract, and it is very difficult to add more information in so small space.

### **Comment**

Line 51. The introduction is very general. The results of some studies should be presented in quantitative terms.

### **Reply**

We have added a short state-of-the-art, reporting some significant studies (carried out in USA, Iberian Peninsula and Italy) about soil mulching in burned areas (see lines 93-110 of the revised MS with tracked changes).

### **Comment**

Line 97. Some studies have been conducted in Spain and Portugal, which the authors should also mention in that section.

### **Reply**

Please, see our reply to Your previous comment. The studies reported have been carried out in Portugal and Spain.

### **Comment**

Line 114. The novelty of this research is a major concern. What is your research novelty?

### **Reply**

We had justified the novelty of our study in the original MS, but, from the Reviewer's concern, we have realized that those explanations were not sufficient. Here, it is the occasion to stress this novelty. The novel aspects of our study are basically two: first, a comparison of two techniques of post-fire management on soils with two different morphological conditions (that is, the profile slope) is not frequent in literature, while the majority of studies (although not all) have compared only one technique to unburned soils. In contrast, we compared one post-fire management technique with two mulch materials, which may be useful for land managers for the choice of the most effective technique. Second, according to eminent literature, much attention has been paid to the environmental contexts of North America, while less research is available in the Mediterranean Basin. The climatic and soil conditions of these areas are particular and different from other environmental contexts. Regarding the climatic aspects, the Mediterranean areas are exposed to heavy and infrequent rainfalls that generate flash floods and intense erosion with hazard to human lives and infrastructures. Moreover, the Mediterranean forest soils are generally shallow and poor of organic matter, and therefore particularly prone to erosion risks, due to the high soil erodibility. In these areas, several studies have experimented post-fire mulching techniques. In general, the majority of these studies have reported a beneficial soil response to these treatments, while some other authors have obtained contrasting results in their experiments, of which we have reported two examples. Therefore, in our honest opinion, more research is needed to indicate whether and how much mulching is effective at controlling and mitigating the hydraulic and erosive hazards in delicate ecosystems, such as the Mediterranean forests. On this regard, the comparison of two mulch materials, such as straw and wood residues, was never compared in the Mediterranean forests, and this may be the novel aspect of our paper.

We have explained better these concepts in the revised text (see lines 121-158), hoping that this is sufficient for the Reviewer's opinion.

**Comment**

Line 134. What is the average years? Based on the data of which meteorological station? What is the distance from the study area to the station?

**Reply**

These data have been collected from the Spanish Meteorological Agency (AEMET), based on data measured at the rain gauging station of Hellín throughout the last 20 years. The distance between the study site and the meteorological station is no more than 20 km. Information added in the text (see lines 178-179).

**Comment**

Line 156. What is the reason for considering these two slope classes?

**Reply**

We have excluded soils with low slope (< 20%), since these hillslopes are less prone to erosion. Then, we have chosen micro-plots on hillslopes with a profile of more or less 30% (lower slope in our study), and extended the study with a noticeable higher steepness (+20%, therefore close to 50%). We have excluded steeper profiles, since in Castilla La Mancha, and, more in general, in Central Eastern Spain, it is uncommon that pine forests grow on so high slopes. We have added some more information in the revised text (see lines 201-203).

**Comment**

Line 159. What is the basis for applying this rate for two types of mulch?

**Reply**

These doses are those suggested by forest services of the Iberian Peninsula, and widely used in literature (e.g., Girona-García et al., 2021; Kim et al., 2008; Lucas-Borja et al., 2019). Information added in the revised text (see lines 206-209).

**Comment**

Line 162. Specifications of two types of mulch including length, width, thickness and density should be mentioned. What was the coverage percentage of these two types of mulch in the field?

**Reply**

The specifications required are the following:

- wood cheap (mean values): length: 3-10 cm; width: 2-4 cm; thickness: 1-2 cm; density: 500-550 kg/m<sup>3</sup>
- straw (mean values): length: 5-25 cm; width: 0.25-1.0 cm; thickness: 0.1-0.7 cm; density: 80-100 kg/m<sup>3</sup>.

These specifications have been added in the text (see lines 208-213).

The cover percentage of these two types of mulch are reported in Figure 4.

**Comment**

Line 172. Why is this rainfall intensity considered? Wouldn't it have been better to have rainfall intensity with a return period of thirty or fifty years?

**Reply**

We deliberately adopted this very high rainfall intensity (with a return period of more than 100 years), in order to simulate the maximum erosion risk not only in this area, but also in other sites with similar soil characteristics, but more intense precipitation (for instance, Southern Italy,

where precipitations with such depths and intensities have a much lower return period). We think that this choice goes towards an extension of the results of this investigation from the local scale to a wider international contexts. We have added some more information in the revised text (see lines 241-246).

**Comment**

Line 181. Number of repetitions in each rainfall intensity?

**Reply**

One simulation with a given rainfall depth and intensity. Information added in the text (see line 240).

**Comment**

Line 198. Why was the Pearson correlation between hydrological properties and covers not investigated?

**Reply**

Thanks for this suggestion. We have carried out a correlation analysis between the hydrological variables and soil covers, but the coefficients of Pearson have been very low for all the investigated variables. An example of this correlation analysis is reported in Figure 5, where the runoff coefficients and soil losses have been regressed on the mulch cover of the plots. We have added some more information in the revised text (see lines 350-351).

**Comment**

Line 202. Given the rainfall repetitions, why not use repeated measures analysis of variance?

**Reply**

The repeated measures analysis of variance would have been useful and more representative if we had worked with natural rainfalls or precipitations simulated with different depths and/or intensities. This is the reason why we excluded the repeated measures analysis of variance, and used a common 2-way ANOVA.

**Comment**

Line 216. Due to the lack of significance, you can not compare the rate of infiltration between treatments.

**Reply**

We totally agree with the Reviewer's opinion about the lack of significance and therefore the low significance of the comparisons. However, these comparisons are useful to give the reader an indication about the variability of the hydrological variables among soil conditions and slopes. Therefore, we would prefer to leave these comparisons as they are now. We are open to remove the related sentences, if the Reviewer still require.

**Comment**

Line 222. Figure 1 is missing.

**Reply**

Sorry for the mistake. We have renumbered the figures.

**Comment**

Line 233. Due to the lack of significance, you can not compare the runoff coefficient between treatments.

**Reply**

Please, see our reply to Your previous comment.

**Comment**

Line 265. The Pearson correlation may be better to explain rather than figure 5.

**Reply**

Please, see our reply to Your previous comment.

**Comment**

Line 273. Please be specify about the number of samples.

**Reply**

Specified.

**Comment**

Line 289. The discussion section is very general. The results of similar research should be quantitatively presented and compared with the results of the present study. Regarding the non-significance of some characteristics between treatments, the causes should be investigated by referring to previous researches.

**Reply**

According to the Reviewer's suggestion, we have compared our results with the findings of other authors working in environments with similar characteristics (see lines 469-493). About the second comment, we have added some more discussions about the reasons of this lack of significance (see lines 387-390 and 406-410).

**Comment**

Line 294. The differences are not significant.

**Reply**

Information added.

**Comment**

Line 403. The discussion part is the repetition of results. It is better to provide a general conclusion and also to provide management recommendations and implications for reducing runoff and sediment after burning in Mediterranean forests based on the results and research data.

**Reply**

We have shortened the conclusion section and added the considerations required (see lines 521-549).

1 **Effects of post-fire mulching with straw and wood chips on soil hydrology in pine forests**  
2 **under Mediterranean conditions**

3  
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18  
19 **Abstract**

20  
21 ~~Since wildfire increases the hydrological response of forest soils, eco-engineering techniques are~~  
22 ~~needed to reduce surface runoff and erosion in burned areas.~~ Mulching is one of the most common  
23 post-fire management techniques, ~~which has been particularly when vegetation residues are used,~~  
24 ~~and the effects of this technique have been widely and deeply studied at the global scale.~~ However,  
25 more research is needed on the hydrological effects of mulching in forest ecosystems under  
26 Mediterranean semi-arid conditions. ~~Targeted monitoring activities on soil mulching using different~~  
27 ~~vegetal materials must indicate the effectiveness of this eco-engineering technique at mitigating the~~  
28 ~~erosion risk in these delicate environments.~~ This study has evaluated water infiltration, surface  
29 runoff and soil loss using a portable rainfall simulator in Central-Eastern Spain after post-fire  
30 treatments. In this area, a large wildfire recently affected a pine forest, and the burned soil was  
31 mulched using wheat straw (dose of 0.3 kg/m<sup>2</sup>) or wood chips (2 kg/m<sup>2</sup>) ~~as post-fire management~~  
32 ~~action~~ on plots with two different slopes (about 30%, lower slope, and 50%, higher slope). The  
33 study has shown that ~~neither~~ the soil condition (burned control vs. soils mulched with straw or  
34 wood chips ~~burning vs. burning and mulching with two material~~) ~~or and~~ the slope (lower vs. higher)

35 ~~did not~~ significantly influence~~d~~ the water infiltration. However, the mean infiltration of the soils  
36 mulched with straw were higher (+40% and +17%, respectively) compared to both the  
37 ~~controluntreated soils~~ and the plots mulched with wood chips. Moreover, lower surface runoff (-  
38 23%) was measured in the mulched soils compared to the ~~burned and not treated~~control plots. The  
39 soil mulching with straw was more effective at decreasing the runoff coefficient (-31%) compared  
40 to ~~plots treated with the application of~~ wood chips (-18%) ~~in comparison to and~~ the ~~control~~burned  
41 ~~and not treated~~ areas. ~~The decrease in runoff was more pronounced in soils with lower slopes. The~~  
42 ~~soil treatments with mulching were particularly effective in reducing the erosion from burned~~  
43 ~~forests.~~ Soil loss was significantly lower in plots treated using straw (-87% compared to the burned  
44 and not treated soils) compared to wood chips (-54%). ~~P,~~ ~~and~~ peaks of 90-95% of reduction in the  
45 soil loss were even recorded in the steeper soils. Finally, we suggest the application of wheat straw  
46 rather than wood chips, since the wheat straw mulch material provides a higher soil cover (on  
47 average 73% against 48% of wood chips) and therefore is more indicated to reduce the hydrological  
48 response in burned soils, as confirmed by the lower runoff (in the average -16%) and erosion (-  
49 73%) measured in this experiment on both gentler and steeper soils.

50

51 **Keywords:** rainfall simulator; water infiltration; surface runoff; soil loss; erosion; post-fire  
52 management; vegetal materials mulching.

53

## 54 1. Introduction

55

56 High-intensity fires, such as the wildfires, alter many environmental components (Pereira et al.,  
57 2018; Pierson et al., 2001; Zema, 2021). Forest ecosystems are particularly threatened by the fire  
58 damage, especially in the Mediterranean areas (Moody et al., 2013; Shakesby, 2011). In forests  
59 under semi-arid conditions, the fire risk is very high, due to the frequent drought and the intrinsic  
60 properties of soils, which are generally shallow and poor in organic matter and nutrients (Cantón et  
61 al., 2011). In these areas, the climate change scenarios forecast an increase in the mean temperature  
62 and reduction in precipitation (Collins et al., 2013), which will certainly aggravate the fire risk and  
63 damage.

64 In forests affected by wildfires, the vegetation is completely removed and the soil is left bare and  
65 thus exposed to rainsplash, surface runoff and erosion (Bodí et al., 2012; ~~R.~~ Shakesby and Doerr,  
66 2006). Moreover, the wildfire heavily alter the chemical properties of soils, such as the pH,  
67 electrical conductivity, and contents of organic matter and nutrients (Alcañiz et al., 2018; Certini,  
68 2005; ~~L. M.~~ Zavala et al., 2014). Moreover, the physical characteristics of burned areas, such as soil

69 water repellency and aggregate stability, are also impacted (Arcenegui et al., 2008; Varela et al.,  
70 2010; Zema et al., 2021a, 2021b). The changes in vegetation cover and soil properties can be long  
71 lasting (~~R~~-Shakesby and Doerr, 2006; L. M. Zavala et al., 2014), and the soils burned by high-  
72 intensity fires may need several years or even decades to restore their pre-fire properties (Certini,  
73 2005; Glenn and Finley, 2010).

74 The most severe impacts of wildfires on forest ecosystems are the alteration in the hydrological  
75 response of burned soils. After fires with high severity, infiltration noticeably decreases, and surface  
76 runoff and erosion increase, often by some order of magnitude (~~R~~-Shakesby and Doerr, 2006;  
77 Zema, 2021). The alteration of soil hydrology due to high-severity fires generally result in  
78 hazardous floods and non-tolerable soil losses. These effects may extend to valley areas with  
79 possible damage of urban infrastructures and human activities (Lucas-Borja et al., 2020; Zema et  
80 al., 2020a; 2020b).

81 In order to avoid these heavy impacts, the adoption of effective post-fire management actions, both  
82 in burned hillslopes and channels draining the fire-affected catchments, is imperative. The literature  
83 proposes many soil conservation techniques for applications in burned environments. Each  
84 technique must be tailored to site and wildfire characteristics (Wittenberg et al., 2020), since its  
85 effectiveness strictly depends on the specific climatic, geomorphological and ecological conditions.  
86 Mulching is one of the most common post-fire management techniques, particularly when  
87 vegetation residues are used (Lucas-Borja et al., 2019; Prosdocimi et al., 2016). Mulch is applied to  
88 protect the soil from the rainfall impacts and help vegetation restoration (Zituni et al., 2019;  
89 Prosdocimi et al., 2016). Straw is commonly used as mulching material on burned soils, but the  
90 mulch cover can be removed by wind in some areas and become too thick in others, which hamper  
91 vegetation regeneration (Carrà et al., 2021; Robichaud et al., 2020). A possible alternative to straw  
92 is the use of forest residues, such as the wood chips, as mulch material.

93 The mulching effectiveness on the hydrological response of burned soils has been experimented in  
94 many environments. (Robichaud et al. (2013) showed that mulch treatments were effective at  
95 reducing overland flow and sediment yields as compared to the controls in wildfire-affected areas of  
96 USA. Again in this country, (Wagenbrenner et al. (2006) reported reductions in sediment yields in  
97 burned and mulched areas by at least 95% relative to the control plots, thanks to the immediate  
98 increase in the amount of ground cover in the mulched plots. Wood chip mulching reduced runoff  
99 and sediment yields by over 50% in a partially-vegetated area of South Korea, and these effects  
100 were consistent regardless of the volume of rainfall (Kim et al., 2008). Regarding the Mediterranean  
101 areas, (Carrà et al. (2022) found that soil mulching with fern residues was effective at reducing  
102 erosion in pine and oak forests of Southern Italy (up to 80%, depending on the species). In the

103 Iberian Peninsula, after a severe wildfire in Galicia (Northern Spain), the mean sediment yields in  
104 soil mulched with straw were significantly lower compared to unburned plots (0.5-0.7 against 2  
105 tons per ha, respectively) (Fernández and Vega, 2014). In Castilla La Mancha (Central Eastern  
106 Spain), reductions in surface runoff by about 10% and soil loss by around 40% were found in  
107 mulched soils in comparison to unburned plots of burned pine forests (M.E. Lucas-Borja et al.,  
108 2019). In a Portuguese eucalypt plantation, in the first post-fire year, the total soil losses were, on  
109 average, 85 and 95% lower following mulching at 3 and 8 tons per ha, respectively, than without  
110 mulching, although erosion was always under the tolerable threshold of 1 ton per ha (Keizer et al.,  
111 2018a).

112 Ample attention has been paid to the effects of an individual management action in one or few  
113 specific environments. In contrast, comparative studies of more than one technique against the  
114 negative hydrological impacts of post-fire management are lower (Zema, 2021). The comparison of  
115 more post-fire management actions in a fire-affected environment would give scientific evidence  
116 about the effectiveness of each action in a territory of given characteristics, with a special concern  
117 on the hydrological effects of the applied action. Moreover, emphasis has been given about case  
118 studies in Northern America, while much less attention has been paid to other environments, such  
119 as the landscapes of the Mediterranean Basin (Lucas-Borja et al., 2022; ~~R.~~ Shakesby and Doerr,  
120 2006). In this semi-arid environment, there is the need of specific analysis of the variables  
121 (infiltration, runoff, erosion) that govern the soil hydrology in forest ecosystems treated with  
122 different post-fire management techniques. The climatic and soil conditions of these areas are  
123 particular and different from other environmental contexts. Regarding the climatic aspects, the  
124 Mediterranean areas are exposed to heavy and infrequent rainfalls that generate flash floods and  
125 intense erosion with hazard to human lives and infrastructures. Moreover, the Mediterranean forest  
126 soils are generally shallow and poor of organic matter, and therefore particularly prone to erosion  
127 risks, due to the high soil erodibility. In these areas, several studies have experimented post-fire  
128 mulching techniques. In general, the majority of these studies have reported a beneficial soil  
129 response to these treatments, while some other authors have obtained contrasting results in their  
130 experiments. For instance, (Fernández et al. (-2012) reported a low effectiveness of soil mulching  
131 coupled to seeding on infiltration, runoff and erosion in a shrubland area in Galicia (Northern  
132 Spain), since the differences in the soil hydrological response to the treatment was not significantly  
133 different from the untreated soils (0.8 tons per ha in the seeded and mulched plots against 2.1 tons  
134 per ha in the untreated plots). (Lucas-Borja et al. (-2018) stated that straw mulching may reduce the  
135 hydraulic conductivity of soil compared to untreated soils, and particularly in the drier season. This  
136 can worsen the hydrological response of soils subjected to wildfire, with particular evidence in



137 ~~summer in the case of heavy storm occurrence. Therefore, more research is needed to~~  
138 ~~monitoring activity can~~ indicate whether and how much mulching is effective at ~~how to~~ controlling  
139 and mitigating the hydraulic and erosive hazards in delicate ecosystems, such as the Mediterranean  
140 forests. On this regard, the comparison of ~~the effectiveness of a set~~ two mulch materials, such as  
141 straw and wood residues, may help ~~of post fire management actions helps~~ landscape planners and  
142 forest hydrologists for the selection of the most suitable soil conservation measures.

143 ~~The hydrological analysis can be carried out by low requirement of money and human resources~~  
144 ~~using portable rainfall simulators. These measuring devices are able to easily quantify the~~  
145 ~~hydrological response of small areas, controlling the characteristics of the precipitation, which~~  
146 ~~furthermore can be setup at the most severe hydrological input (Iserloh et al., 2013). A limitation of~~  
147 ~~the use of small rainfall simulators is the impossibility of simulating some important physical~~  
148 ~~processes that influence runoff and erosion on hillslope or catchment scales, such as the rill erosion,~~  
149 ~~sediment deposition, and connectivity. However, the portable simulators give quick and easy~~  
150 ~~information at least about the overland flow as well as the rainsplash erosion, which are two key~~  
151 ~~mechanisms of soil hydrology as governed by fires.~~

152 To fill these research needs (comparative studies on Mediterranean burned forests treated with post-  
153 fire management techniques, and evaluation of mulching effectiveness on the hydrology of burned  
154 forests using two cover residues), In this vein, the current this study has evaluated the hydrological  
155 behaviour of soil mulched with straw or wood chips after a wildfire in a pine forest of Central-  
156 Eastern Spain. aims to integrate the common knowledge about the effects of post-fire management  
157 actions on soil hydrology of Mediterranean forests affected by severe burns. To this aim, water  
158 infiltration, surface runoff and erosion were evaluated in soils of pine forests in Central Eastern  
159 Spain, More specifically, water infiltration, surface runoff and soil loss were measured on  
160 unburned, and burned and mulched soils using a small portable rainfall simulator together with -  
161 ~~The experimental soils were recently burned by wildfires and immediately covered by mulch layers~~  
162 ~~with straw or wood chips in comparison to burned and untreated areas. Moreover, the soil covers~~  
163 (vegetation, rock, mulch, and bare soil) ~~have been surveyed in the experimental areas, to identify a~~  
164 ~~possible influence on the changes in soil hydrology due to the treatments.~~ We hypothesize that: (i)  
165 mulching is in general able to reduce runoff and erosion compared to the control soils; and (ii) this  
166 technique is more effective on the steep slopes in these semi-arid areas. Finally, the comparison  
167 between two different vegetal materials for mulching should give indications about the more  
168 advisable technique for soil conservation in burned areas.

## 170 2. Materials and methods

171

## 172 2.1. Study area

173

174 The study area is located in the municipality of Liétor (province of Albacete, region of Castilla-La  
175 Mancha, Spain, 38°30'41'' N; 1°56'35'' W) at an elevation between 520 and 770 m above the mean  
176 sea level. The climate is semi-arid (BSk type, according to the Köppen classification (Kottek et al.,  
177 2006)) with mean annual values of temperature and precipitation equal to 16.6 °C and 321 mm,  
178 respectively (weather station of Hellín, about 20 km far from Liétor, according to the historical  
179 records of the last twenty years based on the data of the Spanish Meteorological Agency, AEMET).  
180 Soils are classified as Calcic Aridisols (Nachtergaele, 2001), and its texture is sandy loamy. The  
181 study sites have a north-west aspect and mean slope between 15 and 25%. The dominant overstory  
182 vegetation consists of Aleppo pine (*Pinus halepensis* Mill.) with a shrub layer of kermes oak  
183 (*Quercus cocciferae*) (Peinado et al., 2008). Before the wildfire, the stand density and tree height  
184 were in the range 500 - 650 trees/ha and 7 - 14 m, respectively. The understory vegetation includes  
185 *Rosmarinus officinalis* L., *Brachypodium retusum* (Pers.) Beauv., *Cistus clusii* Dunal, *Lavandula*  
186 *latifolia* Medik., *Thymus vulgaris* L., *Helichrysum stoechas* L., *Stipa tenacissima* L., *Quercus*  
187 *coccifera* L. and *Plantago albicans* L. The economic value of the understory species decreased in  
188 the middle of the 20<sup>th</sup> century, resulting in abandonment of the cultivated areas, which were  
189 reforested with Aleppo pines of natural origin. Therefore, reforested and natural stands of Aleppo  
190 pine (the latter not being affected by wildfire in the last 100 years), about 60-70 years old,  
191 characterize the study area.

192 In July 2021, a wildfire burned 2500 hectares approximately in the municipality of Liétor, close to  
193 the Talave reservoir. In order to limit the expected increases in surface runoff and erosion after  
194 wildfires, the Forest Service of the Castilla La Mancha Region, applied mulching as post-fire  
195 management action. Wheat straw and wood chips were separately used as mulch materials.

196

## 197 2.2. Experimental design

198

199 One week after the wildfire, a study area of 700 ha was selected, including both unburned and  
200 burned forests, which were affected by crown fire with 100% tree mortality. In this burned area,  
201 two sites with two different profiles (low and high slope (%), 30.1 ± 3.9 and 48.1 ± 4.7,  
202 respectively) were identified. We have excluded soils with low slope (< 20%), since these hillslopes  
203 are less prone to erosion, and high slope (> 60%), where, in Central Eastern Spain, it is uncommon  
204 that pine forests grow. In each site, nine plots (three blocks with three replications), each one with

205 an area of  $0.5 \times 0.5$  meters, were installed. One block of three plots was not treated (hereafter  
206 indicated as “control”), a second block was mulched with straw (at a dose of  $0.3 \text{ kg/m}^2$ ), while, in  
207 the third block, a mulch layer of wood chips ( $2 \text{ kg/m}^2$ ) was applied. These application rates are  
208 those suggested by the forest services of the Iberian Peninsula, and widely used in literature (e.g.,  
209 (Girona-García et al., 2021; Kim et al., 2008; M.E. Lucas-Borja et al., 2019)). The main  
210 characteristics of the mulch materials were the following:

211 - wood cheap (mean values): length: 3-10 cm; width: 2-4 cm; thickness: 1-2 cm; density: 500-550  
212  $\text{kg/m}^3$

213 - straw (mean values): length: 5-25 cm; width: 0.25-1.0 cm; thickness: 0.1-0.7 cm; density: 80-100  
214  $\text{kg/m}^3$ .

215 Therefore, the experimental design consisted of three soil conditions (burned soil, soil mulched with  
216 straw, and soil mulched with wood chips)  $\times$  two slopes (low and high)  $\times$  three ~~replicates~~replicated  
217 plots, totalling 18 plots.

218

### 219 2.3. *Hydrological simulations*

220

221 The hydrological analysis can be carried out by low requirement of money and human resources  
222 using portable rainfall simulators. These measuring devices are able to easily quantify the  
223 hydrological response of small areas, controlling the characteristics of the precipitation, which  
224 furthermore can be setup at the most severe hydrological input (Iserloh et al., 2013). A limitation of  
225 the use of small rainfall simulators is the impossibility of simulating some important physical  
226 processes that influence runoff and erosion on hillslope or catchment scales, such as the rill erosion,  
227 sediment deposition, and connectivity. However, the portable simulators give quick and easy  
228 information at least about the overland flow as well as the rainsplash erosion, which are two key  
229 mechanisms of soil hydrology as governed by fires. This is the reason why soil hydrology after the  
230 post-fire treatment has been evaluated in this study using a portable rainfall simulator.

231 In each of the 18 plots identified for the three soil conditions and the two slopes, an artificial rainfall  
232 was produced using an Eijelkamp<sup>®</sup> rainfall simulator (Hlavčová et al., 2019; Iserloh et al., 2013).  
233 For these simulations and the following measurements of infiltration, surface runoff and soil loss,  
234 the methods by Bombino et al. (2019) and Carrà et al. (2021) were adopted. In detail, the simulator  
235 was placed over the ground on a surface area of  $0.3 \text{ m} \times 0.3 \text{ m}$ , caring that the mulch material  
236 applied to the soil was not disturbed by this operation. The height and intensity of the simulated  
237 rainfall was setup at  $26.7 \text{ mm}$  and  $320 \text{ mm/h}$ , while its duration was  $300 \text{ s}$ . The drop diameter and  
238 the falling height of the precipitation were  $5.9 \text{ mm}$  and  $40 \text{ cm}$ , respectively. The precipitation

239 volume in the simulator tank (about 2200 ml) was dosed by varying the pressure head, as suggested  
240 in the operating manual. Before the field experiment, the simulator was calibrated in laboratory by  
241 generating the same rainfall. One rainfall simulation per plot was carried out  
242 We deliberately adopted a very high rainfall intensity (with a return period of more than 100 years  
243 in the studied area), in order to simulate the maximum erosion risk not only in the experimental  
244 conditions, but also in other sites with similar soil characteristics, but more intense precipitation.  
245 For instance, in Southern Italy, precipitations with such depths and intensities have a much lower  
246 return period, and therefore the erosion risk has a higher frequency (Fortugno et al., 2017; Zema et  
247 al., 2022).

248 Throughout the rainfall simulation, the runoff water and sediments were collected in a small bucket  
249 and progressively measured by a meterstick. The runoff height in the bucket was read each 30 s and  
250 subtracted from the rainfall height at the same time. The mixtures of water and sediments ~~was~~were  
251 finally transported to the laboratory in small bottles, and then oven dried at 104 °C for 24 h.

252 The runoff hydrographs were built, reporting the flow rate and the cumulated volume over time.  
253 This allowed the identification of the peak flow. Moreover, the infiltration curves in each plot were  
254 determined by the difference between the runoff rate and the time interval. The mean infiltration  
255 rate was calculated as the difference between the heights of rainfall and runoff divided by the  
256 duration. The runoff coefficient was calculated as the ratio between the cumulative runoff volume  
257 and the simulated rainfall depth. The weight of the sediments was then referred to the area unit, to  
258 calculate the soil loss.

259

#### 260 2.4. *Measurement of soil covers*

261

262 To evaluate whether the changes in soil surface properties (henceforth “covers”) had impacts on soil  
263 hydrology, the vegetation, rock, mulch covers, and the bare soil in percent over the total surveyed  
264 area were also measured at the same dates as the hydrological variables. The measurements were  
265 carried out in as many areas (each 3 m long x 3 m wide, at a maximum distance of 3 m) as the plots.  
266 The grid method (Vogel and Masters, 2001) for vegetation cover, and the photographic method for  
267 the remaining variables (rock and mulch covers, and bare soil) were used. The grid method was  
268 applied, using a 0.50 x 0.50-m grid square on the sampling areas (upstream, in the middle, and  
269 downstream of each area).

270

#### 271 2.5. *Statistical analysis*

272

273 A 2-way ANOVA was separately applied to the observations of the surface runoff and soil loss, in  
274 order to evaluate the statistical significance of the differences among soil conditions and slopes, and  
275 their interactions. The surface runoff and soil loss were the dependent variables, while the soil  
276 condition and slope were the independent factors. The differences in the two hydrological variables  
277 among factors were evaluate using the pairwise comparison by Tukey's test (at  $p < 0.05$ ). The  
278 equality of variance and normal distribution are assumptions of the statistical tests; these  
279 assumptions were evaluated by normality tests or were square root-transformed~~ation~~, when  
280 necessary. The statistical analysis was carried out using the XLSTAT software (release 2019,  
281 Addinsoft, Paris, France).

282

### 283 **3. Results**

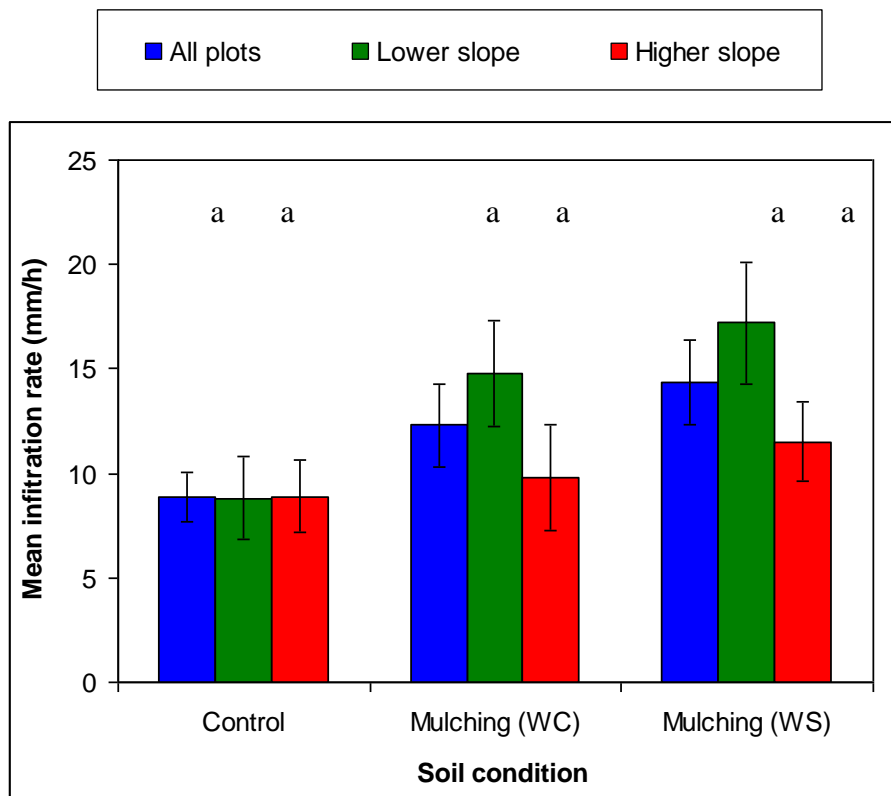
284

285 The differences in the mean infiltration rates among the soil conditions and slopes were never  
286 significant. In more detail, in the burned soils (assumed as control), the infiltration rates were  $8.82 \pm$   
287  $2.01$  and  $8.90 \pm 1.70$  mm/h for the lower and higher slopes, respectively. These rates were higher in  
288 the treated soils,  $14.8 \pm 2.55$  (lower slope) and  $9.8 \pm 2.55$  (higher slope) mm/h in soils supplied with  
289 wood chips, and  $17.2 \pm 2.91$  (lower slope) and  $11.5 \pm 1.91$  (higher slope) mm/h in areas mulched  
290 with wheat straw (Figure [12](#)).

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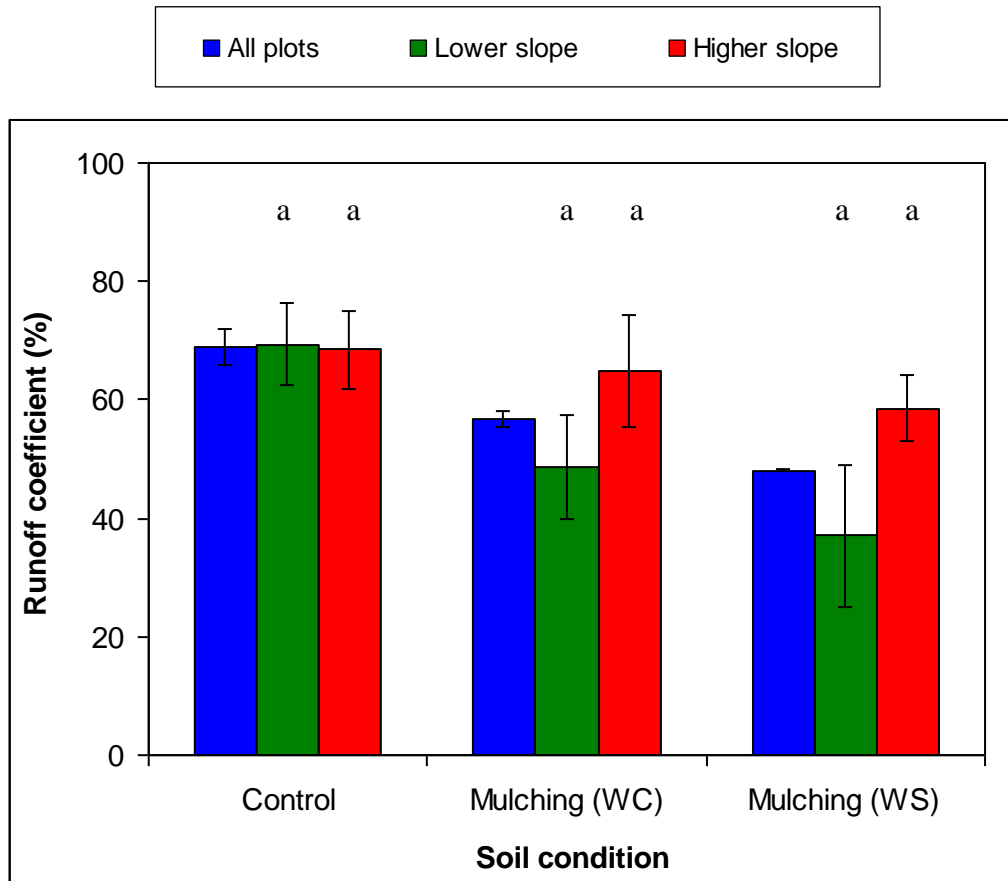
312

Figure 12 – Water infiltration rate (mean ± std. error) measured by a portable rainfall simulator under three conditions (control, mulched with wood chips, WC, or wheat straw, WS) and two slopes of forest soils (Liétor, Castilla La Mancha, Spain). Different letters indicate significant differences among soil conditions and slopes after Tukey’s test ( $p < 0.05$ ); “all plots” stand for the mean value between lower slope and higher slope plots.

The infiltration rates decreased over time (although not being this increase monotonical) (Figure 1SM). Figure 2SM reports the cumulative runoff volumes measured under the three soil conditions and slopes, while the runoff rates are depicted in Figure 3SM. These rates increased over time until the peak, and then decreased until the steady-state values.

For the runoff coefficients, no significant differences were detected among the soil conditions and slopes. The runoff coefficient of the control plots was  $69.4 \pm 6.98\%$  (lower slope) and  $68.5 \pm 6.52\%$  (higher slope). These coefficients decreased in the soils treated with wood chips ( $48.6 \pm 8.87\%$  at the lower slope and  $64.7 \pm 9.49\%$  at the higher slope) and mainly in the areas mulched with wheat straw ( $37 \pm 11.9\%$  at the lower slope and  $58.6 \pm 5.57\%$  at the higher slope (Figure 32).

313



314

315 Figure 23 – Runoff coefficients (mean  $\pm$  std. error) measured by a portable rainfall simulator under  
316 three conditions (control, mulched with wood chips, WC, or wheat straw, WS) and two slopes of  
317 forest soils (Liétor, Castilla La Mancha, Spain). Different letters indicate significant differences  
318 among soil conditions and slopes after Tukey’s test ( $p < 0.05$ ); “all plots” stand for the mean value  
319 between lower slope and higher slope plots.

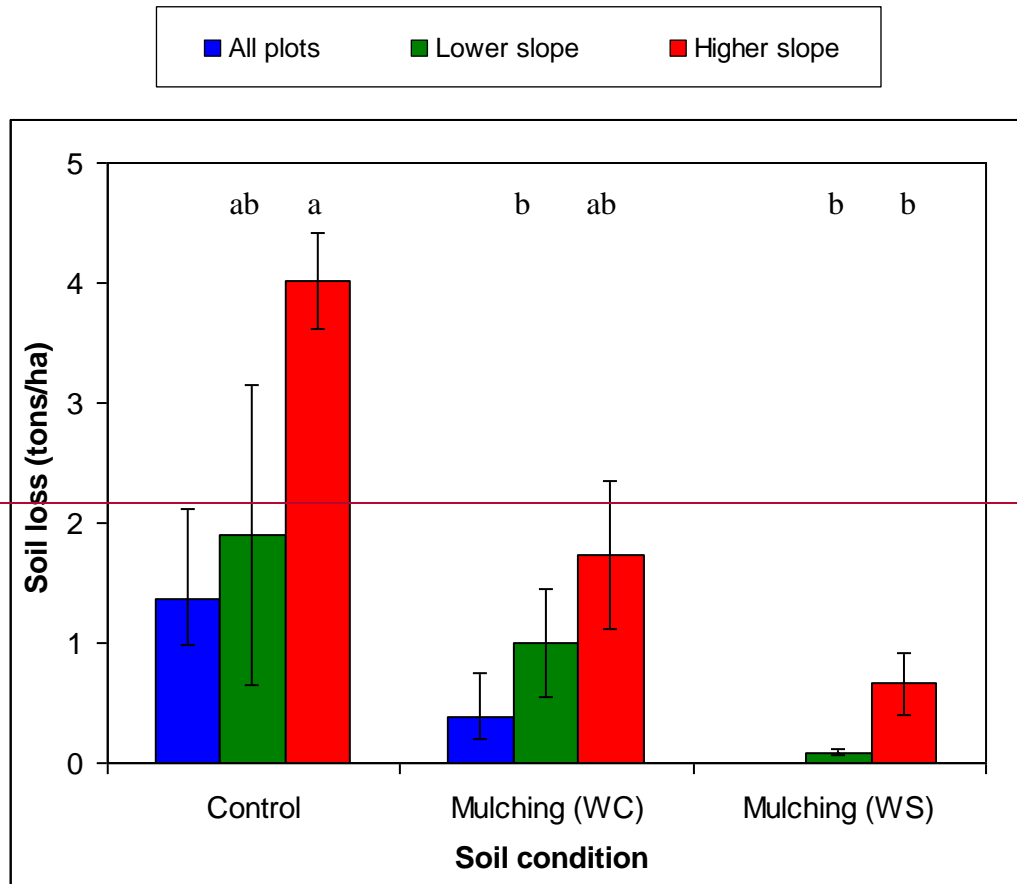
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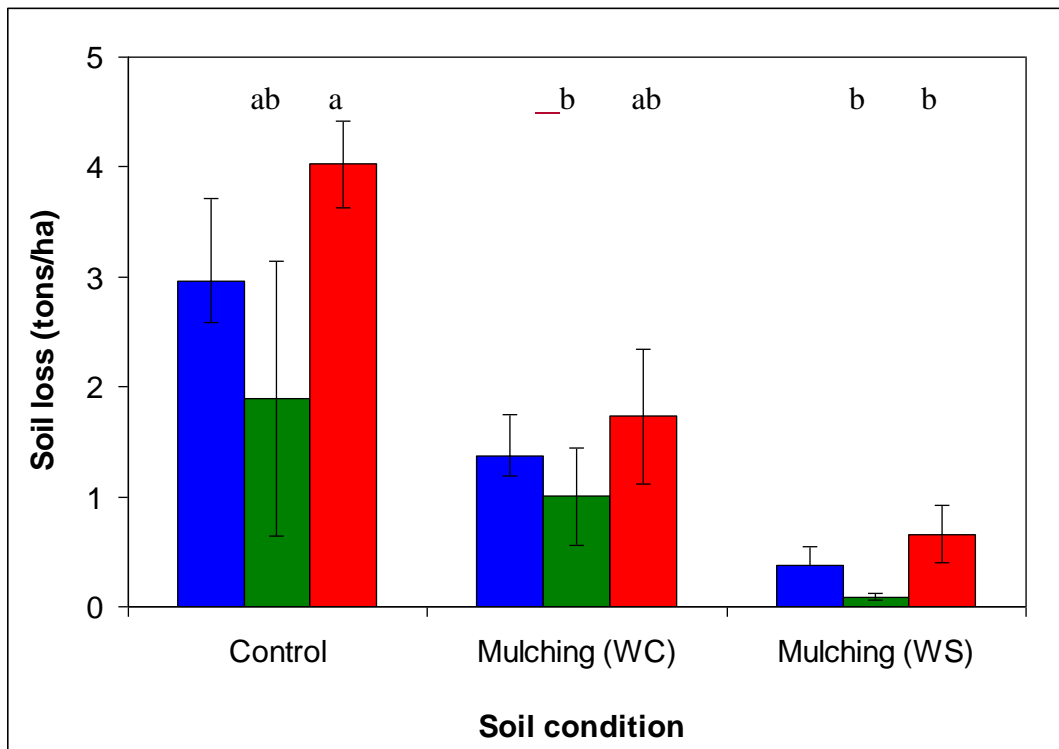
322 The statistical analysis shows that the difference in the measured erosion values were significant  
323 between the mulched and the burned and not treated soils, but not between the latter and the soils  
324 covered with wood chips. In contrast, the difference in the soil loss between the two slopes were  
325 always significant. The control soils showed the highest soil losses,  $1.90 \pm 1.25$  and  $4.02 \pm 0.40$   
326 tons/ha, for lower and higher slopes, respectively. The erosion decreased in the plots treated with  
327 wood chips ( $1 \pm 0.45$ , lower slope, and  $1.73 \pm 0.61$ , higher slope, tons/ha), and mainly in the areas  
328 mulched with wheat straw ( $0.09 \pm 0.03$ , lower slope, and  $0.66 \pm 0.26$ , higher slope, tons/ha). Only  
329 the soil loss of the burned soil with higher slope was significantly different from ~~the values detected~~  
330 ~~in (i) the burned and not treated soils; (ii) and the soils mulched with wheat straw; and (iii) as well as~~  
331 ~~in~~ the soils covered with wood chips at the lower slope (Figure 34).

332

333



334



335

336 Figure 34 – Soil losses (mean ± std. error) measured by a portable rainfall simulator under three  
337 conditions (control, mulched with wood chips, WC, or wheat straw, WS) and two slopes of forest  
338 soils (Liétor, Castilla La Mancha, Spain). Different letters indicate significant differences among



339 soil conditions and slopes after Tukey's test ( $p < 0.05$ ); “all plots” stand for the mean value between  
340 lower slope and higher slope plots.

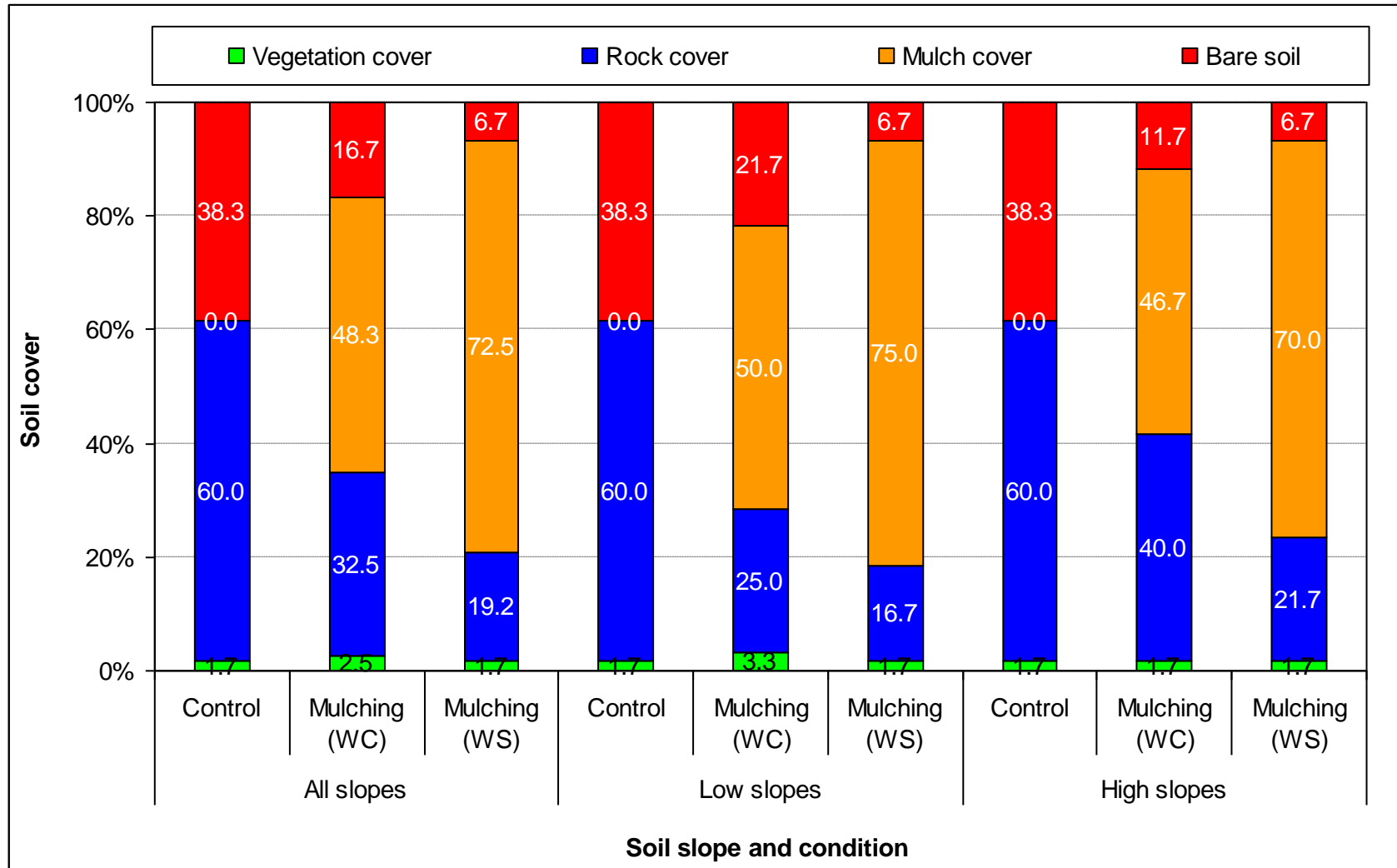
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342

343 The measurement of the soil covers revealed that the vegetation cover was quite limited in all plots  
344 (lower than 3.3%), while the bare area was from 6.7% (soils mulched with straw at both slopes) to  
345 38.3% (control soils, also in this case at both slopes). The rock cover was 60% in the control plots  
346 (at both lower and higher slopes), from 25% (lower slope) to 40% (higher slope) in the areas treated  
347 with wood chips, and 70% and 75%, for lower and higher slopes, respectively, in the soils mulched  
348 with straw. The mulch cover, which was absent in the control plots, was variable between 46.7%  
349 (higher slope) and 50% (lower slope) in the soils treated with wood chips, and between 70% (higher  
350 slope) and 75% (lower slope) in the plots mulched with straw (Figure 45).

351 By regressing using a linear equation each hydrological variable on the different soil covers, low  
352 coefficients of regression were found ( $r^2 < 0.35$ ). More specifically, ~~N~~o evident and significant

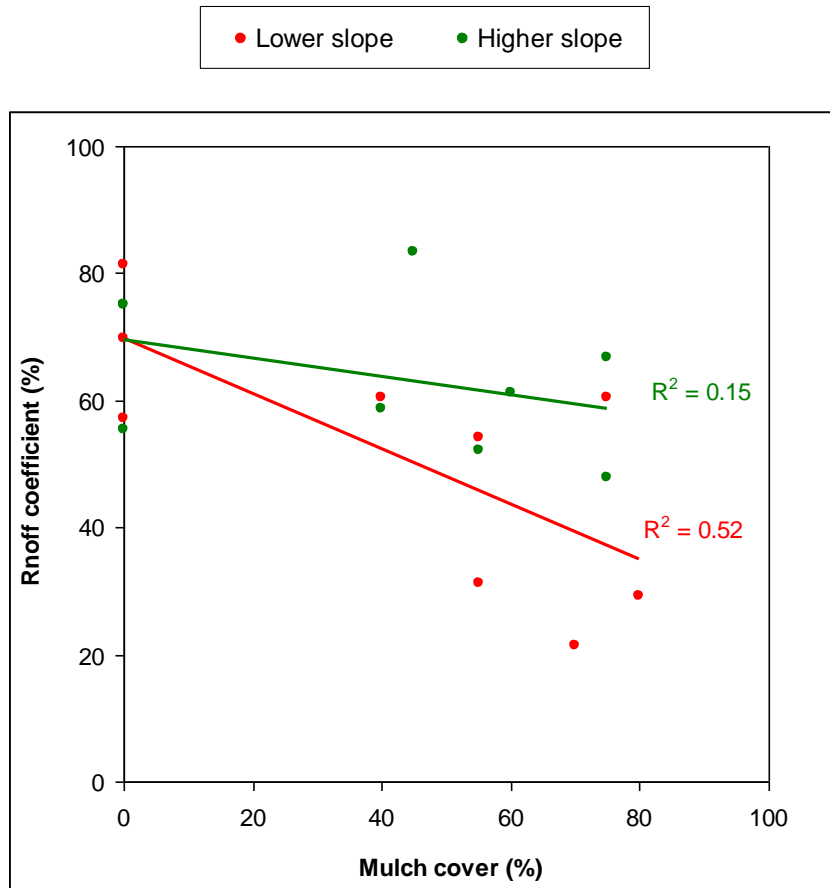
353 correlations were found between the runoff coefficients and soil losses on one side, and the soil  
354 covers on the other side ( $r^2 < 0.52$ ); the only exception was the regression between the soil loss and  
355 the mulch cover in soils with higher slopes ( $r^2 = 0.85$ , Figure 56).



356

357 Figure 45 – Soil covers (in % on the total plot area) measured under three conditions (control, mulched with wood chips, WC, or wheat straw, WS)  
 358 and two slopes in the studied forest (Liétor, Castilla La Mancha, Spain).

359

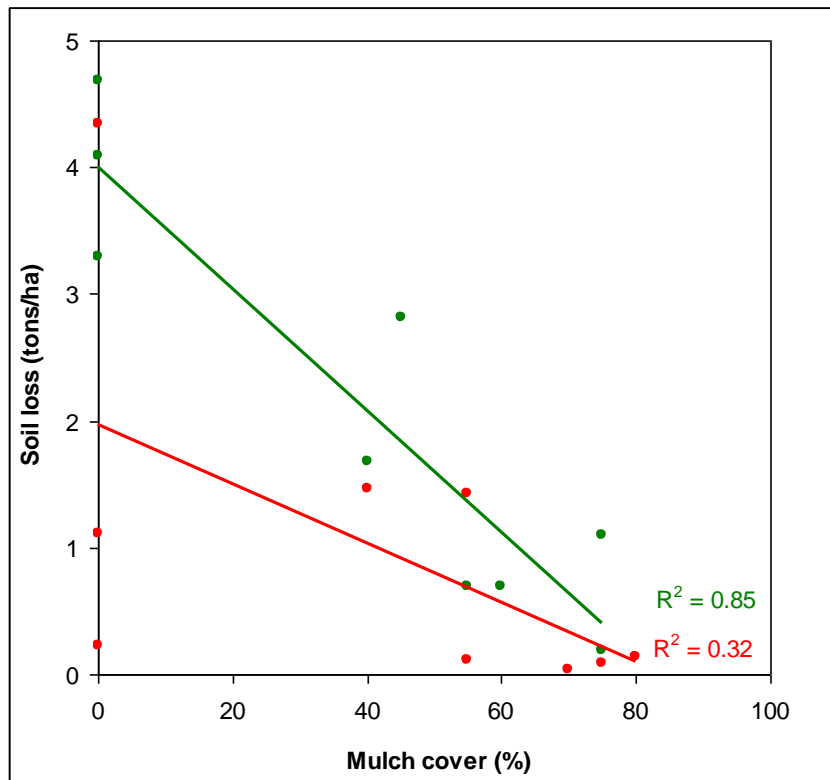


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361

362

(a)



363

364

(b)

365 Figure 56 – Correlations between the mean runoff coefficients (a) and soil losses (b), and the mulch  
366 cover measured on soils (number of plots = 3) under three conditions (control, mulched with wood  
367 chips, WC, or wheat straw, WS) and two slopes in the experimental forest (Liétor, Castilla La  
368 Mancha, Spain).

369

#### 370 4. Discussions

371

372 The experimental monitoring of soils burned by a wildfire and then treated with two post-fire  
373 management techniques (mulching with straw or wood chips) revealed that ~~neither~~ the soil  
374 condition ~~and~~ either the slope or both factors did not significantly influence the water infiltration.  
375 However, the mean infiltration rates measured in the soil mulched with straw were higher compared  
376 to the untreated soils, with differences of 39% (for wheat straw) and 62% (for wood chips)  
377 (although these differences were not statistically significant). In general, the application of straw  
378 was more effective, since the increase in the infiltration rates of soils mulched with this material  
379 was about higher by 15% compared to the mulching with wood chips. Moreover, this increase was  
380 more pronounced for soils with lower slopes; for instance, in the case of mulching with straw, the  
381 mean infiltration rate decreased by 95% in the milder hillslopes against a maximum value of 29%  
382 for the treatment of the steeper soils. The lack of significance of differences in water infiltration  
383 among the soil conditions and slopes is somewhat expected, since the mulch application does not  
384 alter the physical properties of the soil surface, on which infiltration depends (Prosdocimi et al.,  
385 2016). In other words, the time elapsed from the mulch application until the infiltration  
386 measurements was too low for the incorporation of the vegetal material of degrading mulch cover.  
387 The latter, for instance, may have instead altered the organic matter content of soil and therefore its  
388 macroporosity and aggregate stability (Bombino et al., 2021, 2019). According to (Carra et al.,  
389 2021; Carrà et al., 2022), who found a limited effectiveness of mulching one year after fire on the  
390 hydrological response of burned soils, it is necessary to wait some months from fire to achieve non-  
391 significant differences between treated and untreated soils.

392 In our experimental plots, the infiltration followed a temporal decrease from the start of the rainfall  
393 simulation until the steady-state values. This is in accordance with (Carrà et al., 2021), who found  
394 the maximum infiltration rates near the rainfall onset, and a progressive decrease through the  
395 simulation. This may indicate an effect of soil water repellency, which gradually disappeared with  
396 the soil wetting, and the subsequent quick infiltration through preferential flow paths into wettable  
397 layers (DeBano, 1981).

398 The variability of infiltration explains the variations in the runoff response among the studied soil  
399 conditions and slopes. As expected, the increase in water infiltration detected for the mulched soils  
400 resulted in lower surface runoff compared to the ~~burned and not treated~~control plots, although the  
401 differences were not significant between the different soil conditions and slopes. The soil mulching  
402 with straw decreased the runoff coefficient by 31%, and this decrease was close to 20% for the soils  
403 mulched with wood chips. As the trend measured for the infiltration rates, the runoff generation in  
404 the plots with lower slope was reduced compared to the steeper soils, as shown by the reductions in  
405 the runoff coefficients (-70% to -80% for the soils mulched with wood chips or straw, respectively).  
406 The noticeable reduction in runoff volume between the mulched soils and the burned plots without  
407 any treatments can be attributed to the presence of vegetal residues on the plot surface. The lack of  
408 significance in runoff among the three soil conditions agrees with the findings reported by  
409 (Fernández et al., 2012). This work is an example of soil mulching with low effectiveness on runoff  
410 and erosion from burned shrublands of Northern Spain after an experimental fire and rainfall  
411 simulations, which did not noticeably affect runoff and infiltration.  
412 ~~More specifically~~In our study, mulching resulted in two important hydrological effects. First and  
413 mainly, the mulch cover retains part of the rainwater, which evaporates and thus reduces the  
414 hydrological response of the soil. In these plots, the rock cover and the bare area are much higher  
415 compared to the treated areas, whose surface is covered by 50-70% of the mulch material. In  
416 contrast, in the ~~burned and not treated~~control areas, the wildfire has temporarily reduced the  
417 evaporation and interception of rainfall (~~R.~~Shakesby and Doerr, 2006), since the shrub layer and  
418 litter covers were almost totally removed. Although not measured in this study, some important soil  
419 properties (such as repellency level, contents of soil organic matter, minerals and macro-nutrients  
420 (Alcañiz et al., 2018; ~~R.~~Shakesby and Doerr, 2006; ~~L. M.~~Zavala et al., 2014)) could have been  
421 significantly modified by the high-severity fire, and noticeable effects of these changes on soil  
422 hydrology may be expected. Furthermore, the presence of the vegetal residues could have also  
423 affected the runoff rate, since the wood chips or the twigs of the straw mulch slowdown the velocity  
424 of the water stream compared to the burned soil (Lucas-Borja et al., 2022). This effect is more  
425 pronounced in the soil at lower slope that were mulched with wheat straw, due to the higher mulch  
426 cover. The presence of obstacles on the runoff paths increases the travel times of the water stream  
427 on soil surface. Therefore, the time to peak for the formation of the floods is reduced (Zhao et al.,  
428 2016), especially in steeper soils, which are more exposed to the flooding risks in valley areas.  
429 Secondly, the variations in the hydraulic conductivity, although not being significant, may also be  
430 another reason of the differences measured in the soil's hydrological response between the mulched  
431 and untreated areas. An increased water infiltration results in a consequent reduction in the runoff

432 rates. As outlined above, a longer time between the time elapsed from mulch application and the  
433 hydrological measurements should have evidenced a further decrease in the runoff response of the  
434 treated soils, due the mulch degradation and improvement of physical properties of the burned soils.  
435 The general reduction in the hydrological response of the investigated fire-affected areas has  
436 demonstrated how and by what extent the presence of a vegetal cover on the burned soil is  
437 beneficial to reduce the overland flow after precipitation. Also other authors (e.g., Cerdà and Doerr,  
438 2008; Prats et al., 2012) reported a decrease in the surface runoff with increasing covers of dead or  
439 living vegetation as mulch materials.

440 The soil treatments with mulching were particularly effective in reducing the erosion. If averaged  
441 between the two soil slopes, the decrease in the soil loss from the plots treated with wood chips was  
442 lower by 73% compared to the control, and this percentage significantly increased up to 87% in the  
443 case of straw mulch application. Peaks of 90-95% of reduction in the soil loss were even recorded  
444 in the steeper soils. The differences in the effectiveness of the two soil treatments between lower  
445 and steeper slopes were -12% and -35% (both not significant) for mulching with wheat straw and  
446 wood chips, respectively. This reduction was statistically significant compared to the corresponding  
447 control only for the steeper soils mulched with wheat straw (-84%).

448 The beneficial effect of mulching on erosion compared to the ~~burned and not treated control~~ area is  
449 due to the soil protection exerted by the vegetal materials, which prevented the raindrop impact and  
450 sediment entrainment by the overland flow (~~R. A.~~ Shakesby and Doerr, 2006). In the mulched plots,  
451 the portion of the soil surface protected from the rainfall erosivity (due to the presence of the mulch  
452 material or vegetation) and the non-erodible area (covered by rock) was much higher compared to  
453 the ~~burned and not treated control~~ plots, which explain the lower erosion rates. The higher soil losses  
454 detected in the latter soil condition is typical of wildfire-affected areas, where sediment detachment  
455 is enhanced, due to the vegetation removal by fire as well as to the decrease in aggregate stability,  
456 which is typical of the burned areas (Cawson et al., 2012; Moody et al., 2013; ~~L. M. M.~~ Zavala et  
457 al., 2014).

458 Another important consideration raises up from the very high intensity of the simulated rainfall  
459 event. This intensity is typical of an extremely erosive event with a return interval of many years.  
460 After the rainfall simulation, a maximum soil loss of over 4 tons/ha was observed in the burned area  
461 with the highest slope. If we consider that these events may be more than two or three throughout a  
462 hydrological year, it is evident that the wildfire-affected areas of the Mediterranean forests, if not  
463 protected, may be exposed to non-tolerable erosion rates (over 10-12 tons/ha-year for the  
464 agricultural areas, which generally show higher erosion compared to forestland) (Bazzoffi, 2009;  
465 Wischmeier, 1978). In our experiments, soil mulching reduced this erosion rate by a factor of 2-3 in

466 the case of mulching with wood chips, and by 20 on gentler profiles or six on the steeper slopes,  
467 when straw was used as mulch material. Therefore, in mulched soils, the erosion risk is much lower  
468 compared to the ~~burned and not treated~~control soils, and this demonstrates the effectiveness of these  
469 practices of soil conservation in forest areas.

470 Our results are in close agreement with several literature studies that have evaluated soil hydrology  
471 after post-fire mulching. The reductions in soil erosion observed in our study (about 90% in the  
472 plots mulched with straw and 50% in the soils treated with wood chips) are higher compared to the  
473 values reported by (M.E. Lucas-Borja et al., 2019) in the same environment (decrease in soil  
474 erosion by 42% on average), presumably due to the fact that, in that investigation, the soil was  
475 disturbed by other treatments (salvage logging and machinery application). Similar reductions in  
476 soil loss (-85% and -90%) as in our study were also detected by (Keizer et al. (,2018a) and (Prats et  
477 al. (,2016) in treated eucalypt forests of Northern Spain and Central Portugal, respectively.  
478 However, in the study by (Keizer et al., (2018a), the burned soil was mulched with straw at the  
479 same application dose as in our experiment. In the investigation by (Prats et al. (,2016), forest  
480 residues were used as mulch material, but at a halved application dose (10.8 tons/ha) compared to  
481 our study (20 tons/ha). Also (Lopes et al. (,2020) found that soil mulching with wood residues  
482 (application doses between 3 and 8 tons/ha) was effective at reducing the soil erosion, recording  
483 percentages between 70 and 95% of decreases in soil loss after a wildfire burning in a forest stand  
484 of Central Portugal. These authors have indicated the possibility to decrease the application doses of  
485 wood residues without a significant decline in mulching effectiveness on erosion. Their results  
486 should be considered when chipped forest residues are used, such in our study (which used a  
487 noticeable dose). The use of fern residues, tested by (Carrà et al., (2022) in semi-arid forests of  
488 Southern Italy at a dose of 2 tons/ha, reduced erosion by 30% to 80% (thus less than in our study),  
489 but mulching was applied on soils burned by a prescribed fire. The erosion measured in our plots  
490 mulched with straw (0.38 tons/ha) is comparable to the values reported by (Fernández and Vega,  
491 (2014) (0.5 tons/ha), although the climatic conditions are different (semi-arid climate vs. humid  
492 conditions). Our soil loss is however higher compared to the soil loss reported by (Fernández et al.  
493 (,2012) (0.2 tons/ha, again under humid conditions), and this should be due to the low soil  
494 erodibility of those experimental soils.

495 A possible limitation of this study is the only use of simulated rainfall. Compared to the natural  
496 precipitation, the kinetic energy of rainfall is lower under artificial conditions and the rainsplash  
497 erosion is therefore underestimated; moreover, the runoff detachment due to the overland and rill  
498 flows is not evaluated by small devices (Hamed et al., 2002; Loch et al., 2001). However, in this  
499 study the erosion rates at the event scale measured for the burned and mulched areas (up to 1-2

500 tons/ha) are well below the limits of hazardous erosion. Therefore, the difference between the  
501 tolerance limits mentioned above and the experimental values is too high to make unrealistic this  
502 rough comparison.

503 Overall, this investigation has shown that the forest areas burned by wildfires may be subjected to  
504 noticeable erosion, which requires a careful monitoring of this soil condition, to avoid severe on-site  
505 and off-site effects, if the erosion is not properly controlled. This risk becomes urgent on steeper  
506 hillslopes, where the erosion rates can be two-fold compared to the gentler profiles, as in the  
507 experimental conditions. Moreover, these rates can be even higher, considering the limitations of  
508 measurements in small plots and under simulated rainfalls. Effective post-fire actions must be  
509 applied in the burned areas immediately after the wildfire (that is, in the so-called “window-of-  
510 disturbance” (Prosser and Williams, 1998)). In this period, erosion is much higher compared the  
511 unburned areas due to the fire effects (Keizer et al., 2018b; Wilson et al., 2018), since the soil lacks  
512 the protection of the vegetation cover and the entity of the fire-induced changes in soil properties is  
513 the highest over time (Zema, 2021; Lucas-Borja, 2021). This investigation has demonstrated that, in  
514 terms of land management, soil mulching (preferably using straw to achieve the optimal soil  
515 protection) is particularly effective to control the erosion in the burned area left bare by fire, and  
516 this result confirm the first working hypothesis, at least with regard to soil erosion. Moreover, soil  
517 mulching with wood chips and mainly with straw is especially effective on hillslope with gentler  
518 profiles, and therefore the second working hypothesis of our study should be rejected.

## 520 5. Conclusions

521  
522 This study has ~~monitored water infiltration, surface runoff and soil loss using a portable rainfall~~  
523 ~~simulator in Central Eastern Spain, where a large wildfire affected a pine forest and soil mulching~~  
524 ~~with wheat straw or wood chips was carried out as post fire management action on plots with two~~  
525 ~~different slopes. Neither the soil condition (burning vs. burning and mulching with two material) or~~  
526 ~~the slope significantly influenced the water infiltration. However, the mean infiltration of the soils~~  
527 ~~mulched with straw were higher compared to both the untreated soils and the plots mulched with~~  
528 ~~wood chips. Due to the variability of infiltration, lower surface runoff was measured in the mulched~~  
529 ~~soils compared to the burned and not treated plots. demonstrated that The soil mulching with straw~~  
530 ~~is was~~ more effective at decreasing the runoff coefficient compared to the application of wood chips,  
531 ~~particularly . Moreover, the decrease in runoff was more pronounced in soils withon gentler lower~~  
532 ~~slopes. Both The soil treatments with mulchingusing straw and wood chips were particularly~~  
533 effective in reducing the erosion from burned forests, but, a. Also for the soil loss, erosion was



534 significantly lower in plots treated using straw compared to wood chips, ~~and peaks of 90-95% of~~  
535 ~~reduction in the soil loss were even recorded in the steeper soils.~~ The beneficial effects of soil  
536 mulching in burned areas may be ascribed to the presence of vegetal residues on the soil surface,  
537 which: (i) retains part of the rainwater, decreasing the rainfall input on the soil and therefore the  
538 surface runoff; (ii) shadows the soil from the rainfall erosivity, reducing the rainsplash erosion and  
539 therefore the soil loss. The results confirmed that mulching is able to reduce runoff (although not  
540 significantly) and erosion (in this case significantly) compared to the burned and not treated soils.  
541 Therefore ~~Meanwhile, the runoff coefficient and soil loss were lower in the lower slopes compared~~  
542 ~~to the steeper soils.~~ Finally, we suggest to land managers the application of wheat straw rather than  
543 wood chips, since the first mulch material provides a higher soil cover and therefore is more  
544 indicated to reduce the hydrological response in burned soils, ~~as confirmed by the lower runoff and~~  
545 ~~erosion measured in this experiment on both gentler and steeper soils.~~ In contrast, when the specific  
546 objective of the post-fire management is the control of surface runoff against the flooding risk in  
547 valley area, alternatives to the use of mulching should be advised, since straw or wood chips are  
548 more effective at reducing erosion rather than surface runoff. Finally, no lower application doses of  
549 wood chips should be beneficial, since the effectiveness of this mulch material is reduced compared  
550 to other studies.

551

552 **Declaration of Competing Interest**

553

554 The authors declare no known competing financial interests.

555

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557

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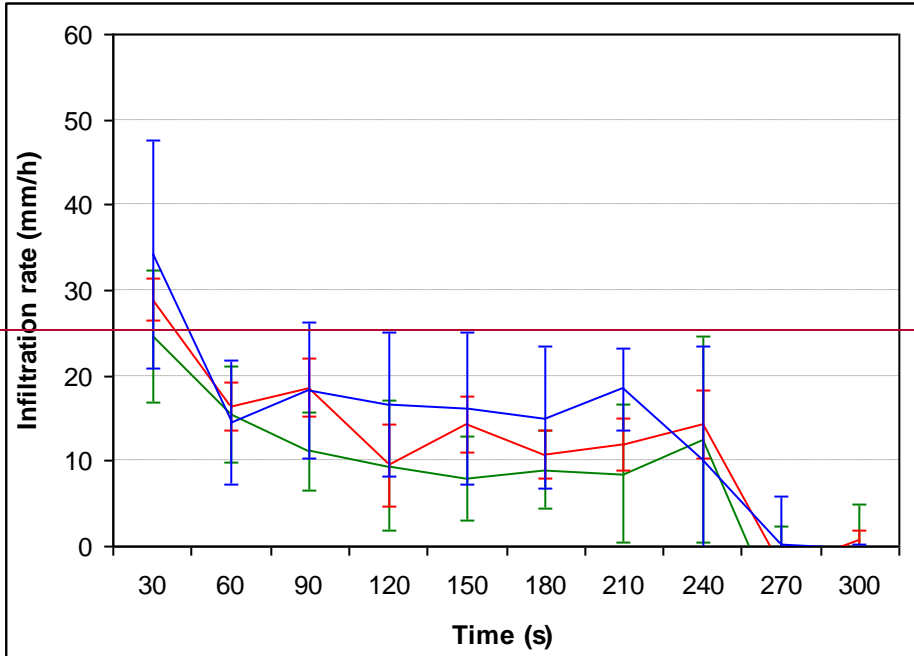
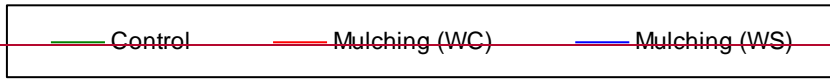
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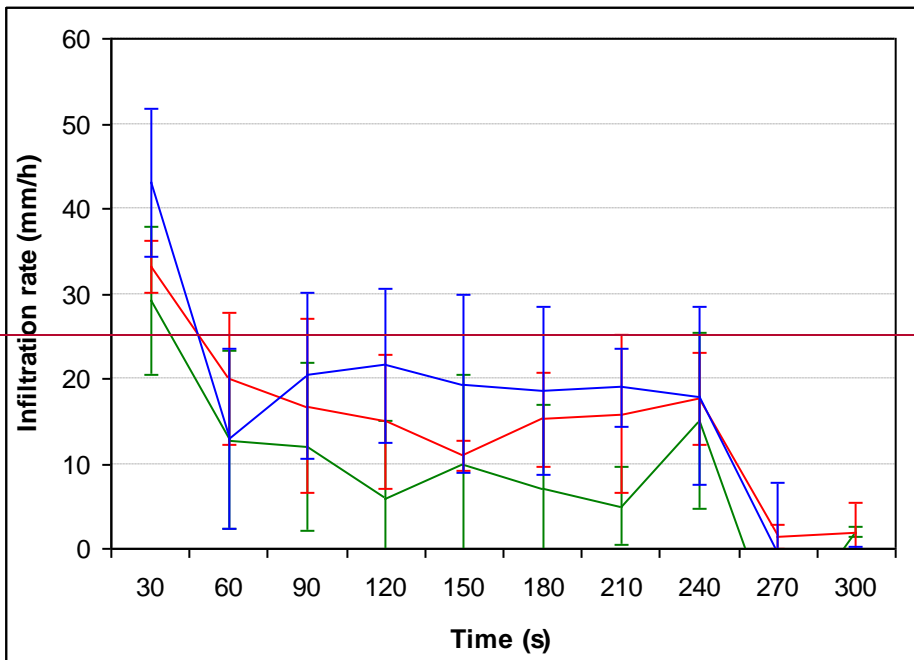
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763 **SUPPLEMENTARY MATERIAL**

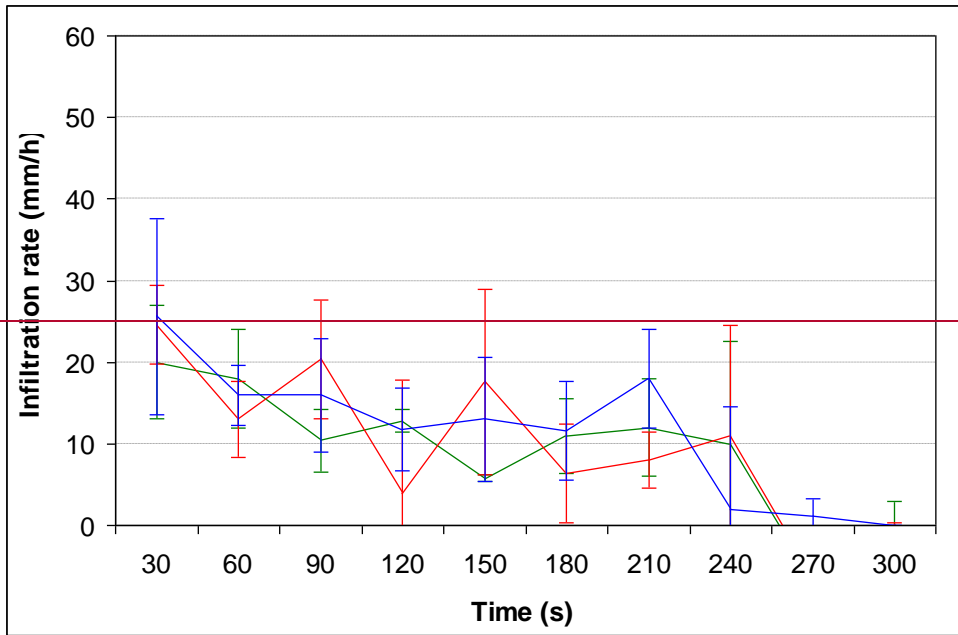


766  
767 (all plots)



769  
770 (lower slope)

771



772

773 (higher slope)

774

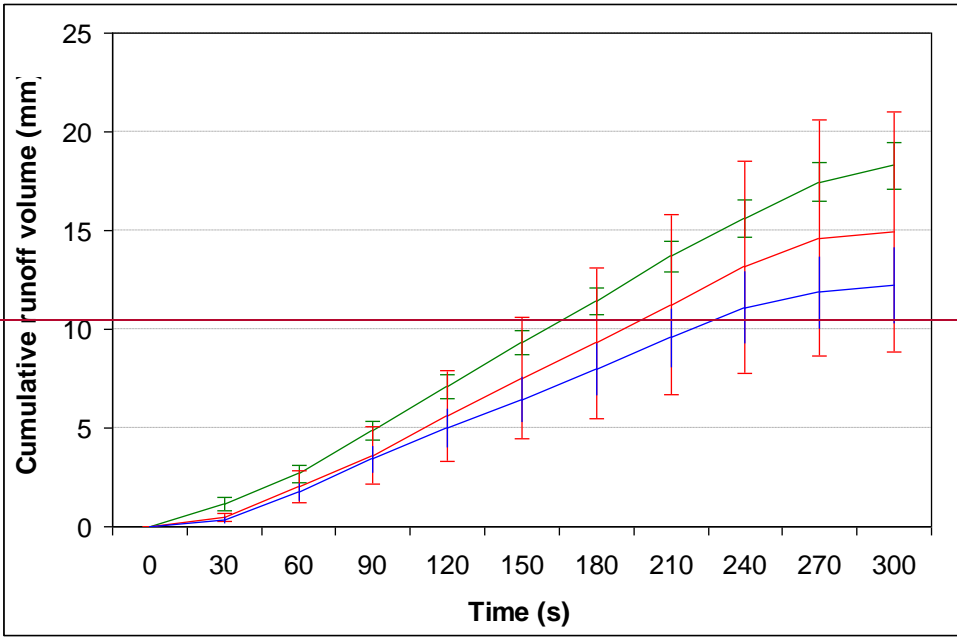
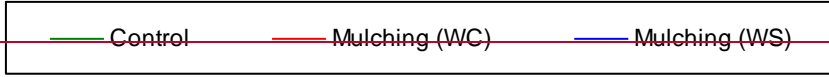
775 **Figure 1SM** — Water infiltration curves (mean  $\pm$  std. error) measured by a portable rainfall simulator

776 under three conditions (control, mulched with wood chips, WC, or wheat straw, WS) and two

777 slopes of forest soils (Liétor, Castilla La Mancha, Spain).

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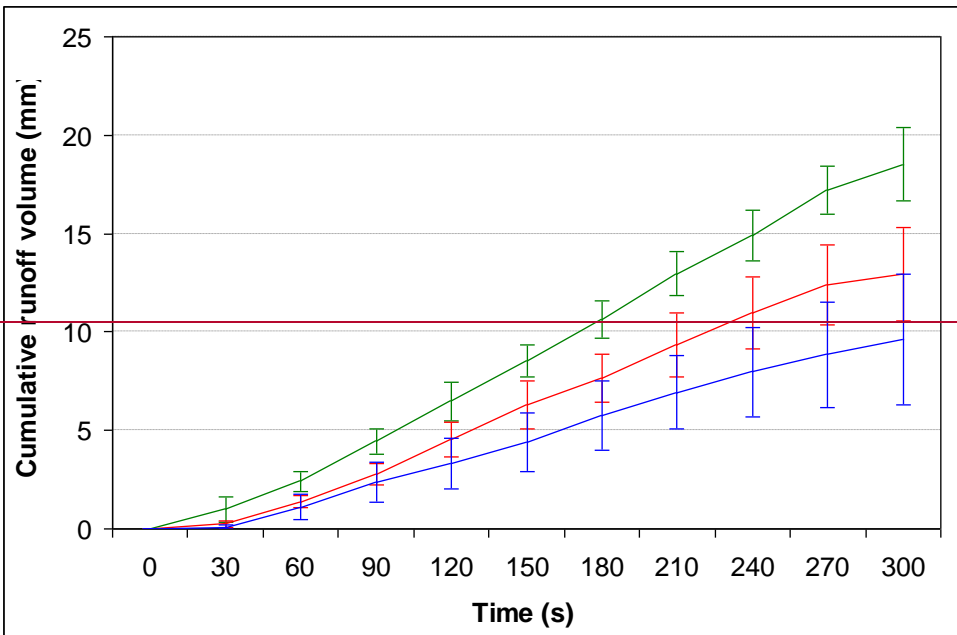


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(all-plots)

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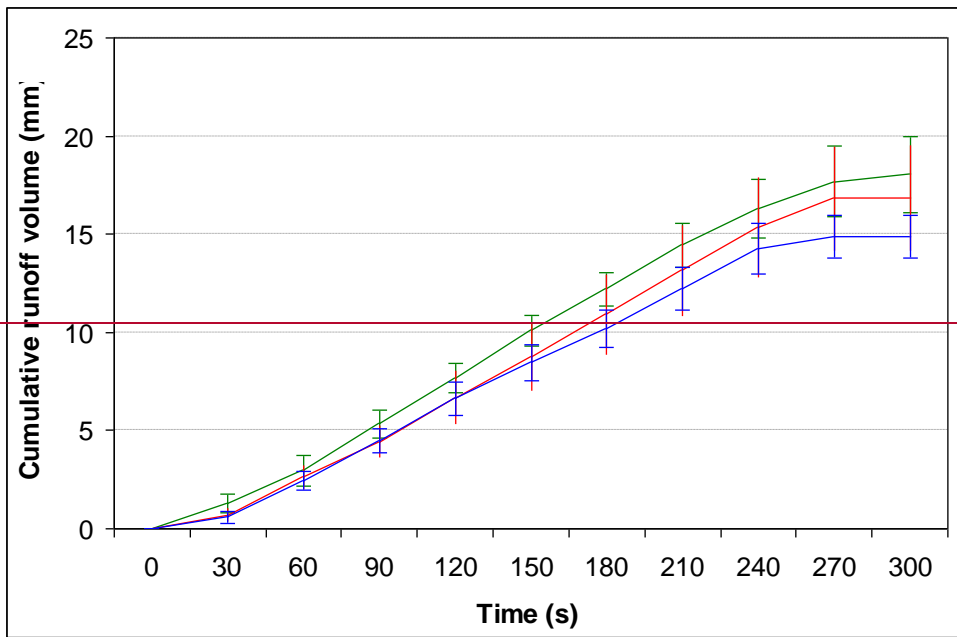


783

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(lower slope)

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(higher slope)

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789

Figure 2SM — Cumulative surface runoff volumes (mean  $\pm$  std. error) measured by a portable rainfall simulator under three conditions (control, mulched with wood chips, WC, or wheat straw, WS) and two slopes of forest soils (Liétor, Castilla La Mancha, Spain).

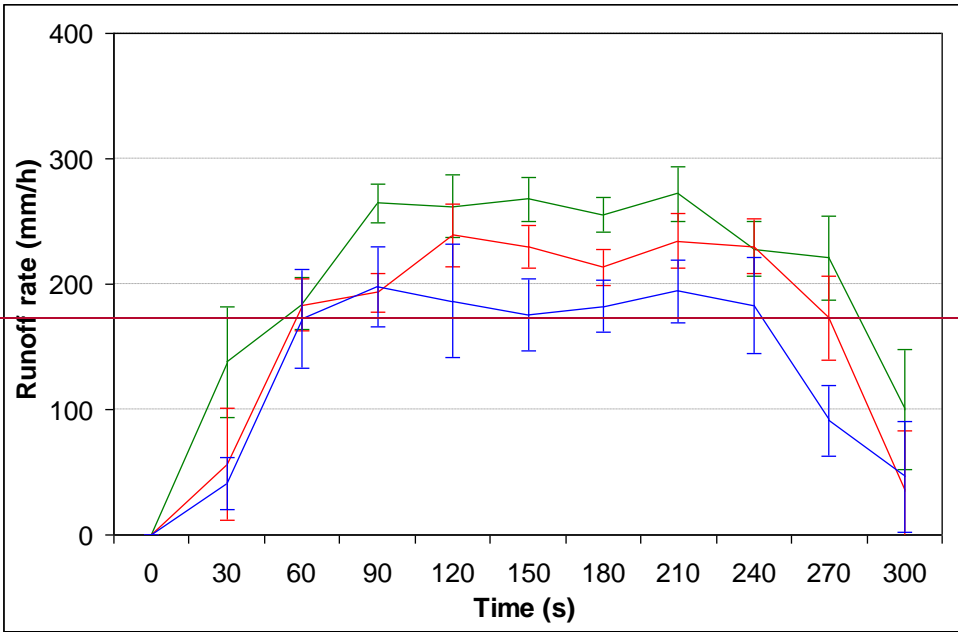
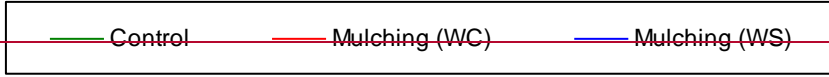
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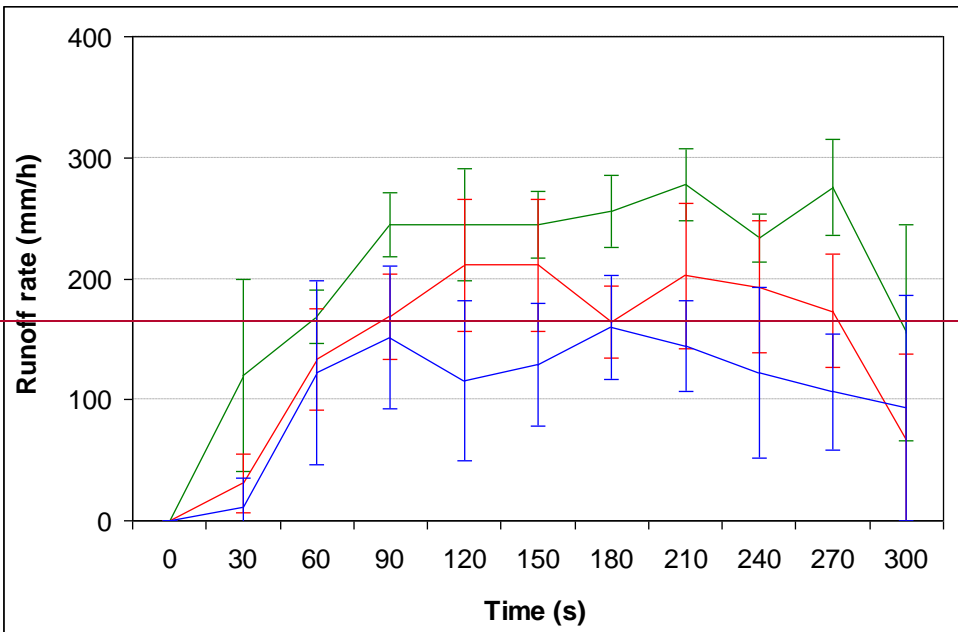
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796 (all plots)

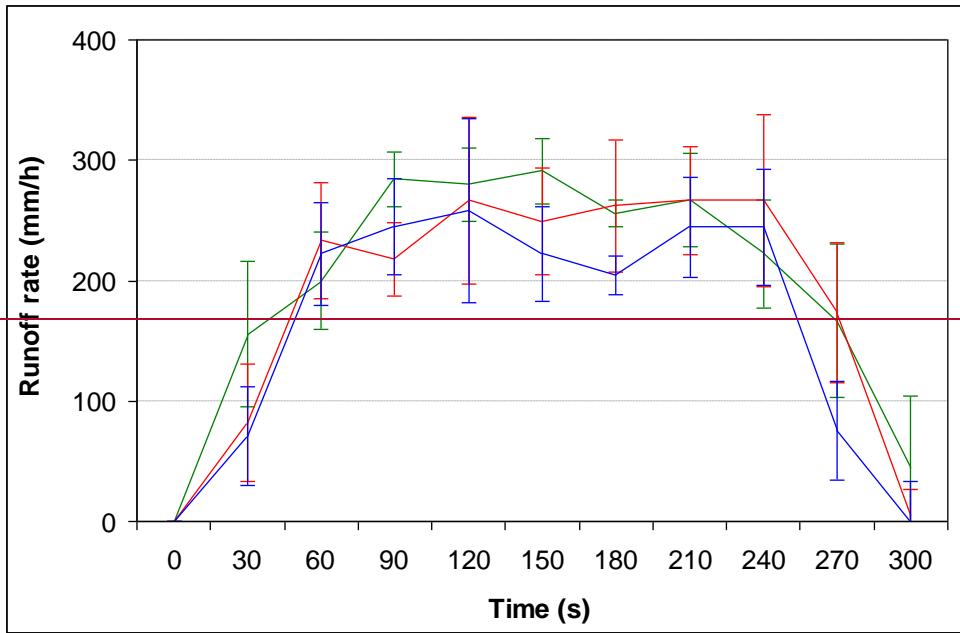
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798

799 (lower slope)

800



801

802 (higher slope)

803

804 ~~Figure 3SM — Surface runoff rates (mean ± std. error) measured by a portable rainfall simulator~~  
 805 ~~under three conditions (control, mulched with wood chips, WC, or wheat straw, WS) and two~~  
 806 ~~slopes of forest soils (Liétor, Castilla La Mancha, Spain).~~

1 **Effects of post-fire mulching with straw and wood chips on soil hydrology in pine forests**  
2 **under Mediterranean conditions**

3  
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18  
19 **Abstract**

20  
21 Mulching is one of the most common post-fire management techniques, which has been widely  
22 studied at the global scale. However, more research is needed on the hydrological effects of  
23 mulching in forest ecosystems under Mediterranean semi-arid conditions. This study has evaluated  
24 water infiltration, surface runoff and soil loss using a portable rainfall simulator in Central-Eastern  
25 Spain after post-fire treatments. In this area, a large wildfire recently affected a pine forest, and the  
26 burned soil was mulched using wheat straw (dose of 0.3 kg/m<sup>2</sup>) or wood chips (2 kg/m<sup>2</sup>) on plots  
27 with two different slopes (about 30%, lower slope, and 50%, higher slope). The study has shown  
28 that the soil condition (burned control vs. soils mulched with straw or wood chips) and slope (lower  
29 vs. higher) did not significantly influence the water infiltration. However, the mean infiltration of  
30 the soils mulched with straw were higher (+40% and +17%, respectively) compared to both the  
31 control and the plots mulched with wood chips. Moreover, lower surface runoff (-23%) was  
32 measured in the mulched soils compared to the control plots. The soil mulching with straw was  
33 more effective at decreasing the runoff coefficient (-31%) compared to plots treated with wood  
34 chips (-18%) and the control areas. Soil loss was significantly lower in plots treated using straw (-

35 87% compared to the burned and not treated soils) compared to wood chips (-54%). Peaks of 90-  
36 95% of reduction in the soil loss were even recorded in the steeper soils. Finally, we suggest the  
37 application of wheat straw rather than wood chips, since the wheat straw mulch material provides a  
38 higher soil cover (on average 73% against 48% of wood chips) and therefore is more indicated to  
39 reduce the hydrological response in burned soils, as confirmed by the lower runoff (in the average -  
40 16%) and erosion (-73%) measured in this experiment on both gentler and steeper soils.

41

42 **Keywords:** rainfall simulator; water infiltration; surface runoff; soil loss; erosion; post-fire  
43 management; vegetal materials mulching.

44

## 45 1. Introduction

46

47 High-intensity fires, such as the wildfires, alter many environmental components (Pereira et al.,  
48 2018; Pierson et al., 2001; Zema, 2021). Forest ecosystems are particularly threatened by the fire  
49 damage, especially in the Mediterranean areas (Moody et al., 2013; Shakesby, 2011). In forests  
50 under semi-arid conditions, the fire risk is very high, due to the frequent drought and the intrinsic  
51 properties of soils, which are generally shallow and poor in organic matter and nutrients (Cantón et  
52 al., 2011). In these areas, the climate change scenarios forecast an increase in the mean temperature  
53 and reduction in precipitation (Collins et al., 2013), which will certainly aggravate the fire risk and  
54 damage.

55 In forests affected by wildfires, the vegetation is completely removed and the soil is left bare and  
56 thus exposed to rainsplash, surface runoff and erosion (Bodí et al., 2012; Shakesby and Doerr,  
57 2006). Moreover, the wildfire heavily alter the chemical properties of soils, such as the pH,  
58 electrical conductivity, and contents of organic matter and nutrients (Alcañiz et al., 2018; Certini,  
59 2005; Zavala et al., 2014). Moreover, the physical characteristics of burned areas, such as soil water  
60 repellency and aggregate stability, are also impacted (Arcenegui et al., 2008; Varela et al., 2010;  
61 Zema et al., 2021a, 2021b). The changes in vegetation cover and soil properties can be long lasting  
62 (Shakesby and Doerr, 2006; L. M. Zavala et al., 2014), and the soils burned by high-intensity fires  
63 may need several years or even decades to restore their pre-fire properties (Certini, 2005; Glenn and  
64 Finley, 2010).

65 The most severe impacts of wildfires on forest ecosystems are the alteration in the hydrological  
66 response of burned soils. After fires with high severity, infiltration noticeably decreases, and surface  
67 runoff and erosion increase, often by some order of magnitude (Shakesby and Doerr, 2006; Zema,  
68 2021). The alteration of soil hydrology due to high-severity fires generally result in hazardous



69 floods and non-tolerable soil losses. These effects may extend to valley areas with possible damage  
70 of urban infrastructures and human activities (Lucas-Borja et al., 2020; Zema et al., 2020a; 2020b).  
71 In order to avoid these heavy impacts, the adoption of effective post-fire management actions, both  
72 in burned hillslopes and channels draining the fire-affected catchments, is imperative. The literature  
73 proposes many soil conservation techniques for applications in burned environments. Each  
74 technique must be tailored to site and wildfire characteristics (Wittenberg et al., 2020), since its  
75 effectiveness strictly depends on the specific climatic, geomorphological and ecological conditions.  
76 Mulching is one of the most common post-fire management techniques, particularly when  
77 vegetation residues are used (Lucas-Borja et al., 2019; Prosdocimi et al., 2016). Mulch is applied to  
78 protect the soil from the rainfall impacts and help vegetation restoration (Zituni et al., 2019;  
79 Prosdocimi et al., 2016). Straw is commonly used as mulching material on burned soils, but the  
80 mulch cover can be removed by wind in some areas and become too thick in others, which hamper  
81 vegetation regeneration (Carrà et al., 2021; Robichaud et al., 2020). A possible alternative to straw  
82 is the use of forest residues, such as the wood chips, as mulch material.

83 The mulching effectiveness on the hydrological response of burned soils has been experimented in  
84 many environments. Robichaud et al. (2013) showed that mulch treatments were effective at  
85 reducing overland flow and sediment yields as compared to the controls in wildfire-affected areas of  
86 USA. Again in this country, Wagenbrenner et al. (2006) reported reductions in sediment yields in  
87 burned and mulched areas by at least 95% relative to the control plots, thanks to the immediate  
88 increase in the amount of ground cover in the mulched plots. Wood chip mulching reduced runoff  
89 and sediment yields by over 50% in a partially-vegetated area of South Korea, and these effects  
90 were consistent regardless of the volume of rainfall (Kim et al., 2008). Regarding the Mediterranean  
91 areas, Carrà et al. (2022) found that soil mulching with fern residues was effective at reducing  
92 erosion in pine and oak forests of Southern Italy (up to 80%, depending on the species). In the  
93 Iberian Peninsula, after a severe wildfire in Galicia (Northern Spain), the mean sediment yields in  
94 soil mulched with straw were significantly lower compared to unburned plots (0.5-0.7 against 2  
95 tons per ha, respectively) (Fernández and Vega, 2014). In Castilla La Mancha (Central Eastern  
96 Spain), reductions in surface runoff by about 10% and soil loss by around 40% were found in  
97 mulched soils in comparison to unburned plots of burned pine forests (Lucas-Borja et al., 2019). In  
98 a Portuguese eucalypt plantation, in the first post-fire year, the total soil losses were, on average, 85  
99 and 95% lower following mulching at 3 and 8 tons per ha, respectively, than without mulching,  
100 although erosion was always under the tolerable threshold of 1 ton per ha (Keizer et al., 2018).

101 Ample attention has been paid to the effects of an individual management action in one or few  
102 specific environments. In contrast, comparative studies of more than one technique against the

103 negative hydrological impacts of post-fire management are lower (Zema, 2021). The comparison of  
104 more post-fire management actions in a fire-affected environment would give scientific evidence  
105 about the effectiveness of each action in a territory of given characteristics, with a special concern  
106 on the hydrological effects of the applied action. Moreover, emphasis has been given about case  
107 studies in Northern America, while much less attention has been paid to other environments, such  
108 as the landscapes of the Mediterranean Basin (Lucas-Borja et al., 2022; Shakesby and Doerr, 2006).  
109 In this semi-arid environment, there is the need of specific analysis of the variables (infiltration,  
110 runoff, erosion) that govern the soil hydrology in forest ecosystems treated with different post-fire  
111 management techniques. The climatic and soil conditions of these areas are particular and different  
112 from other environmental contexts. Regarding the climatic aspects, the Mediterranean areas are  
113 exposed to heavy and infrequent rainfalls that generate flash floods and intense erosion with hazard  
114 to human lives and infrastructures. Moreover, the Mediterranean forest soils are generally shallow  
115 and poor of organic matter, and therefore particularly prone to erosion risks, due to the high soil  
116 erodibility. In these areas, several studies have experimented post-fire mulching techniques. In  
117 general, the majority of these studies have reported a beneficial soil response to these treatments,  
118 while some other authors have obtained contrasting results in their experiments. For instance,  
119 Fernández et al. (2012) reported a low effectiveness of soil mulching coupled to seeding on  
120 infiltration, runoff and erosion in a shrubland area in Galicia (Northern Spain), since the differences  
121 in the soil hydrological response to the treatment was not significantly different from the untreated  
122 soils (0.8 tons per ha in the seeded and mulched plots against 2.1 tons per ha in the untreated plots).  
123 Lucas-Borja et al. (2018) stated that straw mulching may reduce the hydraulic conductivity of soil  
124 compared to untreated soils, and particularly in the drier season. This can worsen the hydrological  
125 response of soils subjected to wildfire, with particular evidence in summer in the case of heavy  
126 storm occurrence. Therefore, more research is needed to indicate whether and how much mulching  
127 is effective at controlling and mitigating the hydraulic and erosive hazards in delicate ecosystems,  
128 such as the Mediterranean forests. On this regard, the comparison of two mulch materials, such as  
129 straw and wood residues, may help landscape planners and forest hydrologists for the selection of  
130 the most suitable soil conservation measure.

131 To fill these research needs (comparative studies on Mediterranean burned forests treated with post-  
132 fire management techniques, and evaluation of mulching effectiveness on the hydrology of burned  
133 forests using two cover residues), this study has evaluated the hydrological behaviour of soil  
134 mulched with straw or wood chips after a wildfire in a pine forest of Central-Eastern Spain. More  
135 specifically, water infiltration, surface runoff and soil loss were measured on unburned, and burned  
136 and mulched soils using a small portable rainfall simulator together with the soil covers (vegetation,

137 rock, mulch, and bare soil). We hypothesize that: (i) mulching is in general able to reduce runoff  
138 and erosion compared to the control soils; and (ii) this technique is more effective on the steep  
139 slopes in these semi-arid areas. Finally, the comparison between two different vegetal materials for  
140 mulching should give indications about the more advisable technique for soil conservation in  
141 burned areas.

142

## 143 **2. Materials and methods**

144

### 145 *2.1. Study area*

146

147 The study area is located in the municipality of Liétor (province of Albacete, region of Castilla-La  
148 Mancha, Spain, 38°30'41'' N; 1°56'35'' W) at an elevation between 520 and 770 m above the mean  
149 sea level. The climate is semi-arid (BSk type, according to the Köppen classification (Kottek et al.,  
150 2006)) with mean annual values of temperature and precipitation equal to 16.6 °C and 321 mm,  
151 respectively (weather station of Hellín, about 20 km far from Liétor, according to the historical  
152 records of the last twenty years based on the data of the Spanish Meteorological Agency, AEMET).  
153 Soils are classified as Calcic Aridisols (Nachtergaele, 2001), and its texture is sandy loamy. The  
154 study sites have a north-west aspect and mean slope between 15 and 25%. The dominant overstory  
155 vegetation consists of Aleppo pine (*Pinus halepensis* Mill.) with a shrub layer of kermes oak  
156 (*Quercus cocciferae*) (Peinado et al., 2008). Before the wildfire, the stand density and tree height  
157 were in the range 500 - 650 trees/ha and 7 - 14 m, respectively. The understory vegetation includes  
158 *Rosmarinus officinalis* L., *Brachypodium retusum* (Pers.) Beauv., *Cistus clusii* Dunal, *Lavandula*  
159 *latifolia* Medik., *Thymus vulgaris* L., *Helichrysum stoechas* L., *Stipa tenacissima* L., *Quercus*  
160 *coccifera* L. and *Plantago albicans* L. The economic value of the understory species decreased in  
161 the middle of the 20<sup>th</sup> century, resulting in abandonment of the cultivated areas, which were  
162 reforested with Aleppo pines of natural origin. Therefore, reforested and natural stands of Aleppo  
163 pine (the latter not being affected by wildfire in the last 100 years), about 60-70 years old,  
164 characterize the study area.

165 In July 2021, a wildfire burned 2500 hectares approximately in the municipality of Liétor, close to  
166 the Talave reservoir. In order to limit the expected increases in surface runoff and erosion after  
167 wildfires, the Forest Service of the Castilla La Mancha Region, applied mulching as post-fire  
168 management action. Wheat straw and wood chips were separately used as mulch materials.

169

170

## 171 2.2. *Experimental design*

172

173 One week after the wildfire, a study area of 700 ha was selected, including both unburned and  
174 burned forests, which were affected by crown fire with 100% tree mortality. In this burned area,  
175 two sites with two different profiles (low and high slope (%),  $30.1 \pm 3.9$  and  $48.1 \pm 4.7$ ,  
176 respectively) were identified. We have excluded soils with low slope ( $< 20\%$ ), since these hillslopes  
177 are less prone to erosion, and high slope ( $> 60\%$ ), where, in Central Eastern Spain, it is uncommon  
178 that pine forests grow. In each site, nine plots (three blocks with three replications), each one with  
179 an area of  $0.5 \times 0.5$  meters, were installed. One block of three plots was not treated (hereafter  
180 indicated as “control”), a second block was mulched with straw (at a dose of  $0.3 \text{ kg/m}^2$ ), while, in  
181 the third block, a mulch layer of wood chips ( $2 \text{ kg/m}^2$ ) was applied. These application rates are  
182 those suggested by the forest services of the Iberian Peninsula, and widely used in literature (e.g.,  
183 (Girona-García et al., 2021; Kim et al., 2008; M.E. Lucas-Borja et al., 2019)). The main  
184 characteristics of the mulch materials were the following:

- 185 - wood cheap (mean values): length: 3-10 cm; width: 2-4 cm; thickness: 1-2 cm; density: 500-550
- 186  $\text{kg/m}^3$
- 187 - straw (mean values): length: 5-25 cm; width: 0.25-1.0 cm; thickness: 0.1-0.7 cm; density: 80-100
- 188  $\text{kg/m}^3$ .

189 Therefore, the experimental design consisted of three soil conditions (burned soil, soil mulched with  
190 straw, and soil mulched with wood chips)  $\times$  two slopes (low and high)  $\times$  three replicated plots,  
191 totalling 18 plots.

192

## 193 2.3. *Hydrological simulations*

194

195 The hydrological analysis can be carried out by low requirement of money and human resources  
196 using portable rainfall simulators. These measuring devices are able to easily quantify the  
197 hydrological response of small areas, controlling the characteristics of the precipitation, which  
198 furthermore can be setup at the most severe hydrological input (Iserloh et al., 2013). A limitation of  
199 the use of small rainfall simulators is the impossibility of simulating some important physical  
200 processes that influence runoff and erosion on hillslope or catchment scales, such as the rill erosion,  
201 sediment deposition, and connectivity. However, the portable simulators give quick and easy  
202 information at least about the overland flow as well as the rainsplash erosion, which are two key

203 mechanisms of soil hydrology as governed by fires. This is the reason why soil hydrology after the  
204 post-fire treatment has been evaluated in this study using a portable rainfall simulator.

205 In each of the 18 plots identified for the three soil conditions and the two slopes, an artificial rainfall  
206 was produced using an Eijelkamp<sup>®</sup> rainfall simulator (Hlavčová et al., 2019; Iserloh et al., 2013).  
207 For these simulations and the following measurements of infiltration, surface runoff and soil loss,  
208 the methods by Bombino et al. (2019) and Carrà et al. (2021) were adopted. In detail, the simulator  
209 was placed over the ground on a surface area of 0.3 m x 0.3 m, caring that the mulch material  
210 applied to the soil was not disturbed by this operation. The height and intensity of the simulated  
211 rainfall was setup at 26.7 mm and 320 mm/h, while its duration was 300 s. The drop diameter and  
212 the falling height of the precipitation were 5.9 mm and 40 cm, respectively. The precipitation  
213 volume in the simulator tank (about 2200 ml) was dosed by varying the pressure head, as suggested  
214 in the operating manual. Before the field experiment, the simulator was calibrated in laboratory by  
215 generating the same rainfall. One rainfall simulation per plot was carried out

216 We deliberately adopted a very high rainfall intensity (with a return period of more than 100 years  
217 in the studied area), in order to simulate the maximum erosion risk not only in the experimental  
218 conditions, but also in other sites with similar soil characteristics, but more intense precipitation.  
219 For instance, in Southern Italy, precipitations with such depths and intensities have a much lower  
220 return period, and therefore the erosion risk has a higher frequency (Fortugno et al., 2017; Zema et  
221 al., 2022).

222 Throughout the rainfall simulation, the runoff water and sediments were collected in a small bucket  
223 and progressively measured by a meterstick. The runoff height in the bucket was read each 30 s and  
224 subtracted from the rainfall height at the same time. The mixtures of water and sediments were  
225 finally transported to the laboratory in small bottles, and then oven dried at 104 °C for 24 h.

226 The runoff hydrographs were built, reporting the flow rate and the cumulated volume over time.  
227 This allowed the identification of the peak flow. Moreover, the infiltration curves in each plot were  
228 determined by the difference between the runoff rate and the time interval. The mean infiltration  
229 rate was calculated as the difference between the heights of rainfall and runoff divided by the  
230 duration. The runoff coefficient was calculated as the ratio between the cumulative runoff volume  
231 and the simulated rainfall depth. The weight of the sediments was then referred to the area unit, to  
232 calculate the soil loss.

233

234

#### 235 2.4. *Measurement of soil covers*

236

237 To evaluate whether the changes in soil surface properties (henceforth “covers”) had impacts on soil  
238 hydrology, the vegetation, rock, mulch covers, and the bare soil in percent over the total surveyed  
239 area were also measured at the same dates as the hydrological variables. The measurements were  
240 carried out in as many areas (each 3 m long x 3 m wide, at a maximum distance of 3 m) as the plots.  
241 The grid method (Vogel and Masters, 2001) for vegetation cover, and the photographic method for  
242 the remaining variables (rock and mulch covers, and bare soil) were used. The grid method was  
243 applied, using a 0.50 x 0.50-m grid square on the sampling areas (upstream, in the middle, and  
244 downstream of each area).

245

#### 246 2.5. *Statistical analysis*

247

248 A 2-way ANOVA was separately applied to the observations of the surface runoff and soil loss, in  
249 order to evaluate the statistical significance of the differences among soil conditions and slopes, and  
250 their interactions. The surface runoff and soil loss were the dependent variables, while the soil  
251 condition and slope were the independent factors. The differences in the two hydrological variables  
252 among factors were evaluate using the pairwise comparison by Tukey’s test (at  $p < 0.05$ ). The  
253 equality of variance and normal distribution are assumptions of the statistical tests; these  
254 assumptions were evaluated by normality tests or were square root-transformed, when necessary.  
255 The statistical analysis was carried out using the XLSTAT software (release 2019, Addinsoft, Paris,  
256 France).

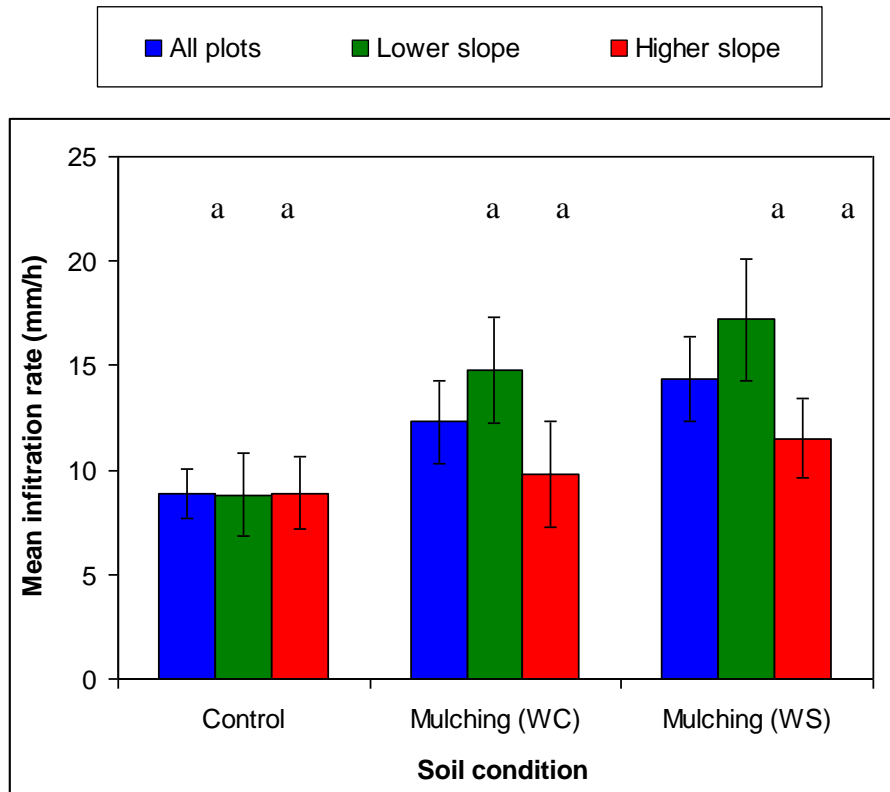
257

### 258 **3. Results**

259

260 The differences in the mean infiltration rates among the soil conditions and slopes were never  
261 significant. In more detail, in the burned soils (assumed as control), the infiltration rates were  $8.82 \pm$   
262  $2.01$  and  $8.90 \pm 1.70$  mm/h for the lower and higher slopes, respectively. These rates were higher in  
263 the treated soils,  $14.8 \pm 2.55$  (lower slope) and  $9.8 \pm 2.55$  (higher slope) mm/h in soils supplied with  
264 wood chips, and  $17.2 \pm 2.91$  (lower slope) and  $11.5 \pm 1.91$  (higher slope) mm/h in areas mulched  
265 with wheat straw (Figure 1).

266



268

269 Figure 1 – Water infiltration rate (mean  $\pm$  std. error) measured by a portable rainfall simulator under  
 270 three conditions (control, mulched with wood chips, WC, or wheat straw, WS) and two slopes of  
 271 forest soils (Liétor, Castilla La Mancha, Spain). Different letters indicate significant differences  
 272 among soil conditions and slopes after Tukey's test ( $p < 0.05$ ); "all plots" stand for the mean value  
 273 between lower slope and higher slope plots.

274

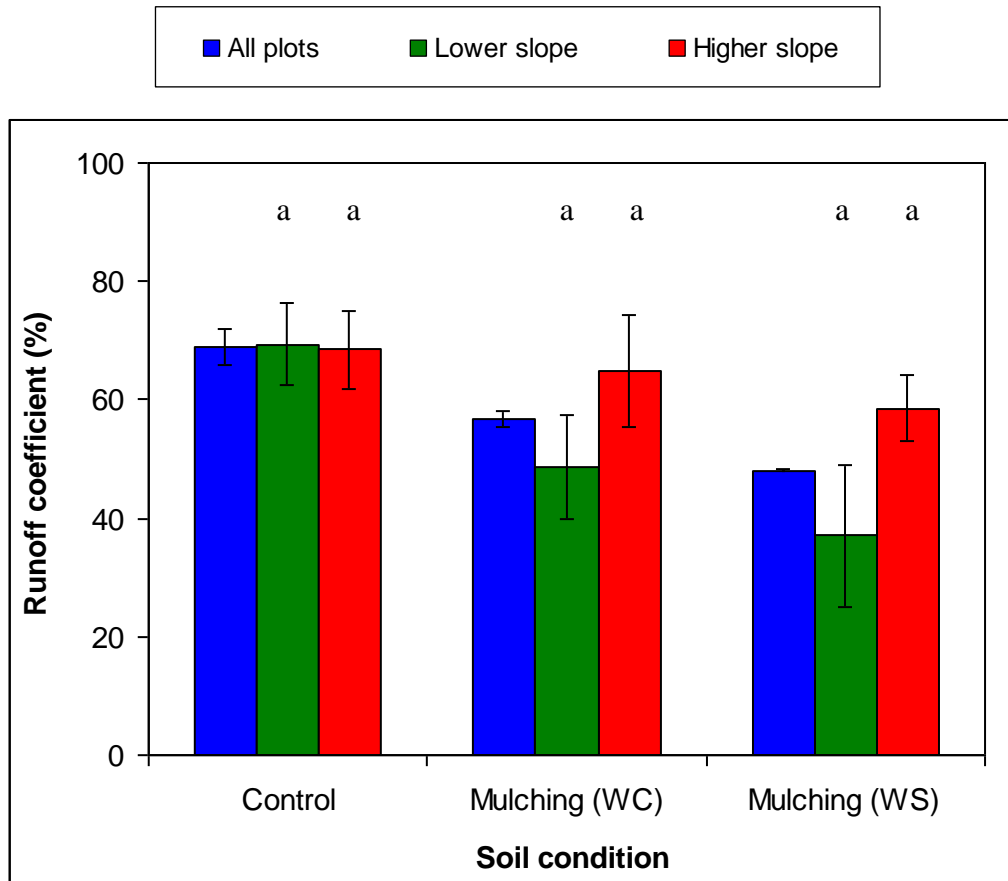
275

276 The infiltration rates decreased over time (although not being this increase monotonical) (Figure  
 277 1SM). Figure 2SM reports the cumulative runoff volumes measured under the three soil conditions  
 278 and slopes, while the runoff rates are depicted in Figure 3SM. These rates increased over time until  
 279 the peak, and then decreased until the steady-state values.

280 For the runoff coefficients, no significant differences were detected among the soil conditions and  
 281 slopes. The runoff coefficient of the control plots was  $69.4 \pm 6.98\%$  (lower slope) and  $68.5 \pm 6.52\%$   
 282 (higher slope). These coefficients decreased in the soils treated with wood chips ( $48.6 \pm 8.87\%$  at  
 283 the lower slope and  $64.7 \pm 9.49\%$  at the higher slope) and mainly in the areas mulched with wheat  
 284 straw ( $37 \pm 11.9\%$  at the lower slope and  $58.6 \pm 5.57\%$  at the higher slope (Figure 2).

285

286



288

289 Figure 2 – Runoff coefficients (mean  $\pm$  std. error) measured by a portable rainfall simulator under  
 290 three conditions (control, mulched with wood chips, WC, or wheat straw, WS) and two slopes of  
 291 forest soils (Liétor, Castilla La Mancha, Spain). Different letters indicate significant differences  
 292 among soil conditions and slopes after Tukey's test ( $p < 0.05$ ); "all plots" stand for the mean value  
 293 between lower slope and higher slope plots.

294

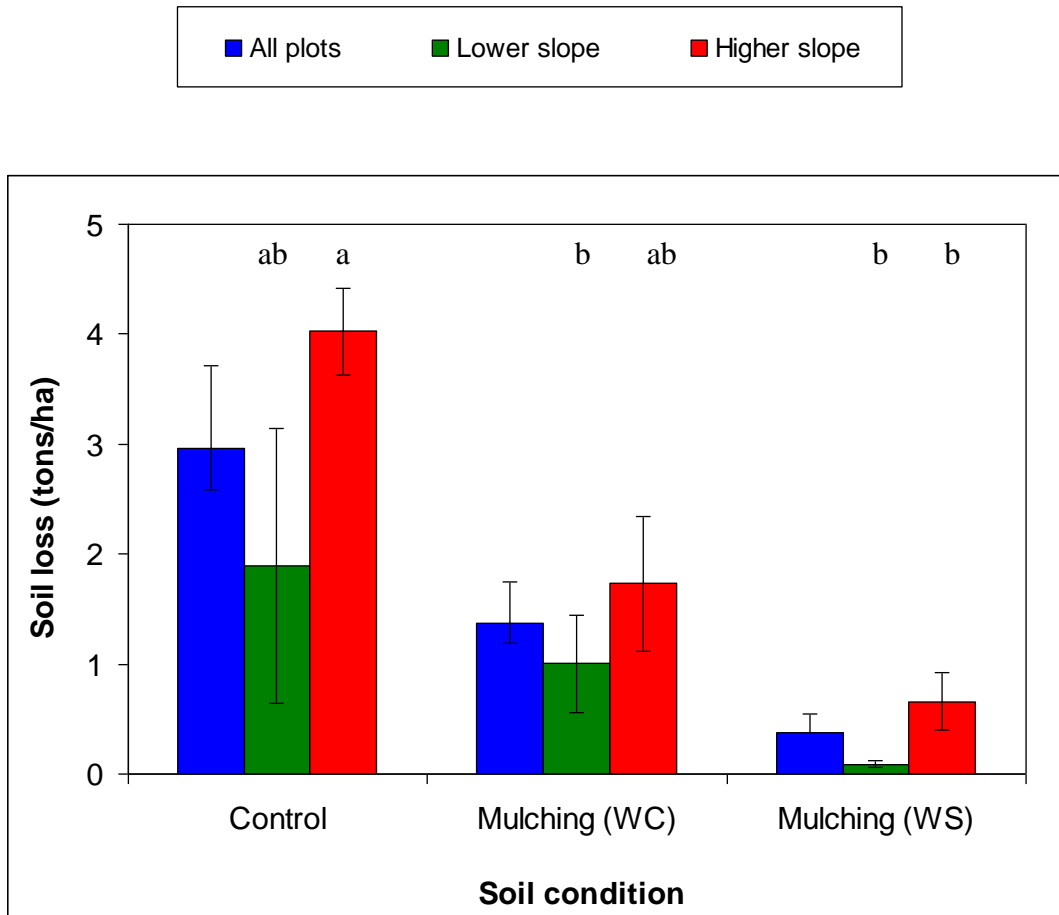
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296 The statistical analysis shows that the difference in the measured erosion values were significant  
 297 between the mulched and the burned and not treated soils, but not between the latter and the soils  
 298 covered with wood chips. In contrast, the difference in the soil loss between the two slopes were  
 299 always significant. The control soils showed the highest soil losses,  $1.90 \pm 1.25$  and  $4.02 \pm 0.40$   
 300 tons/ha, for lower and higher slopes, respectively. The erosion decreased in the plots treated with  
 301 wood chips ( $1 \pm 0.45$ , lower slope, and  $1.73 \pm 0.61$ , higher slope, tons/ha), and mainly in the areas  
 302 mulched with wheat straw ( $0.09 \pm 0.03$ , lower slope, and  $0.66 \pm 0.26$ , higher slope, tons/ha). Only  
 303 the soil loss of the burned soil with higher slope was significantly different from (i) the burned and  
 304 not treated soils; (ii) the soils mulched with wheat straw; and (iii) the soils covered with wood chips  
 305 at the lower slope (Figure 3).

306



307  
308



309

310 Figure 3 – Soil losses (mean  $\pm$  std. error) measured by a portable rainfall simulator under three  
311 conditions (control, mulched with wood chips, WC, or wheat straw, WS) and two slopes of forest  
312 soils (Liétor, Castilla La Mancha, Spain). Different letters indicate significant differences among  
313 soil conditions and slopes after Tukey’s test ( $p < 0.05$ ); “all plots” stand for the mean value between  
314 lower slope and higher slope plots.

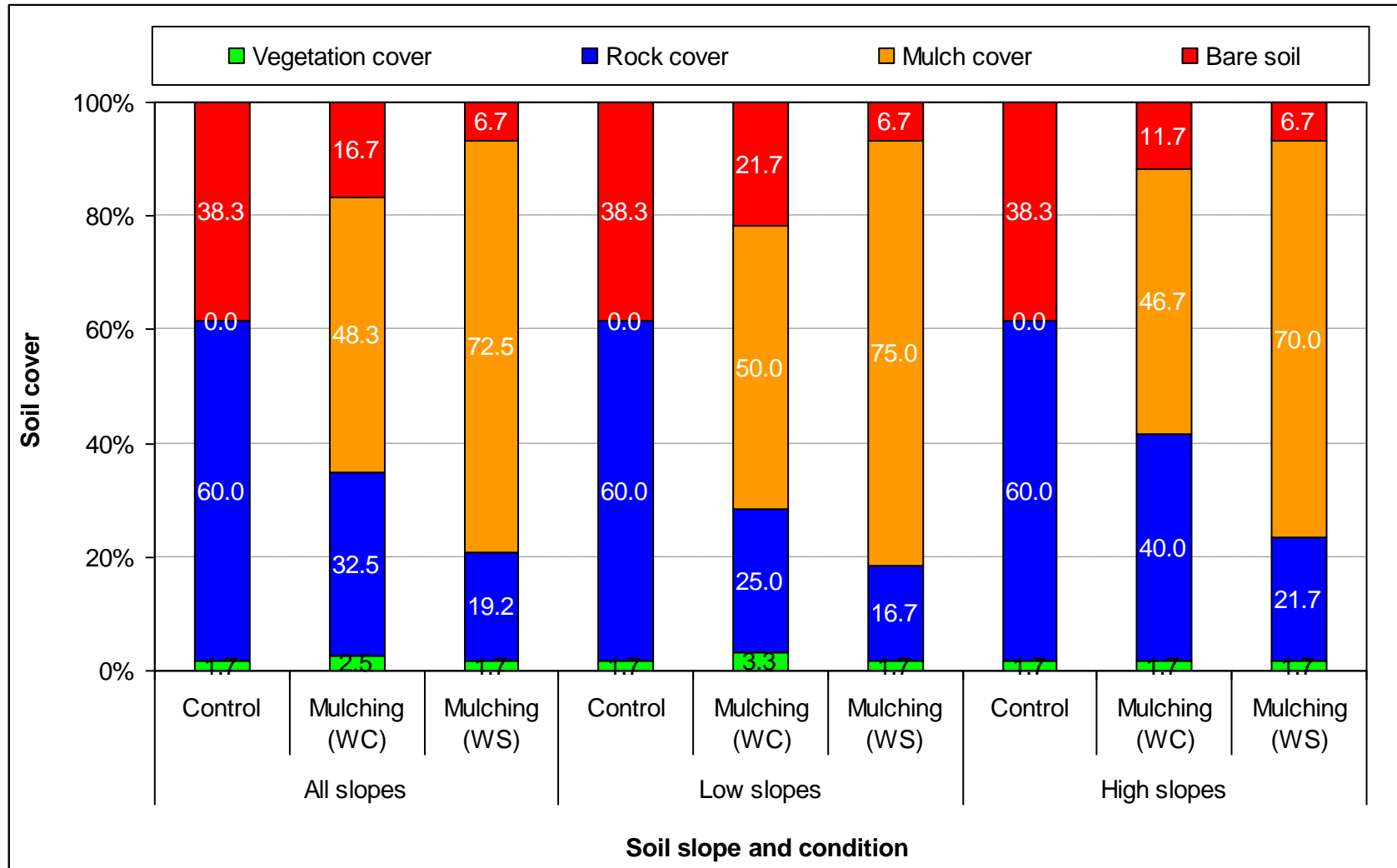
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316

317 The measurement of the soil covers revealed that the vegetation cover was quite limited in all plots  
318 (lower than 3.3%), while the bare area was from 6.7% (soils mulched with straw at both slopes) to  
319 38.3% (control soils, also in this case at both slopes). The rock cover was 60% in the control plots  
320 (at both lower and higher slopes), from 25% (lower slope) to 40% (higher slope) in the areas treated  
321 with wood chips, and 70% and 75%, for lower and higher slopes, respectively, in the soils mulched  
322 with straw. The mulch cover, which was absent in the control plots, was variable between 46.7%  
323 (higher slope) and 50% (lower slope) in the soils treated with wood chips, and between 70% (higher  
324 slope) and 75% (lower slope) in the plots mulched with straw (Figure 4).

325 By regressing using a linear equation each hydrological variable on the different soil covers, low  
326 coefficients of regression were found ( $r^2 < 0.35$ ). More specifically, no evident and significant

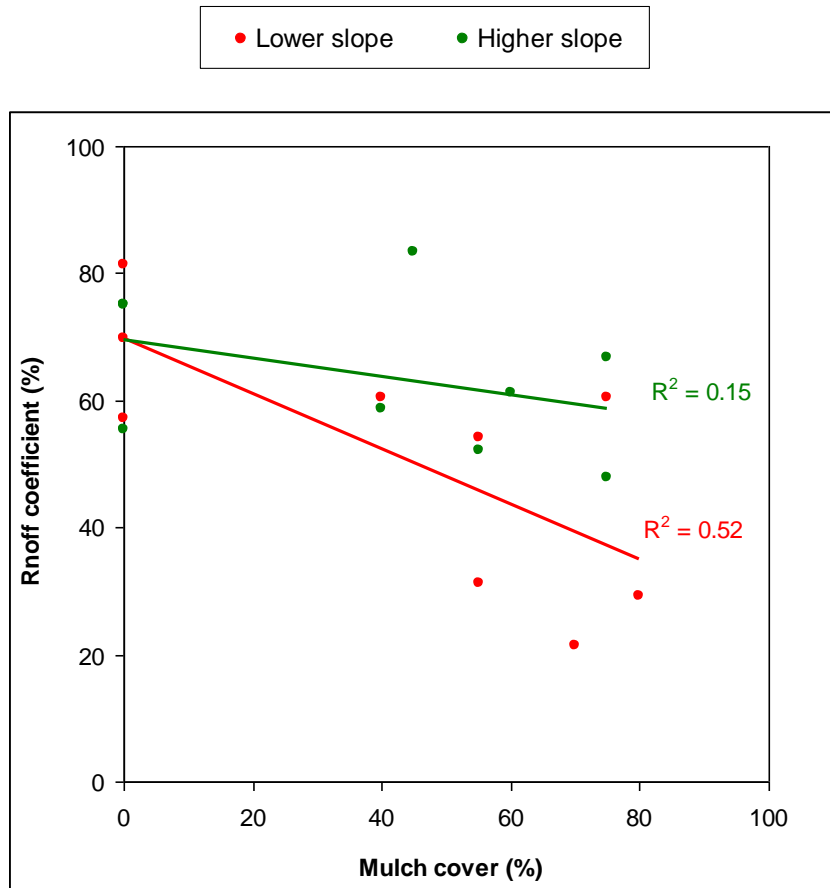
327 correlations were found between the runoff coefficients and soil losses on one side, and the soil  
328 covers on the other side ( $r^2 < 0.52$ ); the only exception was the regression between the soil loss and  
329 the mulch cover in soils with higher slopes ( $r^2 = 0.85$ , Figure 5).



330

331 Figure 4 – Soil covers (in % on the total plot area) measured under three conditions (control, mulched with wood chips, WC, or wheat straw, WS)  
 332 and two slopes in the studied forest (Liétor, Castilla La Mancha, Spain).

333

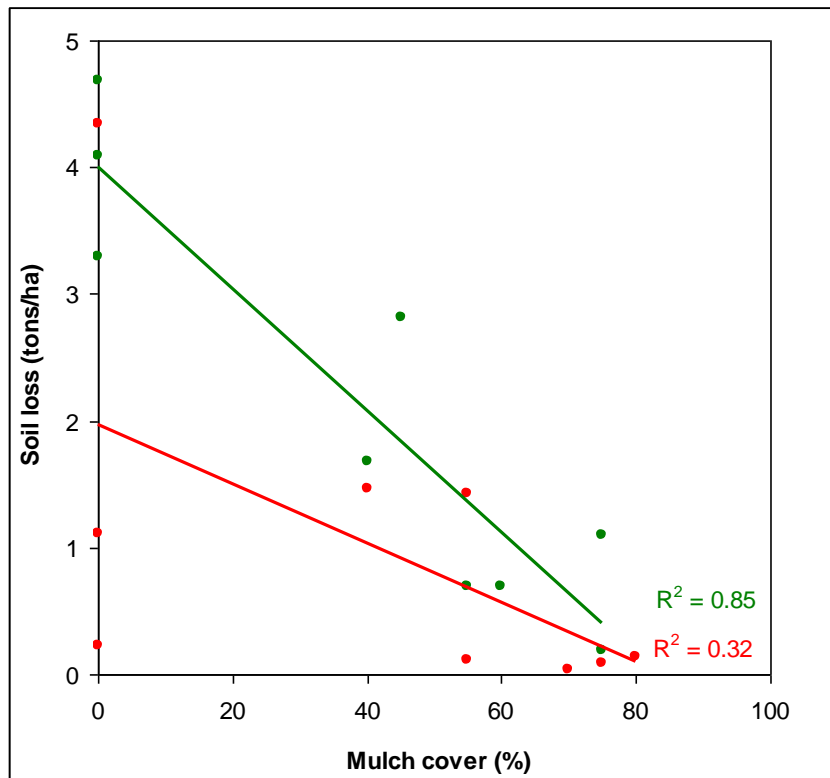


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335

336

(a)



337

338

(b)

339 Figure 5 – Correlations between the mean runoff coefficients (a) and soil losses (b), and the mulch  
340 cover measured on soils (number of plots = 3) under three conditions (control, mulched with wood  
341 chips, WC, or wheat straw, WS) and two slopes in the experimental forest (Liétor, Castilla La  
342 Mancha, Spain).

343

#### 344 **4. Discussions**

345

346 The experimental monitoring of soils burned by a wildfire and then treated with two post-fire  
347 management techniques (mulching with straw or wood chips) revealed that the soil condition and  
348 the slope or both factors did not significantly influence the water infiltration. However, the mean  
349 infiltration rates measured in the soil mulched with straw were higher compared to the untreated  
350 soils, with differences of 39% (for wheat straw) and 62% (for wood chips) (although these  
351 differences were not statistically significant). In general, the application of straw was more  
352 effective, since the increase in the infiltration rates of soils mulched with this material was about  
353 higher by 15% compared to the mulching with wood chips. Moreover, this increase was more  
354 pronounced for soils with lower slopes; for instance, in the case of mulching with straw, the mean  
355 infiltration rate decreased by 95% in the milder hillslopes against a maximum value of 29% for the  
356 treatment of the steeper soils. The lack of significance of differences in water infiltration among the  
357 soil conditions and slopes is somewhat expected, since the mulch application does not alter the  
358 physical properties of the soil surface, on which infiltration depends (Prosdocimi et al., 2016). In  
359 other words, the time elapsed from the mulch application until the infiltration measurements was  
360 too low for the incorporation of the vegetal material of degrading mulch cover. The latter, for  
361 instance, may have instead altered the organic matter content of soil and therefore its macroporosity  
362 and aggregate stability (Bombino et al., 2021, 2019). According to (Carra et al., 2021; Carrà et al.,  
363 2022), who found a limited effectiveness of mulching one year after fire on the hydrological  
364 response of burned soils, it is necessary to wait some months from fire to achieve non-significant  
365 differences between treated and untreated soils.

366 In our experimental plots, the infiltration followed a temporal decrease from the start of the rainfall  
367 simulation until the steady-state values. This is in accordance with (Carrà et al., 2021), who found  
368 the maximum infiltration rates near the rainfall onset, and a progressive decrease through the  
369 simulation. This may indicate an effect of soil water repellency, which gradually disappeared with  
370 the soil wetting, and the subsequent quick infiltration through preferential flow paths into wettable  
371 layers (DeBano, 1981).

372 The variability of infiltration explains the variations in the runoff response among the studied soil  
373 conditions and slopes. As expected, the increase in water infiltration detected for the mulched soils  
374 resulted in lower surface runoff compared to the control plots, although the differences were not  
375 significant between the different soil conditions and slopes. The soil mulching with straw decreased  
376 the runoff coefficient by 31%, and this decrease was close to 20% for the soils mulched with wood  
377 chips. As the trend measured for the infiltration rates, the runoff generation in the plots with lower  
378 slope was reduced compared to the steeper soils, as shown by the reductions in the runoff  
379 coefficients (-70% to -80% for the soils mulched with wood chips or straw, respectively).

380 The noticeable reduction in runoff volume between the mulched soils and the burned plots without  
381 any treatments can be attributed to the presence of vegetal residues on the plot surface. The lack of  
382 significance in runoff among the three soil conditions agrees with the findings reported by  
383 (Fernández et al., 2012). This work is an example of soil mulching with low effectiveness on runoff  
384 and erosion from burned shrublands of Northern Spain after an experimental fire and rainfall  
385 simulations, which did not noticeably affect runoff and infiltration.

386 In our study, mulching resulted in two important hydrological effects. First and mainly, the mulch  
387 cover retains part of the rainwater, which evaporates and thus reduces the hydrological response of  
388 the soil. In these plots, the rock cover and the bare area are much higher compared to the treated  
389 areas, whose surface is covered by 50-70% of the mulch material. In contrast, in the control areas,  
390 the wildfire has temporarily reduced the evaporation and interception of rainfall (Shakesby and  
391 Doerr, 2006), since the shrub layer and litter covers were almost totally removed. Although not  
392 measured in this study, some important soil properties (such as repellency level, contents of soil  
393 organic matter, minerals and macro-nutrients (Alcañiz et al., 2018; Shakesby and Doerr, 2006;  
394 Zavala et al., 2014) could have been significantly modified by the high-severity fire, and noticeable  
395 effects of these changes on soil hydrology may be expected. Furthermore, the presence of the  
396 vegetal residues could have also affected the runoff rate, since the wood chips or the twigs of the  
397 straw mulch slowdown the velocity of the water stream compared to the burned soil (Lucas-Borja et  
398 al., 2022). This effect is more pronounced in the soil at lower slope that were mulched with wheat  
399 straw, due to the higher mulch cover. The presence of obstacles on the runoff paths increases the  
400 travel times of the water stream on soil surface. Therefore, the time to peak for the formation of the  
401 floods is reduced (Zhao et al., 2016), especially in steeper soils, which are more exposed to the  
402 flooding risks in valley areas.

403 Secondly, the variations in the hydraulic conductivity, although not being significant, may also be  
404 another reason of the differences measured in the soil's hydrological response between the mulched  
405 and untreated areas. An increased water infiltration results in a consequent reduction in the runoff

406 rates. As outlined above, a longer time between the time elapsed from mulch application and the  
407 hydrological measurements should have evidenced a further decrease in the runoff response of the  
408 treated soils, due the mulch degradation and improvement of physical properties of the burned soils.  
409 The general reduction in the hydrological response of the investigated fire-affected areas has  
410 demonstrated how and by what extent the presence of a vegetal cover on the burned soil is  
411 beneficial to reduce the overland flow after precipitation. Also other authors (e.g., Cerdà and Doerr,  
412 2008; Prats et al., 2012) reported a decrease in the surface runoff with increasing covers of dead or  
413 living vegetation as mulch materials.

414 The soil treatments with mulching were particularly effective in reducing the erosion. If averaged  
415 between the two soil slopes, the decrease in the soil loss from the plots treated with wood chips was  
416 lower by 73% compared to the control, and this percentage significantly increased up to 87% in the  
417 case of straw mulch application. Peaks of 90-95% of reduction in the soil loss were even recorded  
418 in the steeper soils. The differences in the effectiveness of the two soil treatments between lower  
419 and steeper slopes were -12% and -35% (both not significant) for mulching with wheat straw and  
420 wood chips, respectively. This reduction was statistically significant compared to the corresponding  
421 control only for the steeper soils mulched with wheat straw (-84%).

422 The beneficial effect of mulching on erosion compared to the control area is due to the soil  
423 protection exerted by the vegetal materials, which prevented the raindrop impact and sediment  
424 entrainment by the overland flow (Shakesby and Doerr, 2006). In the mulched plots, the portion of  
425 the soil surface protected from the rainfall erosivity (due to the presence of the mulch material or  
426 vegetation) and the non-erodible area (covered by rock) was much higher compared to the control  
427 plots, which explain the lower erosion rates. The higher soil losses detected in the latter soil  
428 condition is typical of wildfire-affected areas, where sediment detachment is enhanced, due to the  
429 vegetation removal by fire as well as to the decrease in aggregate stability, which is typical of the  
430 burned areas (Cawson et al., 2012; Moody et al., 2013; Zavala et al., 2014).

431 Another important consideration raises up from the very high intensity of the simulated rainfall  
432 event. This intensity is typical of an extremely erosive event with a return interval of many years.  
433 After the rainfall simulation, a maximum soil loss of over 4 tons/ha was observed in the burned area  
434 with the highest slope. If we consider that these events may be more than two or three throughout a  
435 hydrological year, it is evident that the wildfire-affected areas of the Mediterranean forests, if not  
436 protected, may be exposed to non-tolerable erosion rates (over 10-12 tons/ha-year for the  
437 agricultural areas, which generally show higher erosion compared to forestland) (Bazzoffi, 2009;  
438 Wischmeier, 1978). In our experiments, soil mulching reduced this erosion rate by a factor of 2-3 in  
439 the case of mulching with wood chips, and by 20 on gentler profiles or six on the steeper slopes,

440 when straw was used as mulch material. Therefore, in mulched soils, the erosion risk is much lower  
441 compared to the control soils, and this demonstrates the effectiveness of these practices of soil  
442 conservation in forest areas.

443 Our results are in close agreement with several literature studies that have evaluated soil hydrology  
444 after post-fire mulching. The reductions in soil erosion observed in our study (about 90% in the  
445 plots mulched with straw and 50% in the soils treated with wood chips) are higher compared to the  
446 values reported by Lucas-Borja et al., (2019) in the same environment (decrease in soil erosion by  
447 42% on average), presumably due to the fact that, in that investigation, the soil was disturbed by  
448 other treatments (salvage logging and machinery application). Similar reductions in soil loss (-85%  
449 and -90%) as in our study were also detected by Keizer et al. (2018) and Prats et al. (2016) in  
450 treated eucalypt forests of Northern Spain and Central Portugal, respectively. However, in the study  
451 by Keizer et al. (2018), the burned soil was mulched with straw at the same application dose as in  
452 our experiment. In the investigation by Prats et al. (2016), forest residues were used as mulch  
453 material, but at a halved application dose (10.8 tons/ha) compared to our study (20 tons/ha). Also  
454 Lopes et al. (2020) found that soil mulching with wood residues (application doses between 3 and 8  
455 tons/ha) was effective at reducing the soil erosion, recording percentages between 70 and 95% of  
456 decreases in soil loss after a wildfire burning in a forest stand of Central Portugal. These authors  
457 have indicated the possibility to decrease the application doses of wood residues without a  
458 significant decline in mulching effectiveness on erosion. Their results should be considered when  
459 chipped forest residues are used, such in our study (which used a noticeable dose). The use of fern  
460 residues, tested by Carrà et al. (2022) in semi-arid forests of Southern Italy at a dose of 2 tons/ha,  
461 reduced erosion by 30% to 80% (thus less than in our study), but mulching was applied on soils  
462 burned by a prescribed fire. The erosion measured in our plots mulched with straw (0.38 tons/ha) is  
463 comparable to the values reported by Fernández and Vega (2014) (0.5 tons/ha), although the  
464 climatic conditions are different (semi-arid climate vs. humid conditions). Our soil loss is however  
465 higher compared to the soil loss reported by Fernández et al. (2012) (0.2 tons/ha, again under humid  
466 conditions), and this should be due to the low soil erodibility of those experimental soils.

467 A possible limitation of this study is the only use of simulated rainfall. Compared to the natural  
468 precipitation, the kinetic energy of rainfall is lower under artificial conditions and the rainsplash  
469 erosion is therefore underestimated; moreover, the runoff detachment due to the overland and rill  
470 flows is not evaluated by small devices (Hamed et al., 2002; Loch et al., 2001). However, in this  
471 study the erosion rates at the event scale measured for the burned and mulched areas (up to 1-2  
472 tons/ha) are well below the limits of hazardous erosion. Therefore, the difference between the



473 tolerance limits mentioned above and the experimental values is too high to make unrealistic this  
474 rough comparison.

475 Overall, this investigation has shown that the forest areas burned by wildfires may be subjected to  
476 noticeable erosion, which requires a careful monitoring of this soil condition, to avoid severe on-site  
477 and off-site effects, if the erosion is not properly controlled. This risk becomes urgent on steeper  
478 hillslopes, where the erosion rates can be two-fold compared to the gentler profiles, as in the  
479 experimental conditions. Moreover, these rates can be even higher, considering the limitations of  
480 measurements in small plots and under simulated rainfalls. Effective post-fire actions must be  
481 applied in the burned areas immediately after the wildfire (that is, in the so-called “window-of-  
482 disturbance” (Prosser and Williams, 1998)). In this period, erosion is much higher compared the  
483 unburned areas due to the fire effects (Keizer et al., 2018; Wilson et al., 2018), since the soil lacks  
484 the protection of the vegetation cover and the entity of the fire-induced changes in soil properties is  
485 the highest over time (Zema, 2021; Lucas-Borja, 2021). This investigation has demonstrated that, in  
486 terms of land management, soil mulching (preferably using straw to achieve the optimal soil  
487 protection) is particularly effective to control the erosion in the burned area left bare by fire, and  
488 this result confirm the first working hypothesis, at least with regard to soil erosion. Moreover, soil  
489 mulching with wood chips and mainly with straw is especially effective on hillslope with gentler  
490 profiles, and therefore the second working hypothesis of our study should be rejected.

491

## 492 **5. Conclusions**

493

494 This study has demonstrated that soil mulching with straw is more effective at decreasing the runoff  
495 coefficient compared to the application of wood chips, particularly on gentler slopes. Both soil  
496 treatments using straw and wood chips were effective in reducing the erosion from burned forests,  
497 but, also for the soil loss, erosion was significantly lower in plots treated using straw compared to  
498 wood chips. Therefore, we suggest to land managers the application of wheat straw rather than  
499 wood chips, since the first mulch material provides a higher soil cover and therefore is more  
500 indicated to reduce the hydrological response in burned soils. In contrast, when the specific  
501 objective of the post-fire management is the control of surface runoff against the flooding risk in  
502 valley area, alternatives to the use of mulching should be advised, since straw or wood chips are  
503 more effective at reducing erosion rather than surface runoff. Finally, no lower application doses of  
504 wood chips should be beneficial, since the effectiveness of this mulch material is reduced compared  
505 to other studies.

506

507 **Declaration of Competing Interest**

508

509 The authors declare no known competing financial interests.

510

511 **Acknowledgement**

512

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516

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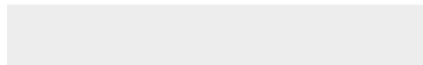




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**Supplementary Material**

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## Soil condition (burned pine forest)



Untreated  
(control)

Mulched (wood  
chips, WC)

Mulched (wheat  
straw, WS)

## Soil slope

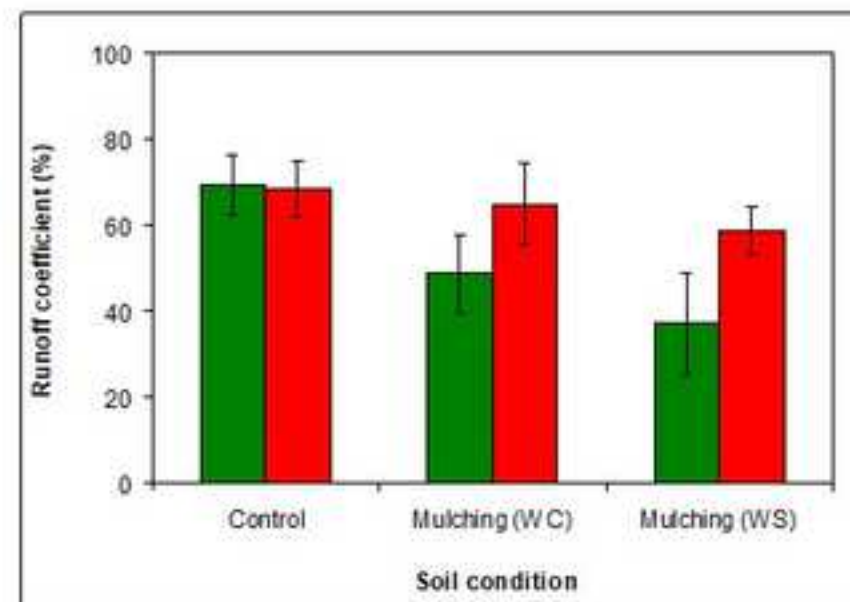


Lower

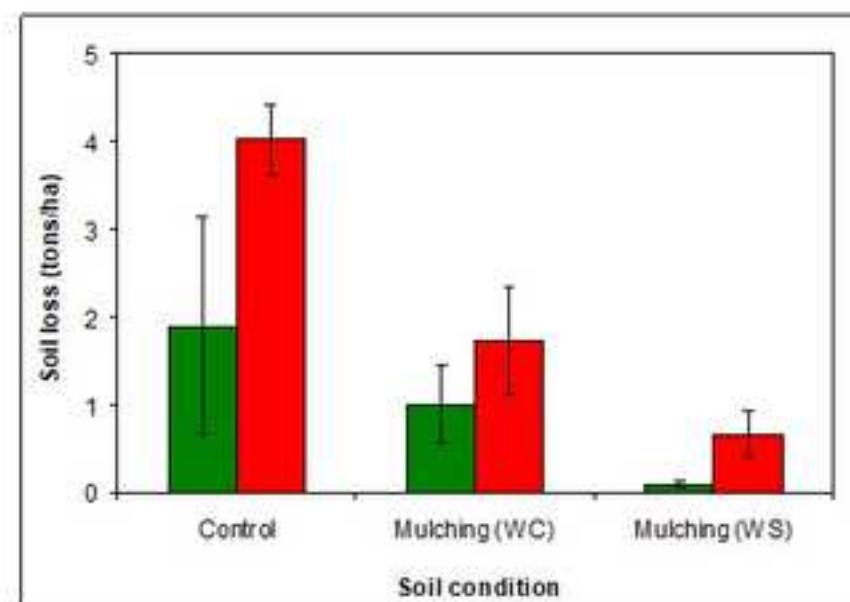


Higher

## Surface runoff



## Soil erosion



**Declaration of interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Demetrio Antonio Zema  
(on behalf of the co-authors)



## Effects of post-fire mulching with straw and wood chips on soil hydrology in pine forests under Mediterranean conditions

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