

Ecological Engineering

Prescribed fire and soil mulching with fern in Mediterranean forests: Effects on surface runoff and erosion --Manuscript Draft--

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Abstract:	<p>Prescribed burning is increasingly used to reduce the wildfire risk, and the need to limit runoff and erosion suggest treating burned soils with mulching. To this aim, fern residues may be more advisable compared to the commonly used straw, since this material is directly available in forests and has lower drawbacks. However, the post-fire hydrological effects of both prescribed fire and soil mulching are contrasting in literature, and fern has not previously experimented as mulching material in Mediterranean forests. To fill these gaps, this study has evaluated the soil hydrological response in small plots installed in three Mediterranean forests (pine, chestnut and oak) after a prescribed fire and mulching treatment with fern. Compared to the unburned soils, runoff and erosion significantly increased immediately after fire (by 150% to 375% for the runoff coefficients, and by 100% to 800% for the soil losses). However, these increases are much lower compared to the highest values reported by some studies. The negative impacts on the hydrological response in burned soils were limited to three-four months. Subsequently, the pre-fire runoff and erosion rates of the burned soils were practically restored, and the hydrological changes were not significant compared to the unburned soils. In the short term after prescribed fire application, soil mulching with fern residues was effective to limit the increase in the hydrological response of the burned and not treated soils, since runoff coefficients and erosion were reduced by 25-30% in oak soils and 70-80% in chestnut and pine forests. The changes surveyed in soil hydrology were associated with variations in the infiltration rates and water repellency immediately after fire, previously detected in the same experimental site. The restoration of water infiltration rates and disappearance of soil repellency gained importance over time, and the incorporation of mulch residues become beneficial in driving the short-term runoff and erosion response of the burned soils.</p>
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COVER LETTERReggio Calabria (Italy), 10th July 2021

Dear Editors,

Prescribed burning is increasingly used to reduce the wildfire risk, but this practice can increase runoff and erosion in the short term. To avoid this risk, ecological engineering techniques, such as mulching, to protect the burned soils may be welcome. Straw is often used, but this material may be expensive to be transported from croplands, and can introduce diseases and parasites in forests. In contrast, fern residues may be more advisable compared to the straw, since this material is native of forests and here directly available in large amounts. However, the post-fire hydrological effects of both prescribed fire and soil mulching are contrasting in literature, and fern has not previously experimented as mulching material in Mediterranean forests.

These literature gaps have inspired the present study, which we propose for possible publication on “Ecological Engineering”. More specifically, the investigation has evaluated the surface runoff and soil loss in small plots installed in three Mediterranean forests (pine, chestnut and oak) throughout one year after a prescribed fire and mulching treatment with fern.

To summarize the main results, runoff and erosion significantly increased immediately after fire in comparison to the unburned soils. However, these increases were much lower compared to the highest values reported by some studies. The negative impacts on the hydrological response in burned soils were limited to three-four months. Subsequently, the pre-fire runoff generation and erosion rates of the soils were practically restored, and the changes were not significant compared to the unburned soils. The application of fern residues as mulching was effective to limit the increase in the hydrological response observed in the burned soils, particularly in chestnut and pine forests, and less in oak soils. Runoff coefficients and erosion were reduced by 25-30% in oak soils and 70-80% in chestnut and pine forests. The changes surveyed in soil hydrology were associated with variations in soil hydraulic conductivity and water repellency (evaluated in a previous study by the authors in the same experimental sites).

Overall, these results can help to support the tasks of landscape managers to identify cheap and effective ecological engineering techniques (such as the mulching with fern) to protect the soils in fire-affected forests. For these reasons, we think that this paper may be of interest for the readers of “Ecological Engineering”. 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)

AUTHORS' REPLIES TO THE EDITOR

Dear Prof. Vymazal,

Thank You for the possibility to revise our manuscript. We have addressed all the comments rby the two Reviewers, and we think that the paper is now improved. We would be grateful if You could reconsider the revised manuscript for publication in *Ecological Engineering*. Finally, thank you again for Your attention.

Kind regards.

AUTHORS' REPLIES TO THE ASSOCIATE EDITOR

Comment

Both reviewers have found your manuscript interesting, however, they both require some revision. Please address all the reviewers' recommendations and remarks and try to accept all of them. The revised MS along with authors' response letter must be submitted at your earliest convenience.

Reply

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 FIRST REVIEWER (# 1)

Comment

This manuscripts presents results of an interesting study on effects of fire on soil hydrological properties as well as on possible measures for reducing soil erosion rates after wildfire. The study is clearly described and the results are presented and discussed in a well understandable way. Conclusions are clearly based on the presented findings and recommendations for practise have been made. In total, this manuscript seems to fit well into the scope of Ecological Engineering and is in a good state for publication after some minor optimizations.

Reply

Dear Prof./Dr., thanks for your revision requests. We are glad about Your positive opinion on our MS. We considered Your suggestions as very useful toward improving our manuscript. Below, please find our replies to each comment.

Comment

1. Could you please explain a bit more in detail, which effect the prescribed fires should have. Which type of fuel has to be removed by these low-intensity fires to avoid more destructive wildfires? In this regard, could you please discuss the rapid regeneration of a litter layer in some of the tested variants, which can certainly be seen as positive with regard to preventing soil erosion. But does this mean that fuel for wildfires is regenerating again after only one year?

Reply

Thanks for this observation that allows a better explanation of the beneficial effects and constraints of the prescribed fire. The latter, applied at low intensity and under controlled environmental conditions (e.g., humid air and absent wind) removes dry litter, and herbaceous and shrub vegetation, which is fuel for forest wildfires in summer or other dry periods. As You correctly observe, litter (but also herbs and shrubs) regenerates after the prescribed fire and this prevents erosion in the vegetation-clear forest. However, this regeneration is insufficient to recover the pre-fire erosion rates (that are much lower compared to the burned soils), and thus post-fire management actions are needed, such as the mulching with vegetal residues that has been tested in our study. It is true that the fuel for wildfires is regenerating again one year after the prescribed fire, and this requires repeated fire applications (more less one each 2-3 years) to control the wildfire risk.

We have shortly added these concepts in the text (see lines 73-78 and 82-85 of the revised MS with tracks).

Comment

2. A central issue of this article is the effect of using fern material as mulching layer instead of other organic material. In this regard the description of the preparation of this mulching material on p. 10 seems to be a bit too superficial. Thus, please describe here more in detail, which plant material was used (only fresh shoots or mixed with dry material?). How was the plant material shredded and further prepared? Which thickness of the mulching layer could be reached with the applied quantity?

Reply

Also this is a useful suggestion. We have added more information about mulch preparation (addition of vegetal residues without mixing to dry material, cutting and shredding of plant material (5 cm max) and mulch layer thickness (2-3 cm) with the applied dose (see lines 224-226).

Comment

3. Can you please explain the specific situation of the chestnut forest site. Why was the litter layer in the beginning most shallow and why did this layer recover slower than in the two other forests?

Reply

Chestnut usually produces less litter compared to the other forest species investigated in this study, and this is the basic reason why the chestnut litter is shallower and with patchy nature, and the recovery is slower. Information added in the text (see lines 567-569).

Comment

4. The text is well-written, but in some (few) parts of the manuscript sentences seem to be incomplete or unnecessary words remained after editing the sentence structure. A final copyediting would be good.

Reply

We have thoroughly revised the text, and have checked the final quality with the help of a native English speaker.

Comment

Some further details:

Tab. 2: *Bellis perennis* is not a shrub species. It is interesting that this species is growing in all three forest types as it is usually found in meadows.

Reply

Sorry for the mistake, it is true that *Bellis perennis* is a herbaceous species. We have corrected the table, since we have only reported the shrub species.

Comment Tab. 4: It would be interesting to compare the measured soil temperatures at the burned sites with soil temperature of the unburned reference sites to get a feeling of the fire impact on soil properties.

Reply

We have also measured the temperature of the unburned soil, which have omitted in the text. This temperature was about 4 °C lower compared to the temperature of the burned soils. Information added in the text (see lines 213-215).

Comment l. 261: "mixing the water in the tank": The term "mixing" is a bit confusing here: You did not mix the content from different tanks but you stirred the water in each tank to get a good suspension. Did you empty and clean the tanks after each sampling event? Samples were taken after every rainfall event or only after heavy events?

Reply

The Reviewer comment raises up from a lack of clearness in the original text. Accordingly, we have changed "mixing" with "stirring" and added more information (tank emptying after each rainfall - not only after the sampled events, - runoff and erosion sampling after the events over 13 mm) (see lines 282-285).

Comment

l. 291/292: According to Tab. 5 the most intense mean rainfall event was recorded on 5 December 2019 with 4.9 mm/h. The maximum rainfall intensity was observed on 11 November 2019. Please check the data in the text.

Reply

This was a clear mistake, and we apologize. We have corrected the comments of the data of Table 5.

Comment l. 491ff: Please introduce the abbreviations "IR" and "SWR" directly after mentioning the full terms in the text.

Reply

Done (see lines 141-142).

Comment

l. 609: You only had three research questions (and 3 answers...).

Reply

Also this was a typo. Again apologises.

AUTHORS' REPLIES TO THE COMMENTS OF THE SECOND REVIEWER (# 4)

Comment

Review of the manuscript "Prescribed fire and soil mulching with fern in Mediterranean forests: Effects on surface runoff and erosion", by Carrà, Bombino, Lucas-Borja, Plaza-Alvarez, D'Agostino & Zema. I think it is a valuable contribution to the knowledge of the effect of fern mulching following fires prescribed to reduce wildfire risk in three typical Mediterranean forests: pine, chestnut and oak. The authors focus on the effects of such practices on surface runoff and erosion. They found that both fluxes increased after fire but only during the first 3-4 months, and that fern residues reduced runoff coefficients and erosion by 25-30% in oak soils and 70-80% in chestnut and pine forests. These results are important because, until this work, the hydrological effects of both prescribed fire and soil mulching were contrasting in literature, and fern had not been previously experimented as mulching material in Mediterranean forests, which in turn are more exposed to severe fires than other ecosystems.

However, I think it cannot be published in its actual form by several formal points I will summarize below:

Reply

Dear Prof./Dr., thanks for Your encouraging opinion about our MS. We consider all Your requests as very useful toward improving our manuscript. Below, please find our replies to each comment.

MAJOR COMMENTS:

Comment

The manuscript is extremely -and unnecessarily- hard to read because the extense and detailed interpretation of Table 6. I think the core of the results are Figures 4 and 5, which are constructed on the basis of Table 6. I suggest to send Table 6 to an Appendix and concentrate the description of results only on Figures 4 and 5.

Within this framework, it would be necessary to reformulate (and shorten) both "Results" and "Discussion". As a consequence, I limit my minor comments to the "Introduction" and "M&M" sections, which do not need major chnages.

Reply

Thanks for this valuable suggestion, which we want to completely valorize. Accordingly, we have moved Table 6 to the Supplementary Material in Appendix, and left only Figures 4 and 5, which have commented with a shorter text. Due to this, the Results section has been completely rewritten. Moreover, we have done our best to remove the redundant text in the Discussion section (see lines 480-486, 559-560, 578 and 583-584 of the revised MS with tracks).

MINOR COMMENTS:

Comment

Most references within text must be corrected. Here, only one example of lines 91-97 (but revise all the manuscript): "According to (González-Pelayo et al., 2010) and (Vega et al., 2005), increases in runoff and erosion by one and two orders of magnitude, respectively, may be observed compared to unburned areas (Cawson et al., 2013). In contrast, (Coelho et al., 2004) and (de Dios Benavides-Solorio and MacDonald, 2005) reported minimal erosion after

prescribed fire (Morris et al., 2013). (Keesstra et al., 2014) reported even lower erosion in areas burned with prescribed fire compared to unburned forests, despite comparable runoff."

Must be: "According to González-Pelayo et al. (2010) and Vega et al. (2005), increases in runoff and erosion by one and two orders of magnitude, respectively, may be observed compared to unburned areas (Cawson et al., 2013). In contrast, Coelho et al. (2004) and de Dios Benavides-Solorio and MacDonald (2005) reported minimal erosion after prescribed fire (Morris et al., 2013). Keesstra et al. (2014) reported even lower erosion in areas burned with prescribed fire compared to unburned forests, despite comparable runoff."

Reply

We apologize for this problem, due to the use of automatic software for reference manager. Of course, we would have cared to format the citations in the text according to the editorial rules by Elsevier in the proofreading process. We have done this in occasion of this revision.

Comment

L62: Replace "Moreover" by "In addition" to avoid redundancy with line 60

Reply

Replaced accordingly.

Comment

L75-76: Move "Francos and Úbeda, 2021" to the end of the three references, to maintain chronological order

Reply

Moved.

Comment

L84: Replace "exposes" by "exposed"

Reply

Replaced.

Comment

L101: Replace "vegetative" by "plant"

Reply

Replaced.

Comment

L107: Replace "drier" by "driest"

Reply

Replaced.

Comment

L 112: Replace "accumulated in thick layer" by "accumulating in thick layers"

Reply

Replaced.

Comment

L120: Replace "lower compared other agro-forest residues (which allows a fast degradation into soil)." by "lower, compared to other agro-forest residues, which allows a fast degradation into soil."

Reply

Replaced.

Comment

L131: Insert "However," before "One year".

Reply

Inserted.

Comment

L136: I suggest to replace "after a prescribed fire and mulching treatment with fern in comparison" by "after a prescribed fire, with and without a mulching treatment with fern, in comparison" to anticipate the three treatments compared.

Reply

Thanks again for this suggestion. Replaced accordingly.

Comment

L156: *Castanea sativa* in italics.

Reply

Changed.

Comment

L157: Replace "stands. Table 1 reports the" by "stands (Table 1)."

Reply

Replaced.

Comment

L158-159: Delete these two lines

Reply

Deleted.

Comment

L160-163: Include graphical scale in the image, and locate the weather station mentioned at line 252

Reply

We have produced a new Figure with the geographical scale and north orientation as well as the location of the weather station.

Comment

L164-169: Traspose lines by columns in Tables 1 and 2, and make only one table: 3 sites in the columns x <12 lines because "species" are mentioned in three lines. Renumber Tables thereafter if you accept this suggestion.

Reply

We have transposed the lines by the columns of the two tables (# 1 and 2) and merged into a new table. Of course, all the remaining tables have been renumbered.

Comment

L175: Insert "All soils are loamy, except the unburned area of the pine forest, which is sandy loam (Table 2 [if you accept the former suggestion])." following "2020) ."

Reply

Inserted.

Comment

L176-178: Delete these three lines

Reply

Deleted.

Comment

L206: Replace the first "(" by ", the dose "

Reply

Replaced.

Comment

L252: I think there was only one weather station, but I am not sure because the image of Fig 1 lacks graphical scale and I am not able to calculate how many cm correspond to 1 km (see comments on lines 160-163).

Reply

Yes, there was only one weather station, whose location has been reported in Figure 1.

Comment

L274: Replace "species" by "stands"

Reply

Replaced.

Comment

L277: Replace "equality" by "homogeneity"

Reply

Replaced.

Comment

L286: I suggest to insert a comma before "516", but I am not English speaker

Reply

Inserted.

Comment

L291-292: I think a contradiction in this sentence "The latter was the most intense event (mean intensity of 26.2 mm/h), while the maximum intensity was recorded for the event of 23 November 2019 (Table 5)." because the maximum intensity recorded in Table 5 was that of November 11.

Reply

This was a clear mistake, and we apologize. We have corrected the comments of the data of Table 5.

Comment

L295-296: Net rainfall is not in Table 5 (nor anywhere). Include it or delete the sentence

Reply

Sorry, but we did not understand this observation, since the net height reported in Table 5 is the net rainfall height.

Comment

L300: Insert "erosive" between "of" and "rainfall"

Reply

Inserted.

Comment

L306-639: Reorganize, as suggested in my major comment above.

Reply

As mentioned above, we have completely rewritten the Results section, and revised and slightly shortened the Discussion section.

1 **Prescribed fire and soil mulching with fern in Mediterranean forests: Effects on**
2 **surface runoff and erosion**

3

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6

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14

15 **Abstract**

16

17 Prescribed burning is increasingly used to reduce the wildfire risk, and the need to limit
18 runoff and erosion [after the fire](#) suggests treating burned soils with mulching. To this
19 aim, fern residues may be more advisable compared to the commonly used straw, since
20 ~~this material~~[fern](#) is directly available in forests and has lower drawbacks. However, the
21 post-fire hydrological effects of both prescribed fire and soil mulching are contrasting in
22 literature, and fern has not previously experimented as mulching material in
23 Mediterranean forests. To fill these gaps, this study has evaluated the soil hydrological
24 response in small plots installed in three Mediterranean forests (pine, chestnut and oak)
25 after a prescribed fire and mulching treatment with fern. Compared to the unburned
26 soils, runoff and erosion significantly increased immediately after fire (by 150% to
27 375% for the runoff coefficients, and by 100% to 800% for the soil losses). However,
28 these increases are much lower compared to the highest values reported by some
29 studies. The negative impacts on the hydrological response in burned soils were limited
30 to three-four months [after burning](#). Subsequently, the pre-fire runoff and erosion rates of
31 the burned soils were practically ~~restored~~[recovered](#), and the hydrological changes were
32 not significant compared to the unburned soils. In the short term after [the](#) prescribed fire
33 application, soil mulching with fern residues was effective to limit the increase in the
34 hydrological response of the burned and not treated soils, since [the](#) runoff coefficients

35 and erosion were reduced by 25-30% in oak soils and 70-80% in ~~chestnut and pine~~
36 forests of chestnut and pine. The changes surveyed in soil hydrology were associated
37 ~~with to~~ variations in the infiltration rates and water repellency immediately after fire,
38 previously detected in the same experimental site. The ~~restoration-recovery~~ of the water
39 infiltration rates and the disappearance of the soil repellency gained importance over
40 time, and the incorporation of mulch residues ~~become~~ became beneficial in driving the
41 short-term runoff and erosion response of the burned soils.

42
43 **Keywords:** ecological engineering techniques; post-fire management; hydrological
44 response; pine; chestnut; oak.

45 46 **1. Introduction**

47
48 Fire, a key ecological factor in the earth system (Francos and Úbeda, 2021), impacts on
49 many components of ecosystems (soil, air, water, plants and fauna, e.g. (DeBano et al.,
50 1998; Lucas-Borja et al., 2019b; Kozłowski, 2012) as well as on the ecosystem services,
51 society and economy (Nadal-Romero et al., 2018; Pereira et al., 2018a). These effects
52 depend on several factors, such as fire history, intensity and severity, fuel quantity,
53 properties and topography of soils, vegetation species, density and cover, weather
54 patterns, etc. (Zavala et al., 2014; Pereira et al., 2018b; Francos et al., 2018; Zema,
55 2021).

56 With specific regard to the environmental impacts, wildfire removes vegetation and
57 reduces its capacity to recover, and determines long-lasting changes in soil properties
58 (Neary et al., 1999; Certini, 2005; Shakesby, 2011). Vegetation removal (which leaves
59 the soil bare) and soil changes (~~resulting in with~~ increased water repellency, destruction
60 of aggregates and reduced water infiltration) due to wildfire increase the surface runoff
61 and erosion rates. Moreover, the transport of nutrients and contaminants downstream of
62 burned forests is enhanced (Neary et al., 1999; Certini, 2005; Shakesby and Doerr,
63 2006; Cawson et al., 2012; Vieira et al., 2015; Zema, 2021). ~~Moreover~~ In addition, the
64 runoff and erosion rates come back to the pre-fire values after five to ten years (Inbar et
65 al., 1998). The increase in flooding and erosion risks after fire is an essential problem
66 for land owners and catchment managers (Prats et al., 2015).

67 In order to limit the negative impacts of high-severity fires, preventing strategies have
68 been adopted since long time (Ferreira et al., 2015). Among these strategies, prescribed

69 fire - the planned use of low-intensity fire to achieve very different goals given certain
70 weather, fuel and topographic conditions (Fernandes et al., 2013) - is considered as a
71 primary and integrated option to reduce the wildfire risk in forests (Alcañiz et al., 2018;
72 Klimas et al., 2020). ~~remove or reduce the fuel that can generate a high-intensity fire~~
73 (Vega et al., 2005; Alcañiz et al., 2018). The low-intensity fire, which is applied under
74 controlled environmental conditions (e.g., humid air and absent wind), removes dry
75 litter, and herbaceous and shrub vegetation, which is fuel for forest wildfires in the
76 summer or other dry periods. Since the fuel for wildfires is regenerating after the
77 prescribed fire, repeated applications are needed to control the wildfire risk over time.
78 Moreover, the Pprescribed fire, which has low-severity and burn patchiness (Cawson et
79 al., 2012; Pereira et al., 2021), avoids high temperature in soil and tree crown burning,
80 which are the most adverse effects of wildfire on soil and plants. In addition, prescribed
81 fire supports regeneration of some plant species (Scharenbroch et al., 2012; Williams et
82 al., 2012; Francos and Úbeda, 2021). Litter, herbs and shrubs regenerate after the
83 prescribed fire, and this prevents erosion in the treated forest. However, this renewed
84 vegetal cover is insufficient to recover the pre-fire erosion rates, and thus post-fire
85 management actions are needed. Increases in runoff and erosion after prescribed fires
86 are lower compared to wildfires, but these risks are still present (Morris et al., 2013;
87 Shakesby et al., 2015). Runoff and erosion increases have been observed after
88 prescribed fires in different ecosystems, such as heathlands, shrublands and gorse (Vega
89 et al., 2005). In the Mediterranean forests, these increases may be even more intense
90 compared to other rainstorms (Fortugno et al., 2017), since and the soils are generally
91 shallow and show with low aggregate stability, and organic matter and nutrient contents
92 (Cantón et al., 2011). Due to the combination of these climate and soil characteristics,
93 the Mediterranean forests may beare more exposes-exposed to excessive runoff and soil
94 erosion rates compared to other ~~ecosystems~~ (Zema et al., 2020a; 2020b). Therefore,
95 there is a need for an improved knowledge about soil hydrology in Mediterranean fire-
96 prone forests, also considering that both wildfires and rainstorms are thought to become
97 more frequent and intense according to the forecasted climate scenarios (Badia and
98 Marti, 2008). However, despite an ample literature about the impacts of fire on soil
99 hydrology, the studies about-on the hydrological effects of prescribed fire are not
100 exhaustive and often contrasting (Cawson et al., 2012; Shakesby et al., 2015).
101 According to ~~(González-Pelayo et al. (2010) and (Vega et al. (2005)~~, increases in
102 runoff and erosion by one and two orders of magnitude, respectively, may be observed

103 compared to the unburned areas (Cawson et al., 2013). In contrast, ~~(Coelho et al. (~~
104 2004) and ~~(de Dios Benavides-Solorio and MacDonald (~~2005) reported minimal
105 erosion after prescribed fire (Morris et al., 2013). ~~(Keesstra et al. (~~2014) reported even
106 lower erosion in areas burned with prescribed fire compared to unburned forests, despite
107 comparable runoff.

108 In order to reduce the soil's susceptibility to runoff and erosion ~~to~~ after a wildfire,
109 several treatments have been proposed and their effectiveness has been verified in many
110 environmental contexts (Lucas-Borja, 2021; Zema, 2021). Among the ecological
111 engineering techniques, which use plant-vegetative residues for soil conservation,
112 mulching is one of the most common post-fire management options (Lucas-Borja et al.,
113 2019a; Prosdocimi et al., 2016). The objective of mulching is protecting soil with a
114 ground cover and improving the soil quality, if used properly and at the correct time
115 (Prosdocimi et al., 2016; Zituni et al., 2019). However, post-fire mulching can also have
116 negative effects. In some cases, mulching reduces the soil hydraulic conductivity under
117 unsaturated conditions compared to the untreated soils, particularly in the ~~drier-driest~~
118 season (Lucas-Borja et al., 2018). Mulching material is selected based on its
119 availability, resistance to degradation, weed spreading risk and other factors (Parhizkar
120 et al., 2021; Prats et al., 2015). Straw is often used as mulch cover in fire-affected areas
121 (Bontrager et al., 2019; Keizer et al., 2018), but its residues can be displaced by wind in
122 some areas, leaving slopes bare, or ~~aeumulated-accumulating~~ in thick layers in other
123 areas, with possible reductions in the post-fire emergence of vegetation ~~emergence~~
124 (Robichaud et al., 2020). Moreover, agricultural straw may contain seeds, chemicals and
125 parasites, which can be the sources of non-native vegetation and plant diseases. Forest
126 residues (e.g., wood strands, chips or shreds) or dead plants may replace straw, because
127 these substrates do not carry non-native seeds or chemical residues, and are more
128 resistant to wind displacement (Robichaud et al., 2020). In Mediterranean forest floor,
129 fern - *Pteridium aquilinum* (L.) Kuhn - is widely available, and this ~~(which~~ avoids the
130 transport ~~costsneed~~ from other locations), and its lignin content is lower compared
131 ~~other agro-forest residues (which allows a fast degradation into soil)~~. Therefore, its use
132 as mulching material in fire-affected areas is preferable to straw. However, ~~toat~~ the best
133 authors' best knowledge, no evaluations about the use of fern to protect the burned soil
134 from runoff and erosion impacts are available in literature. Therefore, the effectiveness
135 of fern mulching to restore the hydrological properties of soils should be assessed, and
136 particularly in the short-term after fire, when the soil is left bare and the soil-changes in

137 ~~the soil properties~~ (e.g., reduced infiltration, soil water repellency and ash cover) can be
138 significant compared to the un~~burned and untreated~~~~affected~~ areas (Cawson et al., 2012;
139 Francos and Úbeda, 2021; Klimas et al., 2020; Wittenberg and Pereira, 2021). A
140 previous study, carried out in the same environment using a rainfall simulator, showed
141 that soil mulching with fern did not increase ~~water infiltration~~~~the water infiltration rates~~
142 ~~(IR)~~ and did not alter soil water repellency ~~(SWR)~~ of ~~the~~ burned soils ~~in the~~
143 ~~measurement point~~~~at the point scale~~ immediately after a prescribed fire. ~~However,~~ ~~One~~
144 year after the soil treatment, the ~~soil hydraulic conductivity IR~~ -noticeably increased and
145 ~~repellency~~~~the SWR~~ completely disappeared (Carrà et al., 2021).

146 To fill the research gaps and extend the previous investigation to the plot scale, this
147 study has evaluated the hydrological response of soils in three forest stands of Calabria
148 (Southern Italy) after a prescribed fire, ~~with or without a~~~~and~~ mulching treatment with
149 fern, in comparison to ~~the~~ undisturbed soils. More specifically, ~~the~~ surface runoff
150 volumes and soil losses were measured after natural precipitation throughout one year
151 after fire ~~together with soil covers~~ in ~~pine, oak and chestnut~~ forests ~~of pine, oak and~~
152 ~~chestnut~~. The specific research questions are the following: (i) how much does the
153 prescribed fire affects runoff and erosion rates on the short term after its application? (ii)
154 how long is the “window of disturbance” (Prosser and Williams, 1998) of soil
155 hydrology due to fire? (iii) are the fern residues effective as mulching cover ~~to~~ ~~at~~ ~~reduce~~
156 ~~reducing the~~ runoff and erosion after fire?

157 The experimental replies to these ~~research~~ questions ~~study~~ may be of help to promote
158 the use of ~~the both~~ prescribed fire against the wildfire risks and ~~of the~~ soil mulching
159 with fern as ecological engineering technique for ~~the~~ ~~conservation of~~ forest soils
160 ~~conservation~~.

161

162 **2. Material and methods**

163

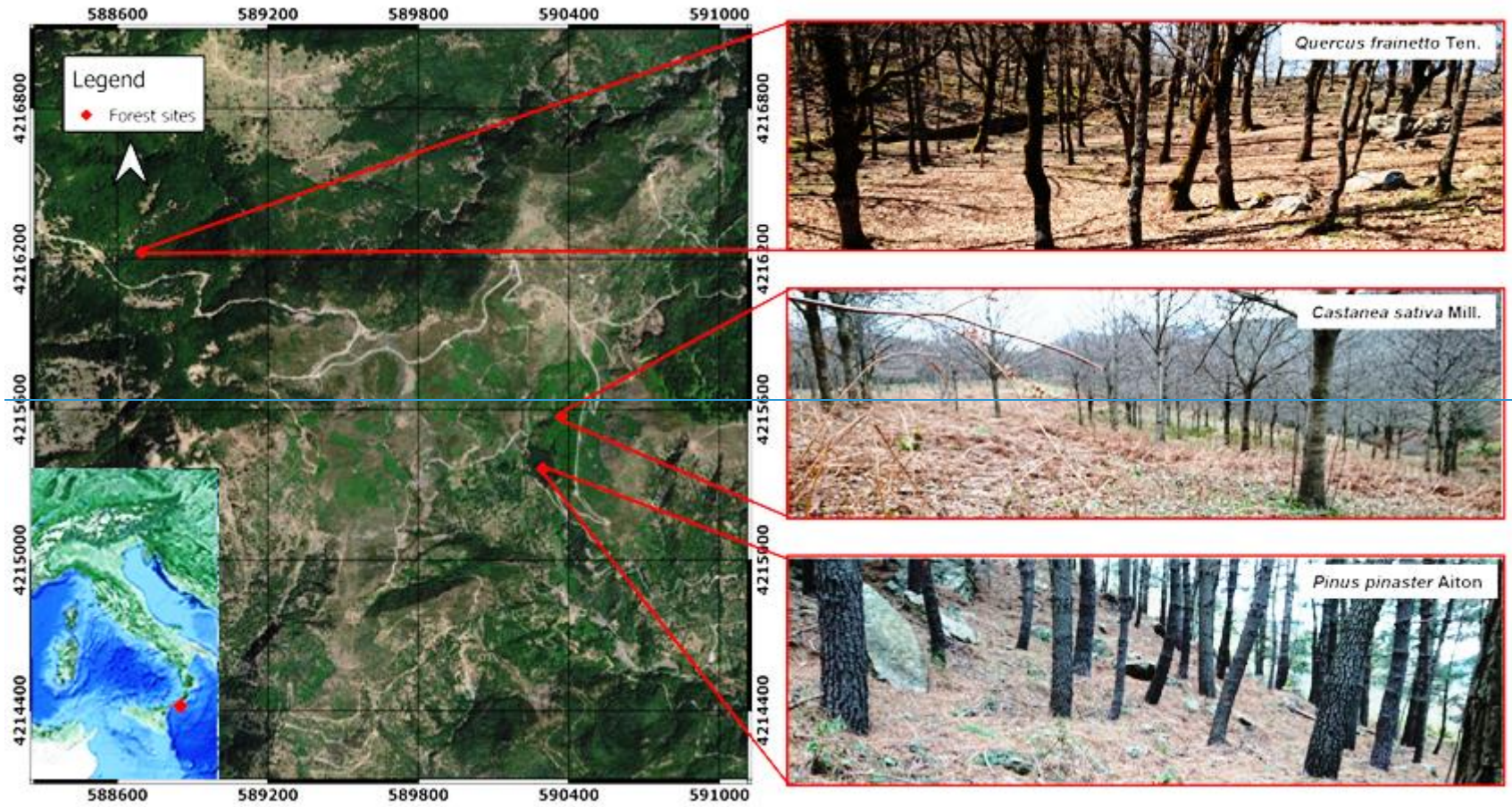
164 *2.1. Study area*

165

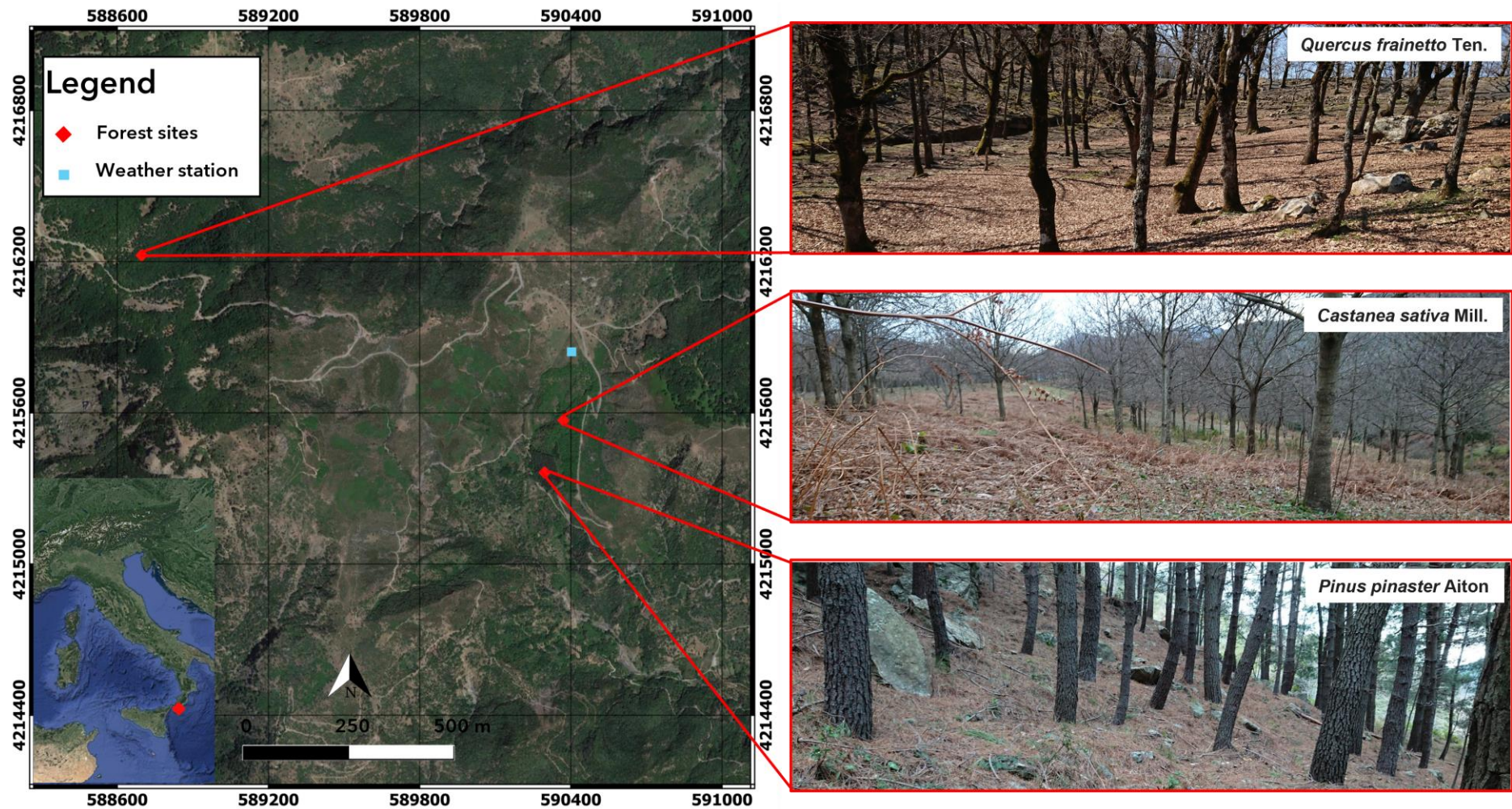
166 The study was carried out in three forest sites (municipality of Samo, Calabria, Southern
167 Italy) between 600 and 900 m above ~~the~~ sea level (Figure 1 and Table 1). ~~of which:~~ (i)
168 ~~The~~ the first area (“Calamacia”) was a pine (*Pinus pinaster* Aiton) stand reforested in
169 1984. ~~The;~~ (ii) the second site (“Rungia”) ~~was~~ a natural oak stand (*Quercus frainetto*
170 Ten.). ~~T;~~ and (iii) the third zone (“Orgaro”) was a chestnut stand (*Castanea sativa* Mill.,

171 about 29-year old). No management actions were carried out in the three forest stands (-
172 Table 1) ~~reports the main characteristics (coordinates, altitude and soil slope) of the~~
173 ~~experimental site, while the main characteristics of tree and shrub species are depicted~~
174 ~~in Table 2.~~

175



176



177

178 Figure 1 - Location of the experimental site (Samo, Calabria, Southern Italy).

179

181 Table 1 - Main characteristics of the experimental forest sites (Samo, Calabria, Southern Italy).

182

<u>Characteristics</u>		<u>Site</u>		
		<u>Calamacia</u>	<u>Rungia</u>	<u>Orgaro</u>
<u>U.T.M. coordinates</u>		<u>590293 E; 4215327 N</u>	<u>588635 E; 4216172 N</u>	<u>590389 E; 4215530 N</u>
<u>Aspect</u>		<u>South-West</u>	<u>North-East</u>	<u>West</u>
<u>Altitude (m a.s.l.)</u>		<u>650-700</u>	<u>900-950</u>	<u>700-750</u>
<u>Slope (%)</u>		<u>20.0 ± 0.82</u>	<u>19.1 ± 1.65</u>	<u>20.3 ± 0.96</u>
<u>Tree</u>	<u>species</u>	<u>Pine</u> <u>(<i>Pinus pinaster</i> Aiton)</u>	<u>Oak</u> <u>(<i>Quercus frainetto</i> Ten.)</u>	<u>Chestnut</u> <u>(<i>Castanea sativa</i> Mill.)</u>
	<u>density (n/ha)</u>	<u>950 ± 86.4</u>	<u>225 ± 44.7</u>	<u>725 ± 89.1</u>
	<u>diameter at breast height (cm)</u>	<u>28.3 ± 9.4</u>	<u>40.7 ± 8.9</u>	<u>20.2 ± 5.6</u>
	<u>height (m)</u>	<u>20.5 ± 1.4</u>	<u>18.2 ± 1.9</u>	<u>9.6 ± 1.2</u>
	<u>basal area (m²/ha)</u>	<u>67.9 ± 6.5</u>	<u>31.1 ± 3.6</u>	<u>24.3 ± 4.4</u>
=		<u><i>Quercus ilex</i> L., <i>Rubus</i> <i>ulmifolius</i> S., <i>Bellis</i> <i>perennis</i> L.</u>	<u><i>Cyclamen hederifolium</i> L., <i>Bellis perennis</i> L.</u>	<u><i>Rubus ulmifolius</i> S., <i>Pteridium aquilinum</i> L., <i>Bellis perennis</i> L.</u>
<u>Litterfall layer depth (cm)</u>		<u>11.7 ± 4.6</u>	<u>12.2 ± 3.9</u>	<u>6.1 ± 4</u>

183 Table 1—Main characteristics of the experimental site (Samo, Calabria, Southern Italy).

184

Site	Main forest species	U.T.M. coordinates	Aspect	Altitude (m a.s.l.)	Slope (%)
Calamacia	Pine	590293-E	South-West	650-700	20.0 ± 0.82
		4215327-N			
Rungia	Oak	588635-E	North-East	900-950	19.1 ± 1.65
		4216172-N			
Orgaro	Chestnut	590389-E	West	700-750	20.3 ± 0.96
		4215530-N			

185

186

187

Table 2—Main characteristics of the three forest stands in the experimental site (Samo, Calabria, Southern Italy).

188

Site	Tree					Litterfall layer depth (cm)	Shrub species
	species	density (n/ha)	diameter at breast height (cm)	height (m)	basal area (m ² /ha)		
Calamacia	pine (<i>Pinus pinaster</i> Aiton)	950 ± 86.4	28.3 ± 9.4	20.5 ± 1.4	67.9 ± 6.5	11.7 ± 4.6	<i>Quercus ilex</i> L., <i>Rubus ulmifolius</i> S., <i>Bellis perennis</i> L.
Rungia	oak (<i>Quercus frainetto</i> Ten.)	225 ± 44.7	40.7 ± 8.9	18.2 ± 1.9	31.1 ± 3.6	12.2 ± 3.9	<i>Cyclamen hederifolium</i> , <i>Bellis perennis</i> L.
Orgaro	chestnut (<i>Castanea sativa</i> Mill.)	725 ± 89.1	20.2 ± 5.6	9.6 ± 1.2	24.3 ± 4.4	6.1 ± 4	<i>Rubus ulmifolius</i> S., <i>Pteridium aquilinum</i> L., <i>Bellis perennis</i> L.

189 The climate of the area is typical of the semi-arid environment (“Csa” class, “Hot-
190 summer Mediterranean” climate, according to Koppen classification (Kottek et al.,
191 2006). Winters are mild and rainy, while summers are warm and dry. The mean annual
192 precipitation and temperature are 1102.3 mm and 17.4 °C, respectively. The minimum
193 temperature is - 4.3 °C, while the maximum is 43.1 °C (weather station of Sant’Agata
194 del Bianco ~~(RC)~~, geographical coordinates 4217548 N, 595159 E, period of 2000-
195 2020).

196 ~~Table 3 shows the main characteristics of these soils for each experimental condition~~
197 ~~(unburned, burned and not treated, and burned and mulched soils). To summarize, all~~
198 All soils ~~were~~ are loamy, except the unburned area of the pine forest, which ~~was~~ is
199 sandy loam (Table 2).

200

201 Table 3-2 - Main characteristics of the soils in the experimental sites measured immediately after the prescribed fire and before the mulching
 202 treatment (Samo, Calabria, Southern Italy).

203

Site	Main forest species	Soil condition	Texture			Type
			silt (%)	clay (%)	sand (%)	
Calamacia	pine	unburned	10.0 ± 1.01	9.0 ± 0.00	81.0 ± 0.99	sandy loam
		burned	6.3 ± 3.06	8.7 ± 0.58	85.0 ± 3.61	
Rungia	oak	unburned	12.7 ± 1.53	9.7 ± 0.58	77.7 ± 1.15	loamy sand
		burned	10.3 ± 2.25	8.7 ± 0.58	81.0 ± 2.02	
Orgaro	chestnut	unburned	12.3 ± 2.31	8.0 ± 1.73	79.7 ± 0.58	
		burned	11.3 ± 1.53	8.7 ± 0.58	80.2 ± 1.04	

204

205
206 *2.2. Prescribed fire operations and mulching application*
207

208 The prescribed fire was ~~carried out~~applied in early June 2019 with the support of the
209 Environmental Regional Agency (“Calabria Verde”) and the surveillance of the
210 National Corp of Firefighters (Figure 2a).

211 The main conditions during fire application ~~to the experimental site~~ (temperatures of
212 fire flame, air and soil) are reported in Table 34. These variables were measured by a
213 thermocouple connected to a datalogger at a soil depth of 2 cm. Wind was practically
214 absent and air humidity was between 50 and 60%. The mean soil temperature was lower
215 than 25 °C with a maximum of 29 °C, about 4 °C higher compared to the temperature of
216 the unburned soils.

217
218 Table 34 – Main conditions during prescribed fire application to the experimental site
219 (Samo, Calabria, Southern Italy).

220

Site	Main forest species	Temperature					
		fire flame		air		soil	
		mean	max	mean	max	mean	max
Calamacia	pine	88.3	712	25.7	102	21.9	22.7
Rungia	oak	98	720	43.0	180	21.0	26.9
Orgaro	chestnut	75	645	29.1	139	24.7	28.8

221
222
223 In the burned area, one day after fire, some plots (see section 2.3) were covered with
224 small pieces (maximum length of 5 cm) of fern. The plants were cut from an adjacent
225 ~~zone area~~ in the same forests and shredded using scissors in pieces of 5 cm as maximum
226 size. The ~~and the~~ fresh residues were spread on the ground without addition of other
227 materials ~~on the ground~~ to form a mulch layer of 2-3 cm. The applied dose was 500 g/m²
228 of fresh weight, which is equivalent to 200 g/m² of dry matter, the dose (commonly
229 used as straw mulching after fire (Lucas-Borja et al., 2018; Vega et al., 2014) (Figure
230 2b).
231

232



233

234

235

(a)



(b)

236

237

238 Figure 2 – Prescribed fire operations (a) and fern mulch applied to three plots of oak (b)

239 in the experimental site (Samo, Calabria, Southern Italy).

240

241

242 2.3. Experimental design

243

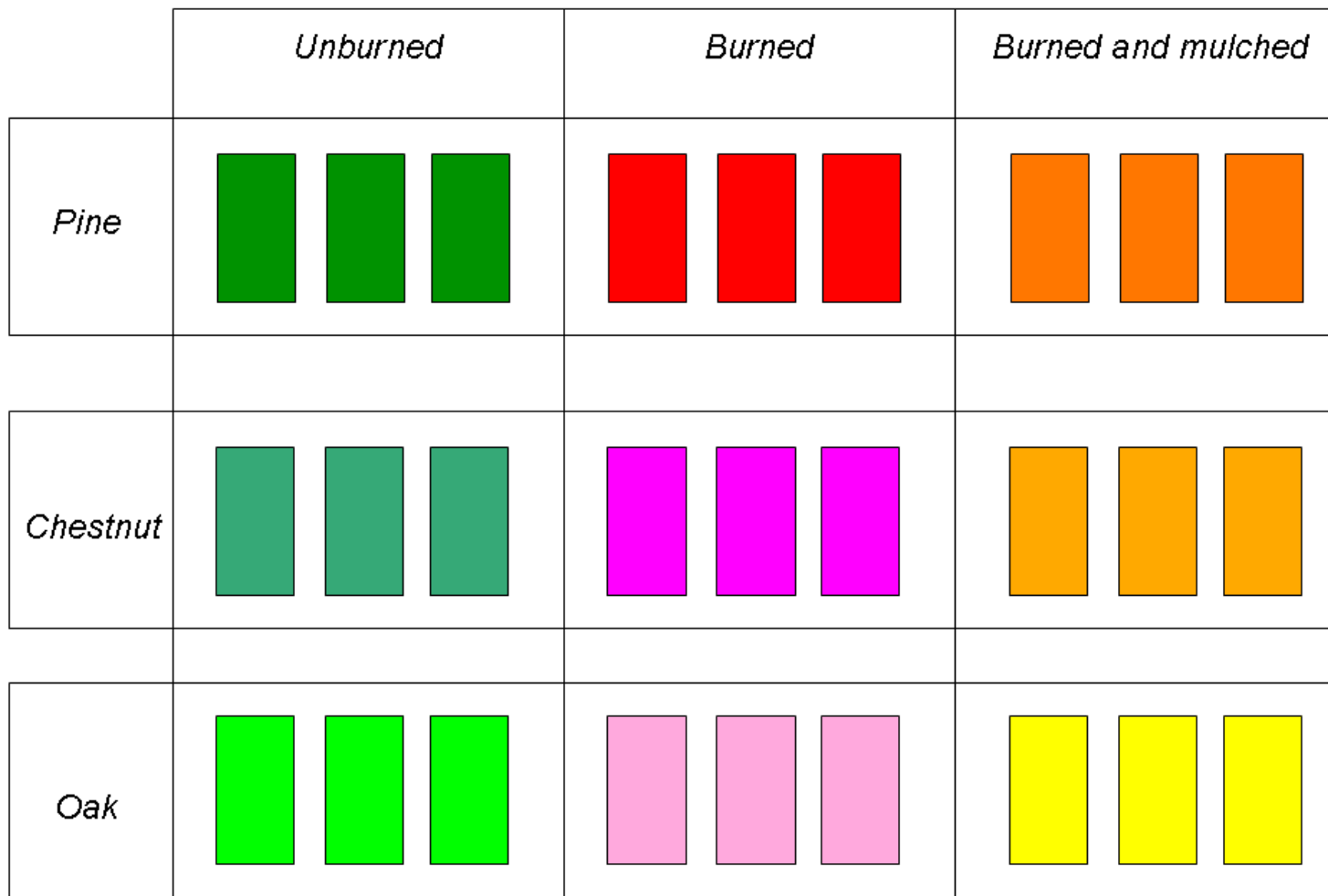
244 One of the most useful tools to study the fire effects is applying experimental fires and
245 measuring their effects on soil hydrology in plots. ~~T~~; this allows the control and
246 evaluation of the fire and soil conditions before, during and after the experiment
247 (González-Pelayo et al., 2010). The current study has adopted the suggested approach
248 and, in each experimental site, nine small plots (three series, each one with three
249 replicated plots) were delimited on forest hillslopes with the same gradient (Table 1).
250 The plots were at a reciprocal distance between 1.5 and 20 m. Three plots were setup in
251 the unburned soils (considered as “control”), while six plots were in the burned area. In
252 the latter ~~soil sites~~, three plots were subjected to mulching with fern. Overall, the
253 experimental design consisted of three forest stands (pine, oak and chestnut) × three soil
254 conditions (unburned, burned and not treated, and burned and mulched) × three
255 replicated plots, for a total of 27 plots (Figure 3).

256

257 2.4. Plot construction

258

259 Immediately after fire, the plots (each one being 3-m long and 1-m wide and covering
260 an area of 3 m²) were hydraulically isolated in each forest area (unburned, burned and
261 not treated, and burned and mulched soil), ~~using Some~~ 0.3-m high metallic sheets ~~were~~
262 ~~therefore~~ inserted up to 0.2 m below the ground surface, in order to prevent the flow of
263 surface water (Figure 2b). Downstream of each plot, a transverse channel was installed,
264 to intercept the ~~water and solid material~~ flows ~~of water and solid material~~. These flows
265 were collected through a pipe into a 100-litre tanks.



266

267 Figure 3 – Scheme and plot layout of the experimental design used for the hydrological monitoring after prescribed fire and soil mulching using
 268 fern (Samo, Calabria, Southern Italy).

269

270

271 2.5. Monitoring of the hydrological variables

272

273 ~~The h~~Hydrological measurements started immediately after site installation (mid-June
274 2019) and were carried out throughout 15 months (until mid-September 2020).

275 A weather station with a tipping bucket rain gauge (measuring sub-hourly data) was
276 installed at a maximum distance of 1 km from the experimental sites, to measure
277 precipitation height, storm duration, and rainfall intensity. ~~Mean~~The mean rainfall
278 intensity was the total rainfall divided by the storm duration. Moreover, an additional
279 rain gauge (measuring only the rainfall height) was installed in each forest site, in order
280 to estimate the rainfall intercepted by the tree canopy, and to check the spatial
281 variability of the rainfall measured by the main weather station.

282 The surface runoff and sediment concentration after precipitation produced by the
283 monitored rainfalls were measured following the procedures suggested by Lucas-Borja
284 et al. (2019b) and Bombino et al. (2021). Only the runoff volumes produced by rainfalls
285 over 13 mm, which can be considered as “erosive events”, according to (Wischmeier
286 and Smith, 1978), were monitored. The collecting tanks were emptied and cleaned after
287 each precipitation - erosive or not - event. To summarize, the runoff samples were
288 collected by mixing the water in the tank was stirred to achieve a good suspension, and
289 collecting three separate samples of the suspension was collected, totalling about 0.5
290 litres. The samples were brought to the laboratory, where they were and oven-dried at
291 105 °C for 24 hours. After drying, the sediments were weighted and referred to the
292 sample volume, in order to calculate the sediment concentration. The soil loss produced
293 by the rainfall-runoff event was estimated by the product of the runoff volume by the
294 sediment concentration. The runoff coefficients were also calculated as the ratio of
295 runoff to rainfall.

296

297 2.7. Statistical analyses

298

299 One-way ANOVA with repeated measures (at each rainfall-runoff event) was applied to
300 the runoff volume and soil loss (response variables) separately for the three forest
301 speciesstands, assuming as factor the soil condition (unburned, burned and not treated,
302 and burned and mulched). The pairwise comparison by Tukey’s test (at $p < 0.05$) was

303 also used to evaluate the statistical significance of the differences in the response
304 variables. In order to satisfy the assumptions of the statistical tests
305 ([homogeneityequality](#) of variance and normal distribution), the data were subjected to
306 normality test or were square root-transformed whenever necessary. All the statistical
307 tests were carried out by with the XLSTAT software ([release 2019.1, Addinsoft, Paris,](#)
308 [France](#)).

309

310 **3. Results**

311

312 *3.1. Rainfall characterization*

313

314 Throughout the monitoring period, 516 rainfall events with a total depth of 1120 were
315 recorded at the rain gauging station. Of these events, only seven were classified as
316 erosive events ~~and then monitored (that is, with depth over 13 mm), according to~~
317 ~~Wischmeier and Smith (1978)~~. The height of these events was in the range of 22.4 (14
318 July 2020) - 156 (11 March 2020) mm, while their duration varied between 7 (14 July
319 2020) and 41 (11 November 2019) hours. ~~The latter event e-latter~~ was ~~characterized by~~
320 ~~the maximum absolute intensitythe most intense event (mean intensity (of 26.2 mm/h),~~
321 ~~while the maximum intensity was recorded for~~ the event of [5 December 2019 had the](#)
322 [highest mean intensity 23 November 2019\(4.90 mm/h\)](#) ~~(Table 5)~~. One event (dated 24
323 July 2020) produced runoff and erosion only in the chestnut plots ([Table 4](#)).

324 The spatial variability of the precipitation among the three forest sites was very low (<
325 5%) for all the monitored events. The net rainfall (due to the interception) was between
326 4-10% (pine and chestnut forests) and 6-12% (oak site) of the total precipitation (Table
327 [45](#)).

328

329

330 Table 45 - Main hydrological variables of erosive rainfall events monitored in the
 331 experimental site (Samo, Calabria, Southern Italy).

332

Date	Height (mm)	Net height (mm)*			Duration (h)	Intensity (mm/h)	
		pine	Oak	chestnut		max	mean
15 Jul 2019	65	61.8	59.8	60.5	36	22.2	1.99
9 Oct 2019	49.9	45.4	43.9	44.9	26	14.6	1.85
11 Nov 2019	142.8	135.7	132.8	132.8	41	26.2	3.49
23 Nov 2019	87.1	82.7	81.0	81.9	19	24.7	4.58
5 Dec 2019	147.2	141.3	138.4	139.8	30	19	4.90
24 Mar 2020	155.9	149.7	146.5	149.7	32	13.8	2.86
14 Jul 2020	22.4	20.6	19.7	20.4	7	12.8	2.58

333 Note: recorded at the rain gauge station under tree canopy in each forest.

334

335 3.2. *Runoff*

336

337 The runoff volumes measured at the experimental plots are reported in Table 1SM of
 338 the Supplementary Materials. In the unburned plots, the maximum runoff (from 13.1 ±
 339 11.2 mm in the pine forest to 18.1 ± 12.9 mm in chestnut forest) was measured always
 340 after the rainfall with the highest height (156 mm, 24 March 2020). In oak forest, a high
 341 runoff (16.4 ± 3.11 mm) was also collected after the event with the highest mean
 342 intensity (26.2 mm/h on 11 November 2019, 143 mm in 41 hours). In one event (9
 343 October 2019, 50 mm), having the lowest height among the erosive rainfalls, no runoff
 344 was collected in the unburned chestnut and oak forests (Table 6).
 345 Conversely, the highest runoff volume in the burned plots was always collected after the
 346 first of the monitored events. More specifically, on 15 July 2019 (one month after the
 347 prescribed fire), the runoff was 22.3 ± 1.35 mm in the chestnut forest, 22.3 ± 4.21 mm
 348 in the pine stand, and 31.3 ± 2.29 in oak plots. The first rainfall event produced the
 349 highest runoff also in the burned and mulched plots of chestnut and oak forests (6.61 ±
 350 1.16 mm and 23 ± 3.69 mm, respectively), while in the pine plots the maximum runoff
 351 (10.4 ± 0.80 mm) was measured after the second event (11 November 2019, 143 mm of
 352 rainfall) (Table 6).

353 These measurements coupled to the rainfall records were the base for the evaluation
354 of~~As mentioned above,~~ the hydrological response of the three soil conditions to burning
355 and post-fire mulching ~~was interpreted~~ in terms of runoff coefficient (that is, ~~which~~
356 ~~standardizes~~ runoff standardised to the unit rainfall). In the unburned plots, this
357 coefficient showed a low variability (0-0.08, pine, 0.07-0.17, chestnut, and 0.00-0.19,
358 oak forest) (Figure 4).

359 In contrast, immediately after the prescribed fire, the runoff coefficient suddenly
360 increased in all forest plots (up to a maximum of ~~0.34 ± 0.02, pine, 0.34 ± 0.06,~~
361 ~~chestnut, and even~~ 0.48 ± 0.04 , in the oak forest). In the pine and chestnut plots of pine
362 and chestnut, a high runoff coefficient was also noticed also after the second storm (0.22
363 ± 0.08 and 0.34 ± 0.11 , respectively). I, ~~while,~~ in the oak forest, this coefficient
364 decreased to values (0.20 ± 0.06) that were very similar to the unburned soil, and
365 remained lower than ~~in the range~~ 0.14 ± 0.02 to 0.18 ± 0.08 . In the ~~the~~ pine and chestnut
366 plots of pine and chestnut, the runoff coefficients decreased over time, and, after the
367 third precipitation event, returned to very low values (lower than 0.13 , pine, and 0.17 ,
368 ~~chestnut~~ between 0.06 ± 0.01 and 0.13 ± 0.04 for pine, as well as 0.09 ± 0.08 and $0.17 \pm$
369 0.08 for chestnut), which were close to the undisturbed soils (Figure 4).

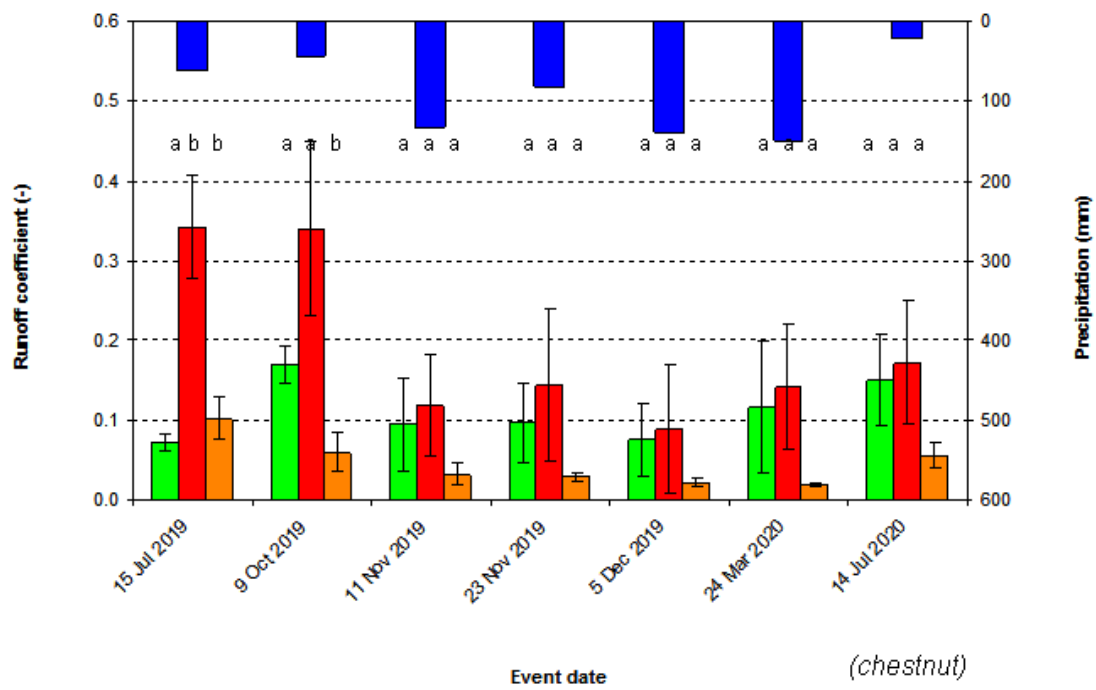
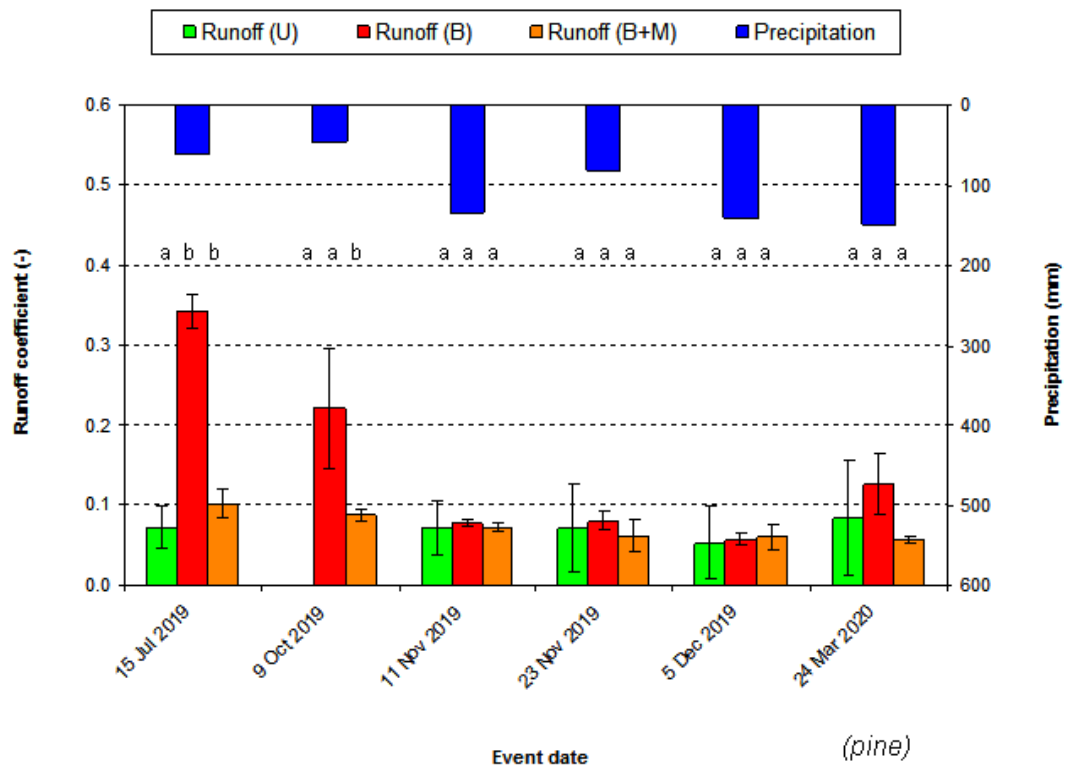
370 Mulching with fern was effective in decreasing the runoff generation capacity
371 immediately after the prescribed fire particularly in the pine and chestnut plots of pine
372 and chestnut. In these forests, the runoff coefficients after the first rainfall event were
373 0.10 ± 0.02 and 0.10 ± 0.03 , respectively. This, ~~which~~ means that the runoff volume
374 collected in the plot tanks was less than one third compared to the burned soils. In
375 contrast, in oak plots, the runoff coefficient was 0.35 ± 0.06 , about 27% less than in the
376 ~~the~~ burned plots. Over time, in burned and mulched plots of pine and oak ~~forests,~~ the
377 runoff coefficients of the unburned soils ~~restored to the values of the unburned soils~~
378 (lower than 0.10 , pine, and 0.12 , oak 0.06 ± 0.01 to 0.09 ± 0.01 , and 0.07 ± 0.06 to 0.12
379 ± 0.01 , respectively); recovered, while, in the ~~the~~ chestnut plots, these coefficients
380 decreased to values significantly lower (less than 0.02 ± 0.01 to 0.06 ± 0.02) that were
381 significantly lower compared to the control soils (Figure 4).

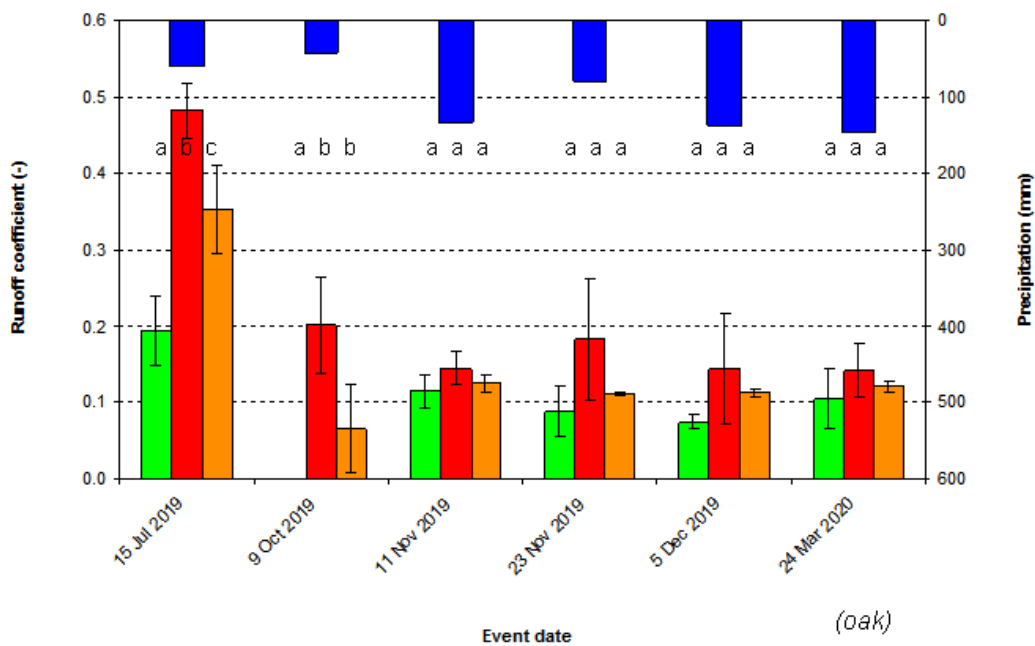
382

383 Table 6—Runoff volume and its sediment concentration measured in plots after prescribed fire and soil mulching using fern (Samo, Calabria,
 384 Southern Italy).
 385

Event date	Runoff volume (mm)						Sediment concentration (g/l)					
	<i>Unburned soil</i>		<i>Burned soil</i>		<i>Burned and mulched soil</i>		<i>Unburned soil</i>		<i>Burned soil</i>		<i>Burned and mulched soil</i>	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
<i>Pine</i>												
15-Jul-2019	4.69	1.74	22.31	1.35	6.63	1.16	1.20	0.34	2.35	0.36	1.64	0.37
9-Oct-2019	0.00	0.00	11.03	3.74	4.37	0.33	0.00	0.00	1.47	0.14	0.26	0.02
11-Nov-2019	10.22	4.80	11.12	0.53	10.35	0.80	0.47	0.45	0.21	0.13	0.18	0.02
23-Nov-2019	6.18	4.78	7.01	1.02	5.41	1.73	0.11	0.12	0.19	0.10	0.03	0.02
5-Dec-2019	7.85	6.59	8.44	1.02	8.91	2.40	0.00	0.00	0.07	0.05	0.00	0.00
24-Mar-2020	13.06	11.16	19.77	5.98	8.81	0.60	0.02	0.02	0.03	0.02	0.03	0.01
<i>Chestnut</i>												
15-Jul-2019	4.69	0.68	22.30	4.21	6.61	1.69	1.65	0.54	2.32	0.18	2.17	0.24
9-Oct-2019	8.44	1.16	16.98	5.44	3.00	1.23	1.86	0.59	2.08	1.14	0.58	0.26
11-Nov-2019	13.45	8.25	16.93	9.04	4.64	1.93	0.27	0.05	0.43	0.13	0.19	0.04
23-Nov-2019	8.39	4.32	12.49	8.29	2.51	0.41	0.30	0.03	0.55	0.11	0.10	0.02

5-Dec-2019	11.10	6.60	13.03	11.86	3.24	0.71	0.10	0.00	0.07	0.06	0.00	0.00
24-Mar-2020	18.13	12.92	22.11	12.07	2.98	0.29	0.16	0.11	0.25	0.12	0.13	0.05
14-Jul-2020	3.37	1.28	3.85	1.72	1.25	0.37	0.00	0.00	0.00	0.00	0.00	0.00
<i>Oak</i>												
15-Jul-2019	12.55	2.90	31.34	2.29	22.98	3.69	1.58	0.15	1.48	0.37	1.51	0.09
9-Oct-2019	0.00	0.00	10.00	3.13	3.27	2.83	0.00	0.00	0.90	0.26	0.51	0.89
11-Nov-2019	16.35	3.11	20.64	3.05	17.81	1.68	0.31	0.06	0.34	0.13	0.32	0.06
23-Nov-2019	7.70	2.80	15.86	6.84	9.66	0.17	0.59	0.22	1.12	0.96	0.89	0.29
5-Dec-2019	11.01	1.30	21.11	10.64	16.52	0.86	0.40	0.17	0.48	0.20	0.40	0.09
24-Mar-2020	16.36	6.01	22.11	5.32	18.78	1.20	0.32	0.06	0.37	0.05	0.29	0.03





387

388 Figure 4 - Precipitation and runoff coefficients measured in plots after prescribed fire
 389 and soil mulching using fern (Samo, Calabria, Southern Italy).

390 Notes: U = unburned soils; B = burned and not treated soils; B + M = burned and mulched soils.
 391 Different letters indicate statistically significant differences after Tukey's test ($p < 0.05$).

392

393

394 *3.3. Erosion*

395

396 The measurements of sediment concentration in the runoff volume, reported in Table
 397 1SM of the Supplementary Materials, allowed the changes in soil erosion rates after the
 398 prescribed fire and post-fire mulching in comparison to the unburned soils. Sediment
 399 concentration in the collected runoff was always the highest for the first event after the
 400 prescribed fire (15 Jul 2019) with one exception. More specifically, for this event, the
 401 burned and not treated soils showed the maximum sediment concentration (from $1.48 \pm$
 402 0.37 g/L., oak, to 2.35 ± 0.36 g/L, pine). In pine and chestnut plots, the latter giving
 403 2.32 ± 0.18 g/L of sediment concentration, this variable was about 2 fold the sediment
 404 concentration measured in the unburned soils (1.20 ± 0.34 g/L and 1.65 ± 0.54 g/L,
 405 respectively). However, in the chestnut forest, this event did not give the maximum
 406 sediment concentration, which was instead measured after the second event after the fire
 407 (1.86 ± 0.59 g/L, 9 Oct 2019) (Table 6).

408

409 Compared to the burned soils, mulch application allowed a noticeable decrease in
410 sediment concentration for this first event only in pine forest (1.64 ± 0.37 g/L), while
411 this variable was only slightly lower in chestnut (2.17 ± 0.24 g/L) and even higher in
412 oak (1.51 ± 0.09 g/L) plots. In general, the relatively high erosion surveyed in the
413 unburned soil was due to the lack of precipitation in the 2-3 months before and
414 immediately after fire, which made the soil drying and therefore exposed to higher
415 rainfall erosivity (Table 6).

416 Throughout the monitoring period after the first event, the sediment concentration was
417 still noticeable for the second event in burned plots (treated or not) of all forest species
418 and also in unburned plots of chestnut, with values over 0.90 ± 0.26 g/L (the latter
419 measured in burned plots of oak without treatment). After 4-5 months, this
420 concentration decreased to very low values in all soil conditions. Mulch cover was able
421 to decrease the sediment concentration to values that were noticeably lower compared to
422 the burned soils and in many cases also to unburned soils (Table 6).

423 While no temporal trend in this decrease was noticed in unburned soils, a monotonic
424 lowering was detected in burned plots of pine (with or without mulching). Moreover,
425 for some events with relatively low precipitation sediment was collected in burned soils
426 (e.g., 9 Oct 2019, 50 mm and 14.6 mm/h, for pine and oak forests), but not in the paired
427 unburned plots. Another event with high precipitation height (5 Dec 2019, 147 mm and
428 19.0 mm/h) gave runoff, but no erosion, due to the fact that this precipitation was snow
429 (which melted immediately producing surface water), which has a negligible detachment
430 capacity (Table 6).

431 As expected, the soil loss, estimated as the product of the runoff volume collected in the
432 tanks by the corresponding sediment concentration, was of low amount in the unburned
433 plots. (up to 5.31 ± 1.40 g/m² in pine forest, and 7.37 ± 2.72 g/m² in oak, both The
434 maximum erosion was estimated in after the first event of 15 Jul 2019, 65 mm and 22.2
435 mm/h in the forests of pine and oak (5.31 ± 1.40 and 7.37 ± 2.72 g/m², respectively),
436 while the rainfall event that produced the highest soil loss (15.34 ± 3.21 g/m²) in
437 the chestnut soil was the in chestnut, the latter after the second event of 9 Oct 2019, 50
438 mm and 14.6 mm/h) (Figure 5).

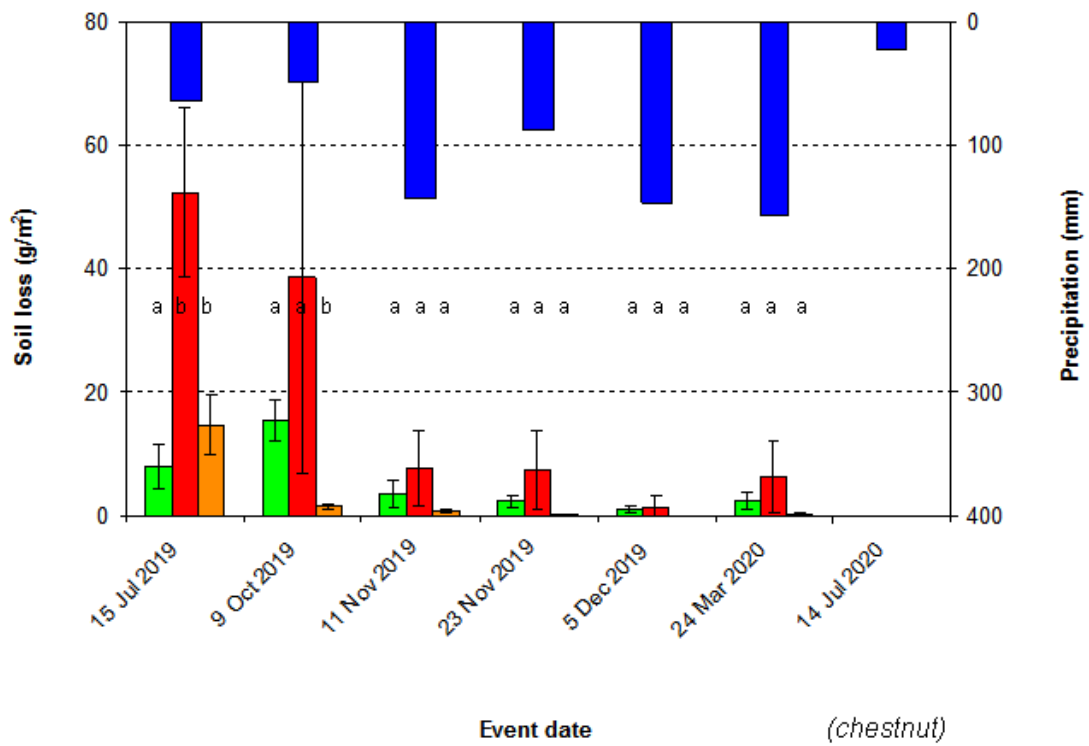
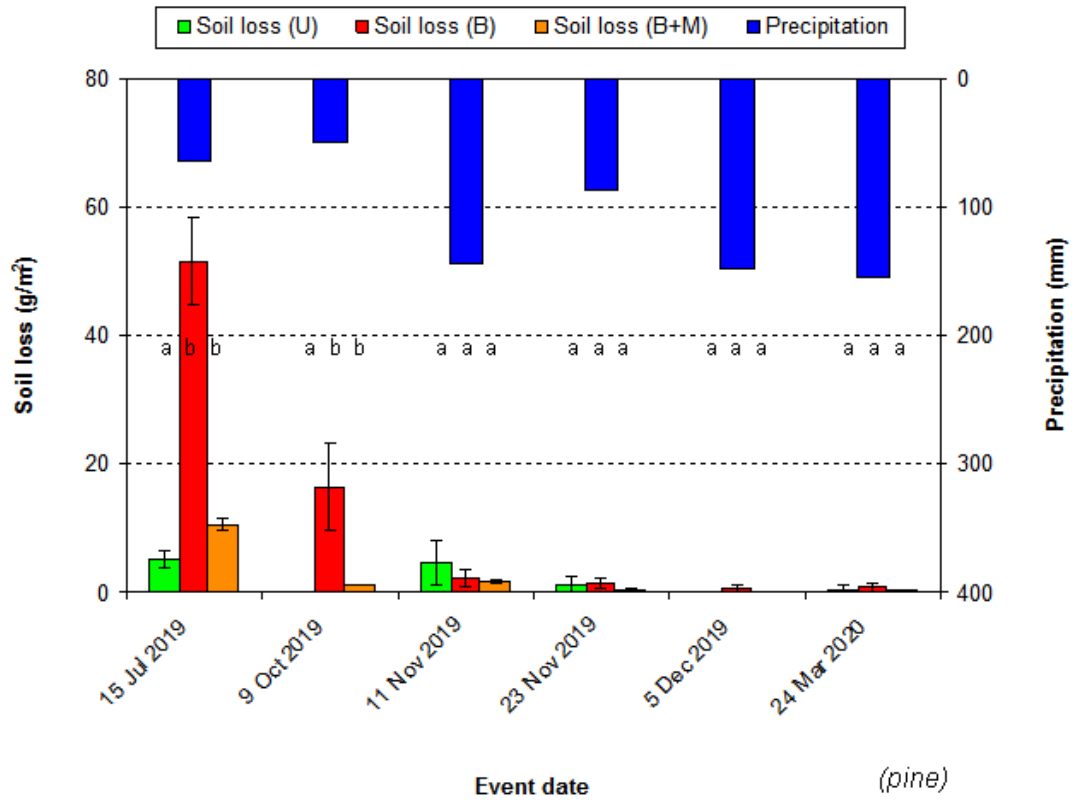
439 For these two rainfall events, erosion increased very much in burned soils of all forests,
440 and mainly in the pine and chestnut soils of pine and chestnut. In these plots, the
441 maximum values of soil loss, equal to 51.61 ± 6.92 and 52.26 ± 13.67 g/m², (first event

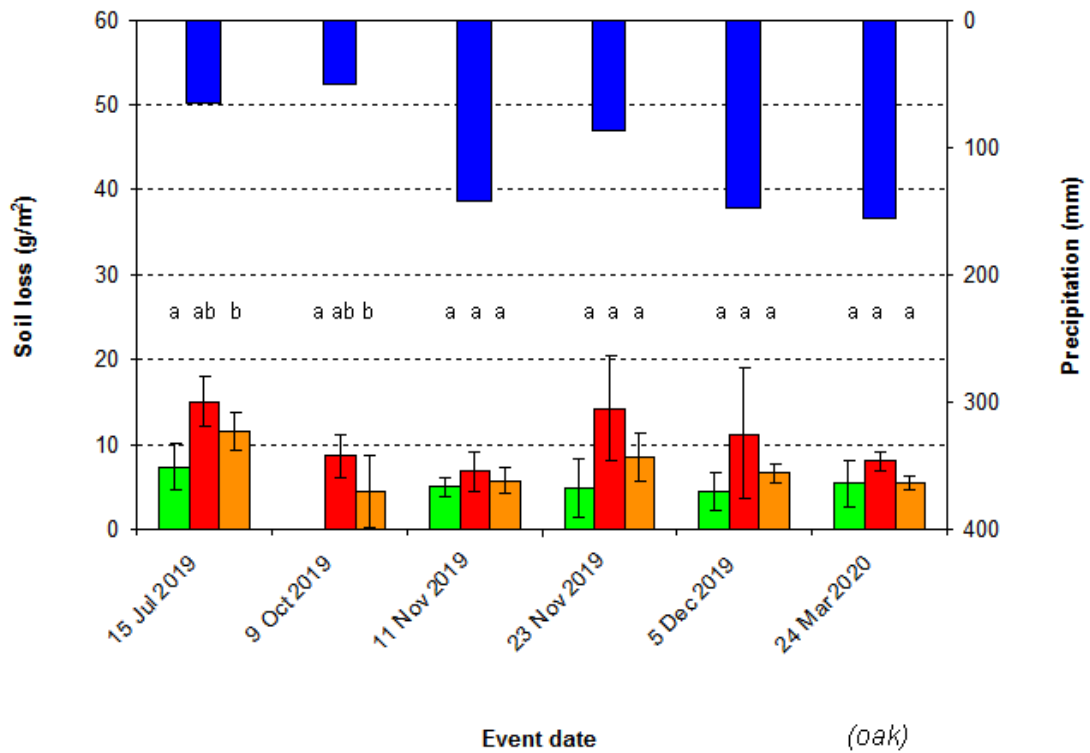
442 of 15 Jul 2019, 65 mm and 22.2 mm/h) were detected after the first event, while i In the
443 oak soils, erosion was noticeably lower, $15.12 \pm 2.87 \text{ g/m}^2$ (although higher compared
444 to the unburned plots). However, mulching was effective to reduce these soil losses, and
445 the whose maximum values ($14.58 \pm 4.80 \text{ g/m}^2$) was detected in chestnut forest ere equal
446 to $10.62 \pm 0.99 \text{ g/m}^2$ (pine forest), $14.58 \pm 4.80 \text{ g/m}^2$ (chestnut), and $11.53 \pm 2.23 \text{ g/m}^2$
447 (oak). The highest erosion in the mulched soils was, always estimated after the first
448 event rainfalls (15 Jul 2019) (Figure 5).

449 After the first two events, soil loss showed a low variability in unburned soils, with a
450 maximum of (in the range 0 to $4.63 \pm 3.57 \text{ g/m}^2$ for pine, $3.55 \pm 2.13 \text{ g/m}^2$ for chestnut,
451 both on 11 Nov 2019, 143 mm and 26.2 mm/h, and $5.44 \pm 2.79 \text{ g/m}^2$ measured in, for
452 oak plots, estimated after the last event of 14 Jul 2020, 22.4 mm and 12.8 mm/h). In
453 burned and not treated soils, erosion decreased over time. Similar erosion rates as, but
454 this decrease let soil loss be similar as the values estimated in the unburned plots were
455 only estimated in the pine forests (from $0.59 \pm 0.47 \text{ g/m}^2$ up to $2.35 \pm 1.43 \text{ g/m}^2$). In
456 contrast, in the plots of the other forest species oak and chestnut, the soil losses were
457 higher compared to the unburned soils (up to $7.78 \pm 6.01 \text{ g/m}^2$ in chestnut, and to 14.16
458 $\pm 6.13 \text{ g/m}^2$, in oak forest), both occurring after in the third and fourth event,
459 respectively) (Figure 5).

460 Covering soil with fern mulch was able to reduce erosion compared to the burned plots,
461 and this beneficial effect was mainly observed in the pine and chestnut forests of pine
462 and chestnut, and less in the oak soils compared to fire-affected plots. The In more
463 detail, maximum soil losses ($1.87 \pm 0.33 \text{ g/m}^2$, pine) was observed after the third
464 event ere equal to 1.87 ± 0.33 and $0.81 \pm 0.16 \text{ g/m}^2$ (both surveyed in the third event of
465 11 Nov 2019, 143 mm and 26.2 mm/h), respectively, while the erosion was always over
466 $5.40 \pm 0.81 \text{ g/m}^2$ in oak plots (event of 24 Mar 2020, 156 mm and 13.8 mm/h). In the
467 pine and mainly chestnut plots of pine and chestnut, for all monitored events the
468 estimated soil losses for all monitored events were even lower in comparison to the
469 unburned soils, while the pre fire erosion rates were restored In the oak forests, the
470 pre-fire erosion rates only recovered only for two events precipitations (the fourth and
471 the sixth events 23 Nov 2019 and 24 Mar 2020) (Figure 5).

472





474 Figure 5 - Precipitation and soil loss measured in plots after prescribed fire and soil
 475 mulching using fern (Samo, Calabria, Southern Italy).
 476

477 Notes: U = unburned soils; B = burned and not treated soils; B + M = burned and mulched soils.
 478 Different letters indicate statistically significant differences after Tukey's test ($p < 0.05$).

479

480 4. Discussion

481

482 4.1. Effects of prescribed fire on runoff and erosion

483

484 ~~Soil hydrology is altered by after fire (also in the case of low intensity, as the prescribed~~
 485 ~~fire) (Cawson et al., 2012; Pereira et al., 2018b; Zema, 2021), and the fire induced~~
 486 ~~changes influence the hydrological response, which in this study has been quantified by~~
 487 ~~the runoff coefficient and soil loss. It is important to limit as much as possible the~~
 488 ~~increases in runoff and erosion rates adopting suitable post-fire management techniques~~
 489 ~~implemented at the hillslope scale (Lucas Borja, 2021), and this study has evaluated the~~
 490 ~~effectiveness of soil mulching using fern.~~

491 All forest soils showed low runoff coefficients (not higher than 0.20), which means that,
 492 also after very intense storms (100-150 mm, having return interval estimated in 3-5
 493 years in this area), the runoff generation capacity of these soils is basically limited. This

494 is mainly due to the high water losses occurring in forest environments, on which high
495 soil infiltration (mainly due to the noticeable organic matter content), tree canopy
496 interception (especially in the broadleaf tree species), water retention by litter and
497 understory, and evapo-transpiration rates are beneficial, e.g., (Imeson et al. ~~(,1992)~~;
498 Llorens et al. ~~(,2011)~~; and Nadal- Romero et al. ~~(,2016)~~). The low runoff generation
499 measured in the undisturbed soils also limited the erosion rates, whose maximum value
500 was 0.15 tons per hectare (in the chestnut forest) for the most intense rainstorm.
501 Cumulating all the ~~monitored~~ erosive events observed in this study, erosion never
502 exceeded 0.33 tons/ha throughout the monitored year, and this value is well below the
503 tolerance limit of the range between 3 ~~to~~ 11.2 tons/ha per year (Bazzoffi, 2009;
504 Wischmeier and Smith, 1978).

505 Immediately after the prescribed fire application, the runoff generation capacity of the
506 soil significantly increased in all forest plots. For the first rainfall event, this increase
507 was quantified between 150% (for the oak forest) and 375% (~~for~~ pine and chestnut
508 forests) compared to the unburned soils, which represent the pre-fire values (~~represented~~
509 by the unburned soils). The higher overland flow recorded immediately after burning
510 was presumably due to the decrease in the roughness of the surface soil (Stoof, 2011),
511 due to vegetation and litter removal, and to the reduction in soil's water storage ~~due to~~
512 vegetation and litter removal (Govers et al., 2000; Shakesby et al., 2015) due to the
513 lower infiltration.

514 The surveyed increase in runoff is in accordance with (~~Andreu et al. (,2001)~~, who
515 reported that the maximum runoff is observed ~~reached~~ during the early storms after the
516 prescribed fire, the first months being the most critical period for runoff production
517 (González-Pelayo et al., 2010; Rubio et al., 2003). In this study, ~~the~~ significant runoff
518 generation observed in this period in this study (about 2 to 4-fold the values measured in
519 the unburned plots) complies with the results of (~~Vega et al. (,2005)~~. These authors;
520 ~~who~~ found increases in runoff between 2 and 5 times the control values in gorse
521 shrublands of Galicia (NW Spain), although the climate of the studied area is ~~having a~~
522 wetter ~~climate~~ compared to Southern Italy. In disagreement with the latter studies,
523 (~~González-Pelayo et al. (2010)~~ reported 10-fold runoff after prescribed burning in a
524 Mediterranean shrub ecosystem close to Valencia (Spain).

525 In our study, immediately after the fire, erosion was in the range 0.09 (oak site) to 0.59
526 (chestnut) tons/ha. Throughout one to five years after prescribed burning, other authors
527 reported erosion in the range 0.2-4.1 tons/ha under natural rainfall in Mediterranean

528 shrubland and grassland (Vega et al., 2005). In contrast, according to (Shakesby et al. (, 529 2015), soil losses at hillslope scale were never higher than 2.41 tons/ha in the first year 530 after the prescribed fire. A large range of soil loss is shown by (Neary and Leonard (, 531 2021), from 0.1 to 15 tons/ha per year after low-intensity fires.

532 The soil loss in our ~~un~~burned plots was much higher compared to the unburned soils 533 throughout four to five months after burning. Immediately after application, fire made 534 the soil exposed to erosion, particularly in ~~the pine and chestnut~~ forests of pine and 535 chestnut, and less in the oak plots. The increase in the erosion rates due to fire is 536 variable from 500% in chestnut to 800% in pine for the first event, while this increase 537 was only 100% in the oak forest. The erosion rates surveyed in ~~the pine and chestnut~~ 538 forests of pine and chestnut are higher than the values reported by (Soto et al. (, 1994) 539 and close to those of (Soler et al. (, 1994). The ~~2-fold~~ soil loss surveyed in oak forest 540 was two-fold compared to the the erosion of the unburned soils, and this value is 541 similar to the increases in burned areas reported by (Vega et al. (, 2005). Therefore, our 542 study has shown that erosion is not minimal following prescribed fires, in contrast with 543 (Morris et al. (, 2013), (Coelho et al. (, 2004), and (de Dios Benavides-Solorio and 544 MacDonald (, 2005), but never remarkable, as found by other research. For instance, 545 according to (González-Pelayo et al. (, 2010), Inbar et al., (1998), Campo et al., (2006), 546 and Cawson et al., (2013), erosion-soil losses can increase even by 100 times the 547 erosion of unburned soils after prescribed fire.

548 The worsened hydrological response of burned soils in the experimental plots was 549 mainly ascribed to two effects: (i) the reductions in the water infiltration rates IR of (in 550 all forest soils ~~of all forest species~~); and (ii) the ~~occurrence of soil water~~ 551 repellency SWR, (particularly in pine and oak soils).

552 These findings statements of our study are supported by ~~the results of~~ the previous study 553 carried out by (Carrà et al., 2021), who have evaluated the ~~water infiltration rate (IR)~~ 554 and ~~soil water repellency (SWR)~~ in the same forest stands, using a portable rainfall 555 simulator to measure the IR, and the Water Drop Penetration Test (Bisdom et al., 1993; 556 Letey, 1969; Woudt, 1959), to estimate the SWR.

557 In more detail, in all forest soils regarding the water infiltration measurements, the 558 prescribed fire reduced the mean IR ~~in the soils of all forest species~~ compared to the 559 unburned conditions. The increase in SWR may also have played an important role in 560 increasing runoff and erosion immediately after fire in ~~the pine and oak~~ soils of pine and 561 oak, since the prescribed burning determined a strong repellency. In contrast, While in

562 ~~the~~ chestnut soils the prescribed fire did not alter the slight ~~repellency~~ SWR found in
563 unburned plots, ~~burning determined a strong repellency in both pine and oak soils, with~~
564 ~~or without mulch cover~~ (Carrà et al., 2021).

565 Presumably, also the litter and vegetation removal by fire may have played an influence
566 on the hydrological response of the burned soils. Since litter and shrub covers were
567 almost completely removed by ~~the~~ fire in ~~the pine and oak~~ forests of pine and oak, the
568 soil was left bare and thus exposed to the soil detachment due to ~~the effects of~~ overland
569 flow ~~in runoff~~ and ~~soil detachment~~ as well as to rainsplash erosion. ~~Theseis fire effects~~
570 of fire ~~were~~ lower in ~~the~~ chestnut forest, where the litter amount over ground was
571 much lower compared to the other soils. Chestnut usually produces less litter than pine
572 and oak, and this is the basic reason why the chestnut litter was shallower, and its
573 recovery was slower compared to the other forest species.

574 The changes in the hydrological response of the burned soils were not permanent, but
575 remained noticeable throughout 3-4 months. Five months after burning, the low ~~pre-fire~~
576 capacity of runoff generation that is typical of ~~capacity of~~ the unburned soils ~~was~~
577 practically ~~recovered~~ stored. ~~T,~~ and the same decreasing trend was noticed for ~~the~~
578 erosion in ~~the~~ pine soils, ~~(~~ where, one year after fire, the soil loss became very similar as
579 the ~~control unburned~~ plots). Although ~~declined declining~~ over time ~~in all forest plots~~,
580 the increased erosion rates, noticed in the ~~chestnut and oak~~ forests of chestnut and oak,
581 ~~are were~~ still evident, but not significant, after more than one year ~~elapsed~~ from fire
582 application, ~~but, in any case, these changes in soil hydrology were not significant~~. This
583 means that the recovery of the pre-fire hydrological conditions in ~~the~~ burned soils ~~is was~~
584 not complete, although this incomplete recovery does not play significant effects on
585 runoff and erosion rates. According to the previous study by ~~(~~ Carrà et al. ~~(~~ 2021), this
586 recovery may be ascribed to the increase in the mean IR and to the disappearance of the
587 SWR disappearance, both detected one year after fire. ~~SWR disappeared in few months,~~
588 ~~losing importance on hydrology of burned soils, which became non-repellent~~.
589 Moreover, in our experimental plots, we visually noticed that, progressively over time,
590 the litter and shrub covers were recovering in the burned soils ~~in oak and pine stands of~~
591 oak and pine, thanks to the vegetation regeneration ~~over the burned soils~~. In contrast, in
592 ~~the~~ chestnut soils, litter cover was still limited after one year, as in the soil condition
593 immediately before and after the prescribed burning. Vegetation recovery and litter
594 accumulation during the growing season reduce ~~d~~ the impacts of heavy storms during
595 the wet season ~~in forests~~, preventing high soil loss (Klimas et al., 2020). Herbaceous

596 and shrub vegetation, and ~~leaf~~-litter covers reduce runoff and erosion rates thanks to
597 rainfall interception, soil surface protection, and evapo-transpiration (DeBano et al.,
598 1998; Sayer, 2006; Stoof et al., 2011; Vega et al., 2005; Walsh and Voigt, 1977).
599 Increases in surface roughness due to the vegetation and litter on the soil determine
600 longer time for overland flow takes to begin during a storm (Cawson et al., 2012;
601 Johansen et al., 2001; Leighton-Boyce et al., 2007; Pierson et al., 2009; Stoof et al.,
602 2011; Vega et al., 2005).

603 Overall, regarding the effects of the prescribed fire on the soil hydrology, our study
604 confirms the “classic” post-fire erosion curve (that is characterised by an early single
605 peak immediately after burning), theoretically reported by (~~Shakesby et al. (2015),~~
606 ~~Shakesby and Doerr (2006),~~ Swanson (1981), with erosion strongly declining in the
607 subsequent period (Klimas et al., 2020). According to the literature, the effects of an
608 individual prescribed burn lasts for a short period, from three months (Stephens et al.,
609 2004) to one year (Bêche et al., 2005; Cawson et al., 2012). Soil loss then declines in
610 the subsequent months after a fire (Neary et al., 2005; Neary and Leonard, 2021), and is
611 extensive in area but small in magnitude (Morris et al., 2014)

612

613 *4.2. Effects of mulching on runoff and erosion*

614

615 ~~Soil-~~The treatment with fern mulch provided an effective soil protection, which was
616 able to improve the hydrological response of burned soils. Mulching is effective in
617 reducing runoff and erosion rates, since the mulch layer provides a cover that reduces
618 raindrop impact, ~~and~~ prevents soil sealing (Lucas-Borja, 2021), promotes infiltration
619 (Bombino et al., 2021, 2019), and decrease runoff velocity (Lal, 1976; Prats et al.,
620 2016); (~~Prats et al., 2016~~). Moreover, the mulch cover synergistically acts with the
621 remaining litter after burning (Vega et al., 2005) towards a reduction in the hydrological
622 response of the burned soils to heavy seasonal storms.

623 However, it should be noticed that the response of the experimental soils was different
624 among the studied forest species in the short term, but very similar between the two
625 monitored hydrological variables. More specifically, fern mulching was particularly
626 effective in reducing the runoff generation capacity immediately after the prescribed fire
627 in both ~~pine and chestnut~~ plots of pine and chestnut. Here, reductions in runoff
628 coefficients and erosion by 70-80% were achieved compared to the burned soils.
629 Conversely, this reduction was much lower (25-30%) in oak plots. The effectiveness of

630 fern mulching in our study is higher compared results with Prats et al., (2015, 2014,
631 2013, 2012), ~~who reported runoff reductions between 40 and 60% produced by~~
632 ~~mulching with forest residues or hydro-mulching during the first year, and~~ (Groen and
633 Woods ~~(,2008)~~ and (Robichaud et al. ~~(,2013)~~). ~~The first authors, who achieved~~
634 ~~decreases in runoff between 30 and 60% using straw mulch under rainfall simulations~~
635 ~~and small paired catchments, respectively. reported runoff reductions between 40 and~~
636 ~~60% produced by mulching with forest residues or hydro-mulching during the first year.~~
637 ~~Groen and Woods (2008) and Robichaud et al. (2013) achieved decreases in runoff~~
638 ~~between 30 and 60% using straw mulch under rainfall simulations and small paired~~
639 ~~catchments, respectively.~~

640 In our study, the beneficial effects of the mulching treatment in the short term were not
641 generally due to the changes in the hydraulic properties of the soils (namely IR and
642 SWR). ~~, and t~~This contrasts the statement by (Lal ~~(,1976)~~, who reports that a mulch
643 layer increases water infiltration and surface storage, and improves soil structure and
644 porosity (Prats et al., 2015). ~~This is confirmed by~~ (Carrà et al. ~~(,2021)~~, ~~who~~ reported
645 that, ~~-~~in the same forest stands, the mean IR slightly increased in the chestnut and oak
646 soils of chestnut and oak, but did not vary in pine forests. According to the same
647 authors, the SWR was not affected by mulching, in ~~accordance-line~~ with (Prats et al.,
648 2015). This result is expected, since the vegetal residues require time to be incorporated
649 into the soil and to play effects on soil hydrology (Bombino et al., 2021, 2019). Instead,
650 mulching ~~played its~~was effectiveness at providing soil with a cover of vegetal residues,
651 as shown by the decreases in bare soil percentage and the progressive establishment of
652 litter (except in chestnut) and shrubs compared to the burned soils.

653 The improvement ~~of-in the~~ hydrological response of the burned forests due to mulching
654 was losing importance over time, since the pre-fire soil hydrology (runoff coefficients
655 and erosion rates) ~~was restored~~ just recovered some months after burning. However, in
656 ~~pine and chestnut~~ soils of pine and chestnut, the runoff generation capacity was even
657 lower compared to the unburned plots, and the same was observed for erosion in the
658 chestnut forest. This means that the soil treatment with mulching may also be effective
659 throughout ~~also~~ several months after fire, since the vegetal residues ~~have been~~are
660 incorporated into the soil, where organic matter increases and plays beneficial effects on
661 soil macroporosity and infiltration capacity (Bombino et al., 2021, 2019; Lucas-Borja et
662 al., 2019b; Shabanpour et al., 2020). As a matter of fact, one year after fire, the study by
663 (Carrà et al. ~~(,2021)~~) demonstrated that the infiltration capacity of soils mulched with

664 fern noticeably increased over time, particularly in the soils of chestnut and oak, and
665 less in the pine forestsoils among-in all soil conditions. However, the incomplete
666 recovery of the pre-fire infiltration values of IR did not significantly alter the runoff and
667 erosion rates compared to the unburned soils, and it may be presumably-presumable that
668 this recovery will complete in the short term (Carrà et al., 2021).

669 One year after fire, the litter cover was-restoredrecovered in the oak and pine forests of
670 oak and pine. However,-but the area with bare soil was higher compared to the soil
671 condition detected immediately after the prescribed burning, since the mulch cover has
672 progressively disappeared due to wind and degradation of the vegetal material. A
673 comparative analysis of the organic matter content among the different soil conditions -
674 not carried out in this study, since it was beyond its hydrological focus - could have
675 quantified the amount of degraded mulch residues incorporated into the soil over time.

676

677 5. Conclusions

678

679 This study has evaluated runoff and erosion in soils of three Mediterranean forests after
680 a prescribed fire and mulching treatment, and the results help in replying to the four
681 three research questions supporting the investigation.

682 First, immediately after the prescribed fire, runoff and erosion significantly increase in
683 all forest plots compared to the unburned soils. However,-but these increases (by 150%
684 to 375% for the runoff coefficients, and by 100% to 800% for the soil losses) are much
685 lower compared to the highest values reported by some studiesin some studies.

686 Secondly, the window of disturbance after fire is limited to three-four months after fire,
687 and, after five months, the pre-fire runoff generation and erosion rates-of the soils are
688 practically restored, and, if the runoff and erosion are still higherincreased compared to
689 the unburned soils, these changes are not significant.

690 Thirdly, the mulch application using fern residues, which is widely available in
691 Mediterranean forest and is more advisable compared to the most common use of straw,
692 is effective to-at limiting the increase in the hydrological response observed in the
693 burned soils. This has been demonstrated by reductions in runoff coefficients and
694 erosion-soil losses by 70-80% (except for oak soils, -25-30% for both runoff and
695 erosion) in the experimental sites.

696 The changes in soil hydrology due to the prescribed fire are due to the reductions in IR,
697 occurrence-of SWR (particularly in pine and oak soils of pine and oak), and litter and

698 vegetation removal. The soil cover due to mulching is effective and its influence on
699 water infiltration and repellency [in the burned soils](#) is very limited ~~on the hydrological~~
700 ~~response of the burned soils.~~ T, while the increases in these hydraulic properties gain
701 importance over time and become beneficial one year after fire, even determining in
702 some cases higher infiltration, and lower runoff and erosion compared to the unburned
703 soils.

704 Further research is needed (i) to validate the results of this study achieved ~~in the~~ plots
705 ~~scale~~ through upscaling ~~to the~~ hillslopes or better catchments ~~scale~~, and (ii) to explore
706 the influence of the physico-chemical properties (particularly ~~for the~~ organic matter
707 content) on [the](#) soil hydrology under burned (with and without treatments) conditions.

708 Overall, the results of this investigation can support the tasks of landscape managers to
709 identify proper fuel management practices for wildfire risk reduction (such as the
710 prescribed fire), and of hydrologists to identify cheap and effective techniques of
711 ecological engineering (such as the mulching with fern) in [the Mediterranean](#) forests.

712

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723

724

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984

985 [Supplementary material](#)

986

987 [Table 1SM - Runoff volume and its sediment concentration measured in plots after prescribed fire and soil mulching using fern \(Samo, Calabria,](#)
 988 [Southern Italy\).](#)

989

<u>Event date</u>	<u>Runoff volume (mm)</u>						<u>Sediment concentration (g/l)</u>					
	<u>Unburned soil</u>		<u>Burned soil</u>		<u>Burned and mulched soil</u>		<u>Unburned soil</u>		<u>Burned soil</u>		<u>Burned and mulched soil</u>	
	<u>Mean</u>	<u>Std. Dev.</u>	<u>Mean</u>	<u>Std. Dev.</u>	<u>Mean</u>	<u>Std. Dev.</u>	<u>Mean</u>	<u>Std. Dev.</u>	<u>Mean</u>	<u>Std. Dev.</u>	<u>Mean</u>	<u>Std. Dev.</u>
<i>Pine</i>												
15 Jul 2019	4.69	1.74	22.31	1.35	6.63	1.16	1.20	0.34	2.35	0.36	1.64	0.37
9 Oct 2019	0.00	0.00	11.03	3.74	4.37	0.33	0.00	0.00	1.47	0.14	0.26	0.02
11 Nov 2019	10.22	4.80	11.12	0.53	10.35	0.80	0.47	0.45	0.21	0.13	0.18	0.02
23 Nov 2019	6.18	4.78	7.01	1.02	5.41	1.73	0.11	0.12	0.19	0.10	0.03	0.02
5 Dec 2019	7.85	6.59	8.44	1.02	8.91	2.40	0.00	0.00	0.07	0.05	0.00	0.00
24 Mar 2020	13.06	11.16	19.77	5.98	8.81	0.60	0.02	0.02	0.03	0.02	0.03	0.01
<i>Chestnut</i>												
15 Jul 2019	4.69	0.68	22.30	4.21	6.61	1.69	1.65	0.54	2.32	0.18	2.17	0.24
9 Oct 2019	8.44	1.16	16.98	5.44	3.00	1.23	1.86	0.59	2.08	1.14	0.58	0.26

11 Nov 2019	13.45	8.25	16.93	9.04	4.64	1.93	0.27	0.05	0.43	0.13	0.19	0.04
23 Nov 2019	8.39	4.32	12.49	8.29	2.51	0.41	0.30	0.03	0.55	0.11	0.10	0.02
5 Dec 2019	11.10	6.60	13.03	11.86	3.24	0.71	0.10	0.00	0.07	0.06	0.00	0.00
24 Mar 2020	18.13	12.92	22.11	12.07	2.98	0.29	0.16	0.11	0.25	0.12	0.13	0.05
14 Jul 2020	3.37	1.28	3.85	1.72	1.25	0.37	0.00	0.00	0.00	0.00	0.00	0.00
<i>Oak</i>												
15 Jul 2019	12.55	2.90	31.34	2.29	22.98	3.69	1.58	0.15	1.48	0.37	1.51	0.09
9 Oct 2019	0.00	0.00	10.00	3.13	3.27	2.83	0.00	0.00	0.90	0.26	0.51	0.89
11 Nov 2019	16.35	3.11	20.64	3.05	17.81	1.68	0.31	0.06	0.34	0.13	0.32	0.06
23 Nov 2019	7.70	2.80	15.86	6.84	9.66	0.17	0.59	0.22	1.12	0.96	0.89	0.29
5 Dec 2019	11.01	1.30	21.11	10.64	16.52	0.86	0.40	0.17	0.48	0.20	0.40	0.09
24 Mar 2020	16.36	6.01	22.11	5.32	18.78	1.20	0.32	0.06	0.37	0.05	0.29	0.03

990

1 **Prescribed fire and soil mulching with fern in Mediterranean forests: Effects on**
2 **surface runoff and erosion**

3

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14

15 **Abstract**

16

17 Prescribed burning is increasingly used to reduce the wildfire risk, and the need to limit
18 runoff and erosion after the fire suggests treating burned soils with mulching. To this
19 aim, fern residues may be more advisable compared to the commonly used straw, since
20 fern is directly available in forests and has lower drawbacks. However, the post-fire
21 hydrological effects of both prescribed fire and soil mulching are contrasting in
22 literature, and fern has not previously experimented as mulching material in
23 Mediterranean forests. To fill these gaps, this study has evaluated the soil hydrological
24 response in small plots installed in three Mediterranean forests (pine, chestnut and oak)
25 after a prescribed fire and mulching treatment with fern. Compared to the unburned
26 soils, runoff and erosion significantly increased immediately after fire (by 150% to
27 375% for the runoff coefficients, and by 100% to 800% for the soil losses). However,
28 these increases are much lower compared to the highest values reported by some
29 studies. The negative impacts on the hydrological response in burned soils were limited
30 to three-four months after burning. Subsequently, the pre-fire runoff and erosion rates of
31 the burned soils were practically recovered, and the hydrological changes were not
32 significant compared to the unburned soils. In the short term after the prescribed fire
33 application, soil mulching with fern residues was effective to limit the increase in the
34 hydrological response of the burned and not treated soils, since the runoff coefficients

35 and erosion were reduced by 25-30% in oak soils and 70-80% in forests of chestnut and
36 pine. The changes surveyed in soil hydrology were associated to variations in the
37 infiltration rates and water repellency immediately after fire, previously detected in the
38 same experimental site. The recovery of the water infiltration rates and the
39 disappearance of the soil repellency gained importance over time, and the incorporation
40 of mulch residues became beneficial in driving the short-term runoff and erosion
41 response of the burned soils.

42

43 **Keywords:** ecological engineering techniques; post-fire management; hydrological
44 response; pine; chestnut; oak.

45

46 **1. Introduction**

47

48 Fire, a key ecological factor in the earth system (Francos and Úbeda, 2021), impacts on
49 many components of ecosystems (soil, air, water, plants and fauna, e.g. DeBano et al.,
50 1998; Lucas-Borja et al., 2019b; Kozłowski, 2012) as well as on the ecosystem services,
51 society and economy (Nadal-Romero et al., 2018; Pereira et al., 2018a). These effects
52 depend on several factors, such as fire history, intensity and severity, fuel quantity,
53 properties and topography of soils, vegetation species, density and cover, weather
54 patterns, etc. (Zavala et al., 2014; Pereira et al., 2018b; Francos et al., 2018; Zema,
55 2021).

56 With specific regard to the environmental impacts, wildfire removes vegetation and
57 reduces its capacity to recover, and determines long-lasting changes in soil properties
58 (Neary et al., 1999; Certini, 2005; Shakesby, 2011). Vegetation removal (which leaves
59 the soil bare) and soil changes (resulting in increased water repellency, destruction of
60 aggregates and reduced water infiltration) due to wildfire increase the surface runoff and
61 erosion rates. Moreover, the transport of nutrients and contaminants downstream of
62 burned forests is enhanced (Neary et al., 1999; Certini, 2005; Shakesby and Doerr,
63 2006; Cawson et al., 2012; Vieira et al., 2015; Zema, 2021). In addition, the runoff and
64 erosion rates come back to the pre-fire values after five to ten years (Inbar et al., 1998).
65 The increase in flood and erosion risks after fire is an essential problem for land owners
66 and catchment managers (Prats et al., 2015).

67 In order to limit the negative impacts of high-severity fires, preventing strategies have
68 been adopted since long time (Ferreira et al., 2015). Among these strategies, prescribed

69 fire - the planned use of low-intensity fire to achieve very different goals given certain
70 weather, fuel and topographic conditions (Fernandes et al., 2013) - is considered as a
71 primary and integrated option to reduce the wildfire risk in forests (Alcañiz et al., 2018;
72 Klimas et al., 2020). The low-intensity fire, which is applied under controlled
73 environmental conditions (e.g., humid air and absent wind), removes dry litter, and
74 herbaceous and shrub vegetation, which is fuel for forest wildfires in the summer or
75 other dry periods. Since the fuel for wildfires is regenerating after the prescribed fire,
76 repeated applications are needed to control the wildfire risk over time. Moreover, the
77 prescribed fire, which has low-severity and burn patchiness (Cawson et al., 2012;
78 Pereira et al., 2021), avoids high temperature in soil and tree crown burning, which are
79 the most adverse effects of wildfire on soil and plants. In addition, prescribed fire
80 supports regeneration of some plant species (Scharenbroch et al., 2012; Williams et al.,
81 2012; Francos and Úbeda, 2021). Litter, herbs and shrubs regenerate after the prescribed
82 fire, and this prevents erosion in the treated forest. However, this renewed vegetal cover
83 is insufficient to recover the pre-fire erosion rates, and thus post-fire management
84 actions are needed. Increases in runoff and erosion after prescribed fires are lower
85 compared to wildfires, but these risks are still present (Morris et al., 2013; Shakesby et
86 al., 2015). Runoff and erosion increases have been observed after prescribed fires in
87 different ecosystems, such as heathlands, shrublands and gorse (Vega et al., 2005). In
88 the Mediterranean forests, these increases may be even more intense compared to other
89 rainstorms (Fortugno et al., 2017), since the soils are generally shallow and show low
90 aggregate stability, and organic matter and nutrient contents (Cantón et al., 2011). Due
91 to the combination of these climate and soil characteristics, the Mediterranean forests
92 are more exposed to excessive runoff and soil erosion rates compared to other
93 ecosystems (Zema et al., 2020a; 2020b). Therefore, there is a need for an improved
94 knowledge about soil hydrology in Mediterranean fire-prone forests, also considering
95 that both wildfires and rainstorms are thought to become more frequent and intense
96 according to the forecasted climate scenarios (Badia and Marti, 2008). However, despite
97 an ample literature about the impacts of fire on soil hydrology, the studies on the
98 hydrological effects of prescribed fire are not exhaustive and often contrasting (Cawson
99 et al., 2012; Shakesby et al., 2015). According to González-Pelayo et al. (2010) and
100 Vega et al. (2005), increases in runoff and erosion by one and two orders of magnitude,
101 respectively, may be observed compared to the unburned areas (Cawson et al., 2013). In
102 contrast, Coelho et al. (2004) and de Dios Benavides-Solorio and MacDonald (2005)

103 reported minimal erosion after prescribed fire (Morris et al., 2013). Keesstra et al.
104 (2014) reported even lower erosion in areas burned with prescribed fire compared to
105 unburned forests, despite comparable runoff.

106 In order to reduce the soil's susceptibility to runoff and erosion after a wildfire, several
107 treatments have been proposed and their effectiveness has been verified in many
108 environmental contexts (Lucas-Borja, 2021; Zema, 2021). Among the ecological
109 engineering techniques, which use plant residues for soil conservation, mulching is one
110 of the most common post-fire management options (Lucas-Borja et al., 2019a;
111 Prosdocimi et al., 2016). The objective of mulching is protecting soil with a ground
112 cover and improving the soil quality, if used properly and at the correct time
113 (Prosdocimi et al., 2016; Zituni et al., 2019). However, post-fire mulching can also have
114 negative effects. In some cases, mulching reduces the soil hydraulic conductivity under
115 unsaturated conditions compared to the untreated soils, particularly in the driest season
116 (Lucas-Borja et al., 2018). Mulching material is selected based on its availability,
117 resistance to degradation, weed spreading risk and other factors (Parhizkar et al., 2021;
118 Prats et al., 2015). Straw is often used as mulch cover in fire-affected areas (Bontrager
119 et al., 2019; Keizer et al., 2018), but its residues can be displaced by wind in some
120 areas, leaving slopes bare, or accumulating in thick layers in other areas, with possible
121 reductions in the post-fire emergence of vegetation (Robichaud et al., 2020). Moreover,
122 agricultural straw may contain seeds, chemicals and parasites, which can be the sources
123 of non-native vegetation and plant diseases. Forest residues (e.g., wood strands, chips or
124 shreds) or dead plants may replace straw, because these substrates do not carry non-
125 native seeds or chemical residues, and are more resistant to wind displacement
126 (Robichaud et al., 2020). In Mediterranean forest floor, fern - *Pteridium aquilinum* (L.)
127 Kuhn - is widely available, and this avoids the transport costs from other locations.
128 Therefore, its use as mulching material in fire-affected areas is preferable to straw.
129 However, to the authors' best knowledge, no evaluations about the use of fern to protect
130 the burned soil from runoff and erosion impacts are available in literature. Therefore,
131 the effectiveness of fern mulching to restore the hydrological properties of soils should
132 be assessed, and particularly in the short-term after fire, when the soil is left bare and
133 the changes in the soil properties (e.g., reduced infiltration, soil water repellency and
134 ash cover) can be significant compared to the unburned and untreated areas (Cawson et
135 al., 2012; Francos and Úbeda, 2021; Klimas et al., 2020; Wittenberg and Pereira, 2021).
136 A previous study, carried out in the same environment using a rainfall simulator,

137 showed that soil mulching with fern did not increase the water infiltration rates (IR) and
138 did not alter soil water repellency (SWR) of the burned soils at the point scale
139 immediately after a prescribed fire. However, one year after the soil treatment, the IR
140 noticeably increased and the SWR completely disappeared (Carrà et al., 2021).

141 To fill the research gaps and extend the previous investigation to the plot scale, this
142 study has evaluated the hydrological response of soils in three forest stands of Calabria
143 (Southern Italy) after a prescribed fire, with or without a mulching treatment with fern,
144 in comparison to the undisturbed soils. More specifically, the surface runoff volumes
145 and soil losses were measured after natural precipitation throughout one year after fire
146 in forests of pine, oak and chestnut. The specific research questions are the following:
147 (i) how much does the prescribed fire affect runoff and erosion rates on the short term
148 after its application? (ii) how long is the “window of disturbance” (Prosser and
149 Williams, 1998) of soil hydrology due to fire? (iii) are the fern residues effective as
150 mulching cover at reducing the runoff and erosion after fire?

151 The experimental replies to these research questions may be of help to promote the use
152 of the prescribed fire against the wildfire risk and of the soil mulching with fern as
153 ecological engineering technique for the conservation of forest soils.

154

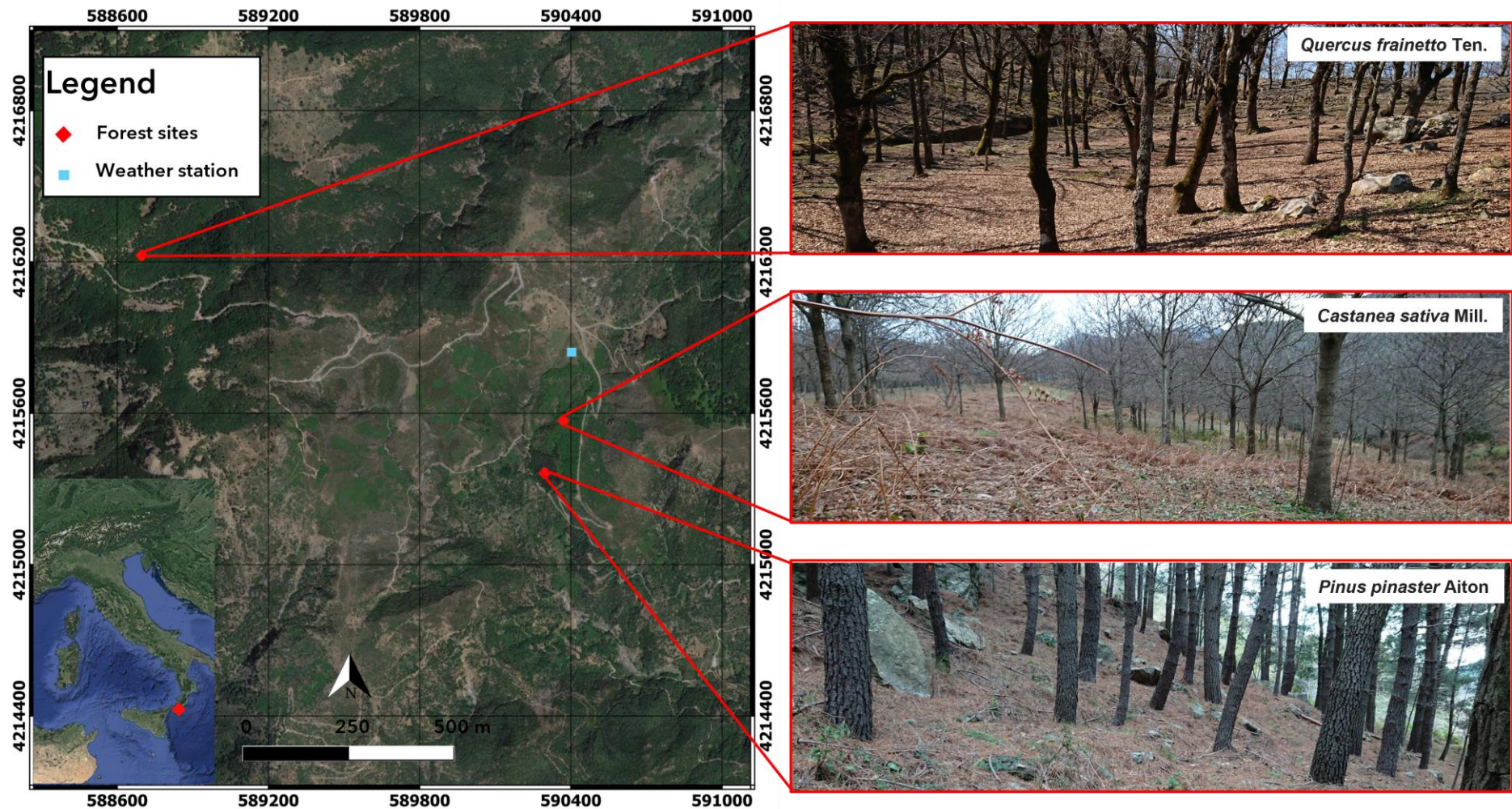
155 **2. Material and methods**

156

157 *2.1. Study area*

158

159 The study was carried out in three forest sites (municipality of Samo, Calabria, Southern
160 Italy) between 600 and 900 m above the sea level (Figure 1 and Table 1). The first area
161 (“Calamacia”) was a pine (*Pinus pinaster* Aiton) stand reforested in 1984. The second
162 site (“Rungia”) was a natural oak stand (*Quercus frainetto* Ten.). The third zone
163 (“Orgaro”) was a chestnut stand (*Castanea sativa* Mill., about 29-year old). No
164 management actions were carried out in the three forest stands (Table 1).



165

166 Figure 1 - Location of the experimental site (Samo, Calabria, Southern Italy).

167

168

169 Table 1 - Main characteristics of the experimental forest sites (Samo, Calabria, Southern Italy).

170

Characteristics		Site		
		<i>Calamacia</i>	<i>Rungia</i>	<i>Orgaro</i>
U.T.M. coordinates		590293 E; 4215327 N	588635 E; 4216172 N	590389 E; 4215530 N
Aspect		South-West	North-East	West
Altitude (m a.s.l.)		650-700	900-950	700-750
Slope (%)		20.0 ± 0.82	19.1 ± 1.65	20.3 ± 0.96
Tree	species	Pine <i>(Pinus pinaster Aiton)</i>	Oak <i>(Quercus frainetto Ten.)</i>	Chestnut <i>(Castanea sativa Mill.)</i>
	density (n/ha)	950 ± 86.4	225 ± 44.7	725 ± 89.1
	diameter at breast height (cm)	28.3 ± 9.4	40.7 ± 8.9	20.2 ± 5.6
	height (m)	20.5 ± 1.4	18.2 ± 1.9	9.6 ± 1.2
	basal area (m ² /ha)	67.9 ± 6.5	31.1 ± 3.6	24.3 ± 4.4
-		<i>Quercus ilex L., Rubus ulmifolius S.</i>	<i>Cyclamen hederifolium</i>	<i>Rubus ulmifolius S., Pteridium aquilinum L.</i>
Litterfall layer depth (cm)		11.7 ± 4.6	12.2 ± 3.9	6.1 ± 4

171 The climate of the area is typical of the semi-arid environment (“Csa” class, “Hot-
172 summer Mediterranean” climate, according to Koppen classification (Kottek et al.,
173 2006). Winters are mild and rainy, while summers are warm and dry. The mean annual
174 precipitation and temperature are 1102 mm and 17.4 °C, respectively. The minimum
175 temperature is - 4.3 °C, while the maximum is 43.1 °C (weather station of Sant’Agata
176 del Bianco, geographical coordinates 4217548 N, 595159 E, period of 2000-2020).
177 All soils are loamy, except the unburned area of the pine forest, which is sandy loam
178 (Table 2).

179 Table 2 - Main characteristics of the soils in the experimental sites measured immediately after the prescribed fire and before the mulching
 180 treatment (Samo, Calabria, Southern Italy).

181

Site	Main forest species	Soil condition	Texture			Type
			silt (%)	clay (%)	sand (%)	
Calamacia	pine	unburned	10.0 ± 1.01	9.0 ± 0.00	81.0 ± 0.99	sandy loam
		burned	6.3 ± 3.06	8.7 ± 0.58	85.0 ± 3.61	
Rungia	oak	unburned	12.7 ± 1.53	9.7 ± 0.58	77.7 ± 1.15	loamy sand
		burned	10.3 ± 2.25	8.7 ± 0.58	81.0 ± 2.02	
Orgaro	chestnut	unburned	12.3 ± 2.31	8.0 ± 1.73	79.7 ± 0.58	
		burned	11.3 ± 1.53	8.7 ± 0.58	80.2 ± 1.04	

182

183

184 *2.2. Prescribed fire operations and mulching application*

185

186 The prescribed fire was applied in early June 2019 with the support of the
187 Environmental Regional Agency (“Calabria Verde”) and the surveillance of the
188 National Corp of Firefighters (Figure 2a).

189 The main conditions during fire application (temperatures of fire flame, air and soil) are
190 reported in Table 3. These variables were measured by a thermocouple connected to a
191 datalogger at a soil depth of 2 cm. Wind was practically absent and air humidity was
192 between 50 and 60%. The mean soil temperature was lower than 25 °C with a
193 maximum of 29 °C, about 4 °C higher compared to the temperature of the unburned
194 soils.

195

196 Table 3 – Main conditions during prescribed fire application to the experimental site
197 (Samo, Calabria, Southern Italy).

198

Site	Main forest species	Temperature					
		fire flame		air		soil	
		mean	max	mean	max	mean	max
Calamacia	pine	88	712	25.7	102	21.9	22.7
Rungia	oak	98	720	43.0	180	21.0	26.9
Orgaro	chestnut	75	645	29.1	139	24.7	28.8

199

200

201 In the burned area, one day after fire, some plots (see section 2.3) were covered with
202 small pieces (maximum length of 5 cm) of fern. The plants were cut from an adjacent
203 area in the same forests and shredded using scissors in pieces of 5 cm as maximum size.

204 The fresh residues were spread on the ground without addition of other materials to
205 form a mulch layer of 2-3 cm. The applied dose was 500 g/m² of fresh weight, which is
206 equivalent to 200 g/m² of dry matter, the dose commonly used as straw mulching after
207 fire (Lucas-Borja et al., 2018; Vega et al., 2014) (Figure 2b).

208

209



210

211

212

(a)



(b)

Figure 2 – Prescribed fire operations (a) and fern mulch applied to three plots of oak (b) in the experimental site (Samo, Calabria, Southern Italy).

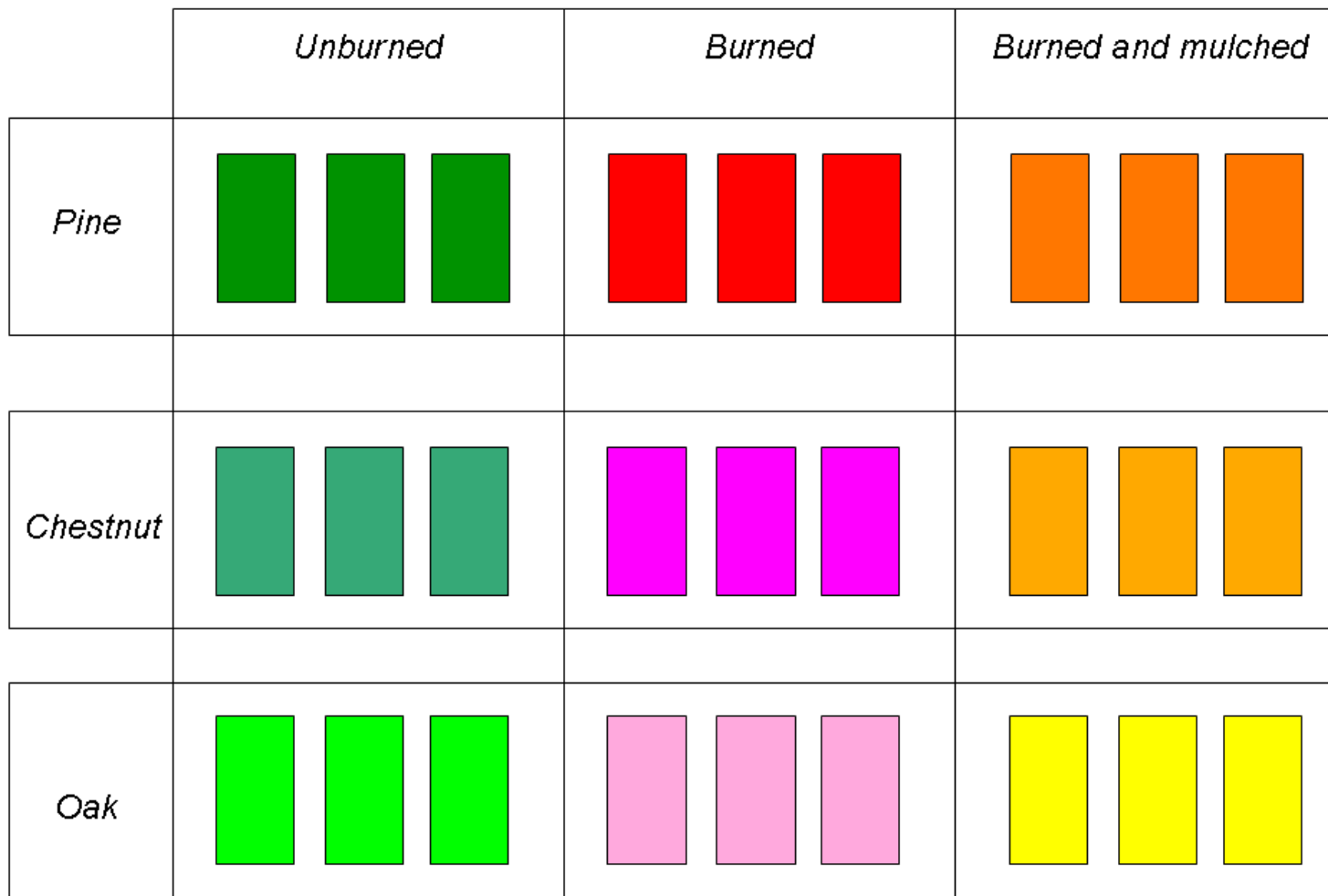
2.3. Experimental design

One of the most useful tools to study the fire effects is applying experimental fires and measuring their effects on soil hydrology in plots. This allows the control and evaluation of the fire and soil conditions before, during and after the experiment (González-Pelayo et al., 2010). The current study has adopted the suggested approach and, in each experimental site, nine small plots (three series, each one with three replicated plots) were delimited on forest hillslopes with the same gradient (Table 1). The plots were at a reciprocal distance between 1.5 and 20 m. Three plots were setup in the unburned soils (considered as “control”), while six plots were in the burned area. In the latter sites, three plots were subjected to mulching with fern. Overall, the experimental design consisted of three forest stands (pine, oak and chestnut) × three soil conditions (unburned, burned and not treated, and burned and mulched) × three replicated plots, for a total of 27 plots (Figure 3).

234 *2.4. Plot construction*

235

236 Immediately after fire, the plots (each one being 3-m long and 1-m wide and covering
237 an area of 3 m²) were hydraulically isolated in each forest area (unburned, burned and
238 not treated, and burned and mulched soil). Some 0.3-m high metallic sheets were
239 therefore inserted up to 0.2 m below the ground surface, in order to prevent the flow of
240 surface water (Figure 2b). Downstream of each plot, a transverse channel was installed,
241 to intercept the flows of water and solid material. These flows were collected through a
242 pipe into 100-litre tanks.



243

244 Figure 3 – Scheme and plot layout of the experimental design used for the hydrological monitoring after prescribed fire and soil mulching using
 245 fern (Samo, Calabria, Southern Italy).

246

247 *2.5. Monitoring of the hydrological variables*

248

249 The hydrological measurements started immediately after site installation (mid-June
250 2019) and were carried out throughout 15 months (until mid-September 2020).

251 A weather station with a tipping bucket rain gauge (measuring sub-hourly data) was
252 installed at a maximum distance of 1 km from the experimental sites, to measure
253 precipitation height, storm duration, and rainfall intensity. The mean rainfall intensity
254 was the total rainfall divided by the storm duration. Moreover, an additional rain gauge
255 (measuring only the rainfall height) was installed in each forest site, in order to estimate
256 the rainfall intercepted by the tree canopy, and to check the spatial variability of the
257 rainfall measured by the main weather station.

258 The surface runoff and sediment concentration after precipitation were measured
259 following the procedures suggested by Lucas-Borja et al. (2019b) and Bombino et al.
260 (2021). Only the runoff volumes produced by rainfalls over 13 mm, which can be
261 considered as “erosive events”, according to (Wischmeier and Smith, 1978), were
262 monitored. The collecting tanks were emptied and cleaned after each precipitation -
263 erosive or not - event. To summarize, the runoff water in the tank was stirred to achieve
264 a good suspension, and three separate samples of the suspension was collected, totalling
265 about 0.5 litres. The samples were brought to the laboratory, and oven-dried at 105 °C
266 for 24 hours. After drying, the sediments were weighted and referred to the sample
267 volume, in order to calculate the sediment concentration. The soil loss produced by the
268 rainfall-runoff event was estimated by the product of the runoff volume by the sediment
269 concentration. The runoff coefficients were also calculated as the ratio of runoff to
270 rainfall.

271

272 *2.7. Statistical analyses*

273

274 One-way ANOVA with repeated measures (at each rainfall-runoff event) was applied to
275 the runoff volume and soil loss (response variables) separately for the three forest
276 stands, assuming as factor the soil condition (unburned, burned and not treated, and
277 burned and mulched). The pairwise comparison by Tukey’s test (at $p < 0.05$) was also
278 used to evaluate the statistical significance of the differences in the response variables.
279 In order to satisfy the assumptions of the statistical tests (homogeneity of variance and

280 normal distribution), the data were subjected to normality test or were square root-
 281 transformed whenever necessary. All the statistical tests were carried out by with the
 282 XLSTAT software (release 2019.1, Addinsoft, Paris, France).

283

284 **3. Results**

285

286 *3.1. Rainfall characterization*

287

288 Throughout the monitoring period, 516 rainfall events with a total depth of 1120 were
 289 recorded at the rain gauging station. Of these events, only seven were classified as
 290 erosive events and then monitored. The height of these events was in the range of 22.4
 291 (14 July 2020) - 156 (11 March 2020) mm, while their duration varied between 7 (14
 292 July 2020) and 41 (11 November 2019) hours. The latter event was characterized by the
 293 maximum absolute intensity (26.2 mm/h), while the event of 5 December 2019 had the
 294 highest mean intensity (4.90 mm/h). One event (dated 24 July 2020) produced runoff
 295 and erosion only in the chestnut plots (Table 4).

296 The spatial variability of the precipitation among the three forest sites was very low (<
 297 5%) for all the monitored events. The net rainfall (due to the interception) was between
 298 4-10% (pine and chestnut forests) and 6-12% (oak site) of the total precipitation (Table
 299 4).

300

301 Table 4 - Main hydrological variables of erosive rainfall events monitored in the
 302 experimental site (Samo, Calabria, Southern Italy).

303

Date	Height (mm)	Net height (mm)*			Duration (h)	Intensity (mm/h)	
		pine	oak	chestnut		max	mean
15 Jul 2019	65	61.8	59.8	60.5	36	22.2	1.99
9 Oct 2019	49.9	45.4	43.9	44.9	26	14.6	1.85
11 Nov 2019	142.8	135.7	132.8	132.8	41	26.2	3.49
23 Nov 2019	87.1	82.7	81.0	81.9	19	24.7	4.58
5 Dec 2019	147.2	141.3	138.4	139.8	30	19	4.90
24 Mar 2020	155.9	149.7	146.5	149.7	32	13.8	2.86

14 Jul 2020	22.4	20.6	19.7	20.4	7	12.8	2.58
-------------	------	------	------	------	---	------	------

Note: recorded at the rain gauge station under tree canopy in each forest.

304

305

306 3.2. *Runoff*

307

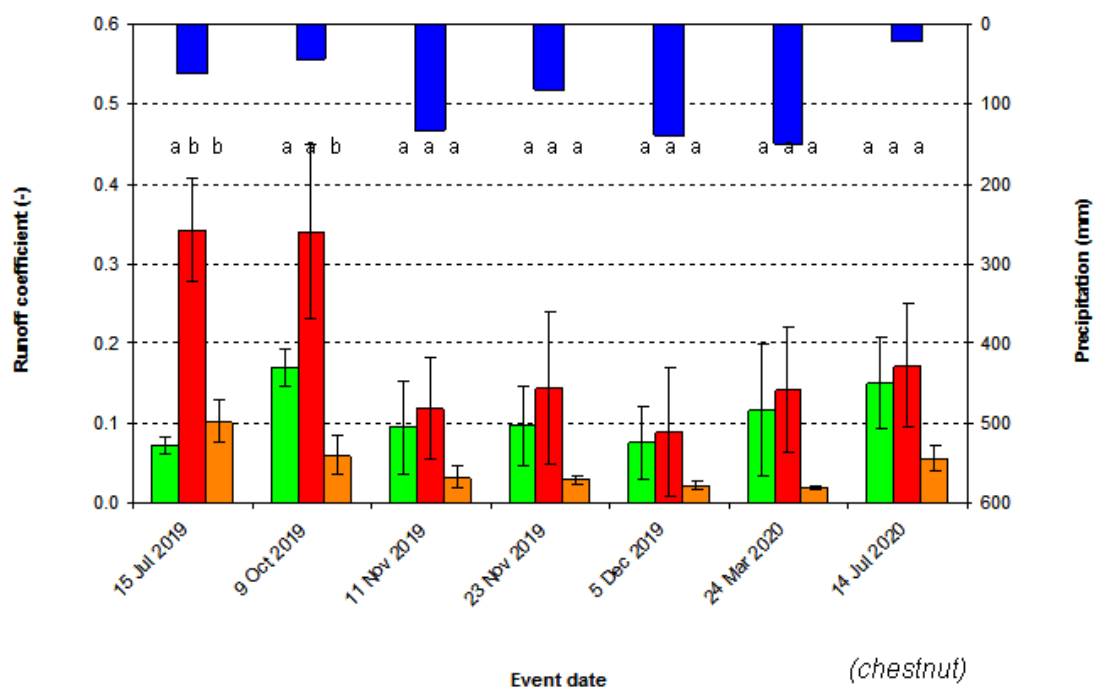
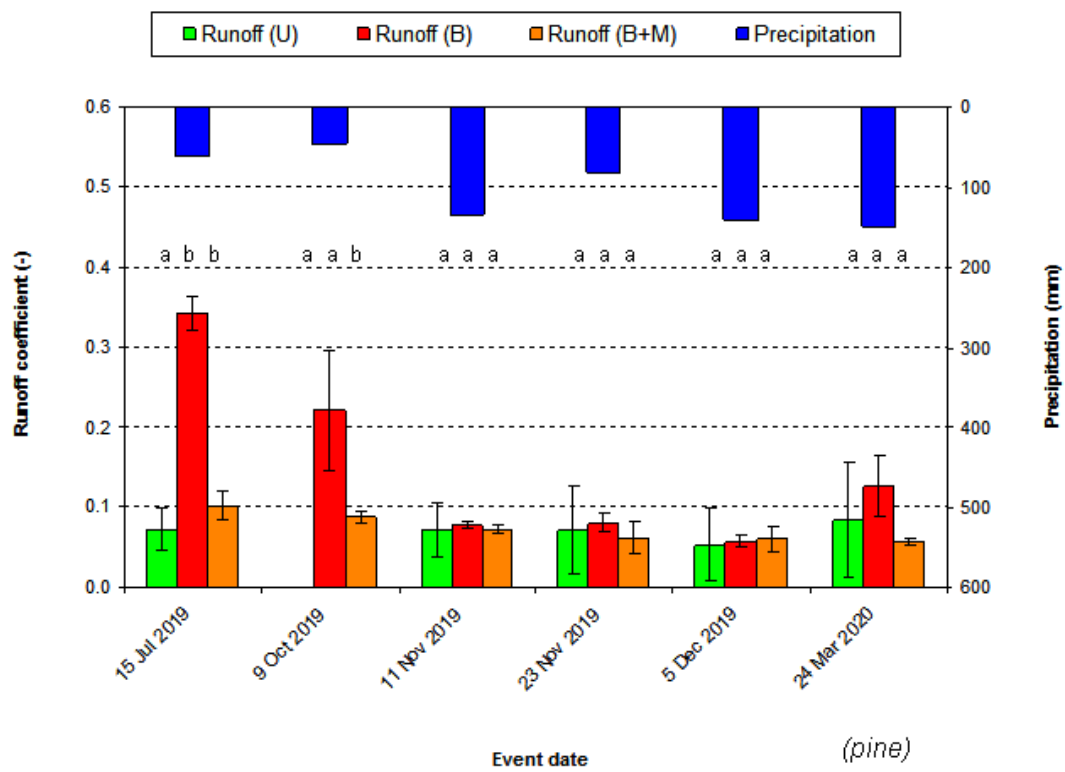
308 The runoff volumes measured at the experimental plots are reported in Table 1SM of
 309 the Supplementary Materials. These measurements coupled to the rainfall records were
 310 the base for the evaluation of the hydrological response of the three soil conditions to
 311 burning and post-fire mulching in terms of runoff coefficient (that is, runoff
 312 standardised to the unit rainfall). In the unburned plots, this coefficient showed a low
 313 variability (0-0.08, pine, 0.07-0.17, chestnut, and 0.00-0.19, oak forest) (Figure 4).

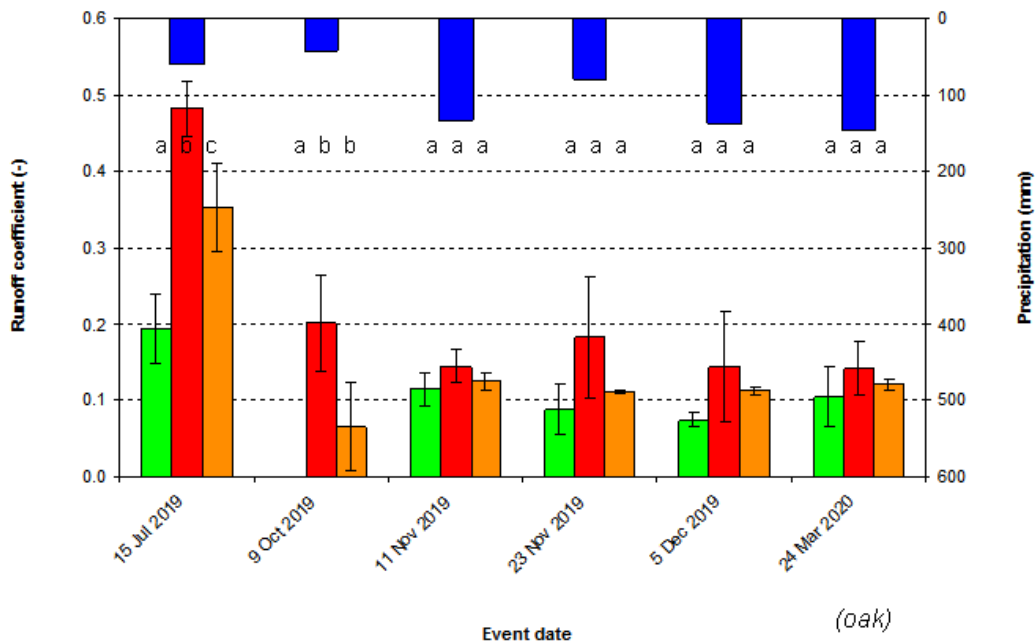
314 In contrast, immediately after the prescribed fire, the runoff coefficient suddenly
 315 increased in all forest plots (up to a maximum of 0.48 ± 0.04 in the oak forest). In the
 316 plots of pine and chestnut, a high runoff coefficient was also noticed also after the
 317 second storm (0.22 ± 0.08 and 0.34 ± 0.11 , respectively). In the oak forest, this
 318 coefficient decreased to values (0.20 ± 0.06) that were very similar to the unburned soil,
 319 and remained lower than 0.18. In the plots of pine and chestnut, the runoff coefficients
 320 decreased over time, and, after the third precipitation event, returned to very low values
 321 (lower than 0.13, pine, and 0.17, chestnut), which were close to the undisturbed soils
 322 (Figure 4).

323 Mulching with fern was effective in decreasing the runoff generation capacity
 324 immediately after the prescribed fire particularly in the plots of pine and chestnut. In
 325 these forests, the runoff coefficients after the first rainfall event were 0.10 ± 0.02 and
 326 0.10 ± 0.03 , respectively. This means that the runoff volume collected in the plot tanks
 327 was less than one third compared to the burned soils. In contrast, in oak plots, the runoff
 328 coefficient was 0.35 ± 0.06 , about 27% less than in the burned plots. Over time, in
 329 burned and mulched plots of pine and oak, the runoff coefficients of the unburned soils
 330 (lower than 0.10, pine, and 0.12, oak) recovered, while, in the chestnut plots, these
 331 coefficients decreased to values (less than 0.06) that were significantly lower compared
 332 to the control soils (Figure 4).

333

334





336

337 Figure 4 - Precipitation and runoff coefficients measured in plots after prescribed fire
 338 and soil mulching using fern (Samo, Calabria, Southern Italy).

339 Notes: U = unburned soils; B = burned and not treated soils; B + M = burned and mulched soils.
 340 Different letters indicate statistically significant differences after Tukey's test ($p < 0.05$).

341

342

343 3.3. Erosion

344

345 The measurements of sediment concentration in the runoff volume, reported in Table
 346 1SM of the Supplementary Materials, allowed the changes in soil erosion rates after the
 347 prescribed fire and post-fire mulching in comparison to the unburned soils.

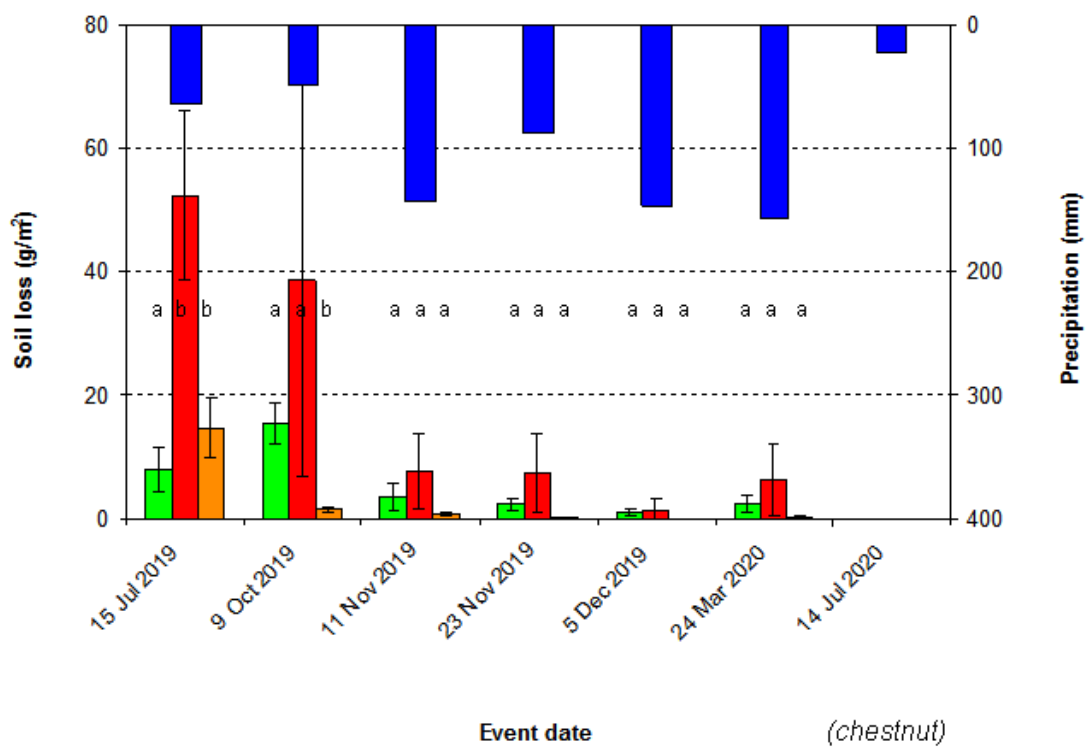
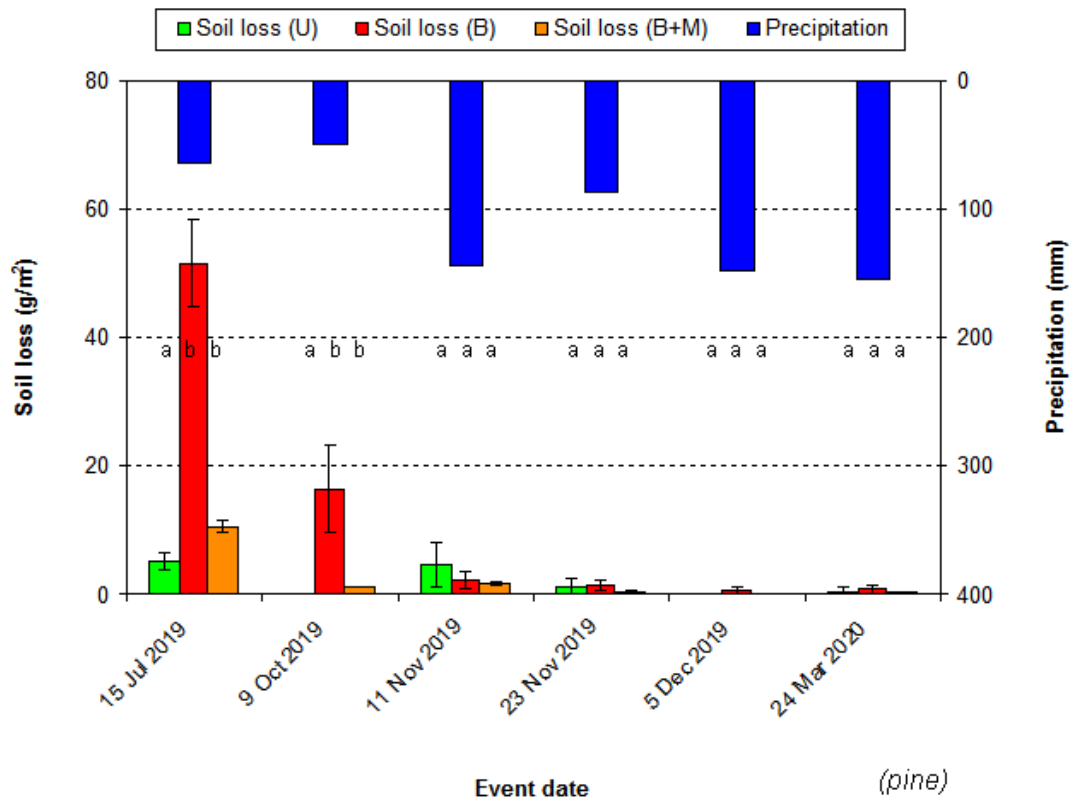
348 As expected, the soil loss was of low amount in the unburned plots. The maximum
 349 erosion was estimated after the first event in the forests of pine and oak (5.31 ± 1.40 and
 350 7.37 ± 2.72 g/m², respectively), while the rainfall event that produced the highest soil
 351 loss (15.34 ± 3.21 g/m²) in the chestnut soil was the second event (Figure 5).

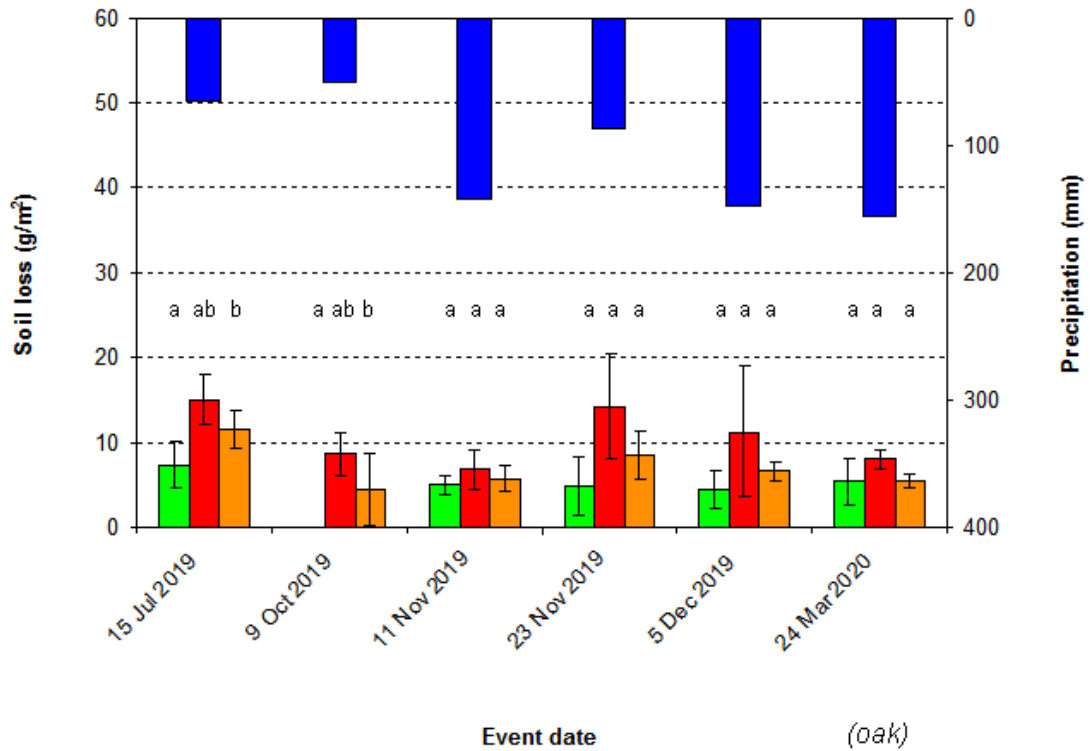
352 For these two rainfall events, erosion increased very much in burned soils of all forests,
 353 and mainly in the soils of pine and chestnut. In these plots, the maximum values of soil
 354 loss, equal to 51.61 ± 6.92 and 52.26 ± 13.67 g/m², were detected after the first event. In
 355 the oak soils, erosion was noticeably lower, 15.12 ± 2.87 g/m² (although higher
 356 compared to the unburned plots). However, mulching was effective to reduce these soil

357 losses, and the maximum value ($14.58 \pm 4.80 \text{ g/m}^2$) was detected in chestnut forest. The
358 highest erosion in the mulched soils was always estimated after the first rainfall (Figure
359 5).

360 After the first two events, soil loss showed a low variability in unburned soils, with a
361 maximum of $5.44 \pm 2.79 \text{ g/m}^2$ measured in oak plots after the last event. In burned and
362 not treated soils, erosion decreased over time. Similar erosion rates as in the unburned
363 plots were only estimated in the pine forests (up to $2.35 \pm 1.43 \text{ g/m}^2$). In contrast, in the
364 plots of oak and chestnut, the soil losses were higher compared to the unburned soils
365 (up to $14.16 \pm 6.13 \text{ g/m}^2$, oak forest), occurring after the third or fourth event (Figure 5).
366 Covering soil with fern mulch was able to reduce erosion compared to the burned plots,
367 and this beneficial effect was mainly observed in the forests of pine and chestnut. The
368 maximum soil losses ($1.87 \pm 0.33 \text{ g/m}^2$, pine) was observed after the third event, while
369 the erosion was always over $5.40 \pm 0.81 \text{ g/m}^2$ in oak plots. In the plots of pine and
370 chestnut, for all monitored events the soil losses were even lower in comparison to the
371 unburned soils. In the oak forest, the pre-fire erosion rates only recovered for two
372 precipitations (the fourth and the sixth events) (Figure 5).

373





375
 376 Figure 5 - Precipitation and soil loss measured in plots after prescribed fire and soil
 377 mulching using fern (Samo, Calabria, Southern Italy).

378 Notes: U = unburned soils; B = burned and not treated soils; B + M = burned and mulched soils.
 379 Different letters indicate statistically significant differences after Tukey's test ($p < 0.05$).

380

381 4. Discussion

382

383 4.1. Effects of prescribed fire on runoff and erosion

384

385 All forest soils showed low runoff coefficients (not higher than 0.20), which means that,
 386 also after very intense storms (100-150 mm, having return interval estimated in 3-5
 387 years in this area), the runoff generation capacity of these soils is basically limited. This
 388 is mainly due to the high water losses occurring in forest environments, on which high
 389 soil infiltration (mainly due to the noticeable organic matter content), tree canopy
 390 interception (especially in the broadleaf tree species), water retention by litter and
 391 understory, and evapo-transpiration rates are beneficial, e.g., Imeson et al. (1992),
 392 Llorens et al. (2011), and Nadal-Romero et al. (2016). The low runoff generation
 393 measured in the undisturbed soils also limited the erosion rates, whose maximum value
 394 was 0.15 tons per hectare (in the chestnut forest) for the most intense rainstorm.

395 Cumulating all the erosive events observed in this study, erosion never exceeded 0.33
396 tons/ha throughout the monitored year, and this value is well below the tolerance limit
397 of the range 3 to 11.2 tons/ha per year (Bazzoffi, 2009; Wischmeier and Smith, 1978).
398 Immediately after the prescribed fire application, the runoff generation capacity of the
399 soil significantly increased in all forest plots. For the first rainfall event, this increase
400 was quantified between 150% (for the oak forest) and 375% (pine and chestnut)
401 compared to the unburned soils, which represent the pre-fire values. The higher
402 overland flow recorded immediately after burning was presumably due to the decrease
403 in the roughness of the surface soil (Stoof, 2011), due to vegetation and litter removal,
404 and to the reduction in soil's water storage (Govers et al., 2000; Shakesby et al., 2015)
405 due to the lower infiltration.

406 The surveyed increase in runoff is in accordance with Andreu et al. (2001), who
407 reported that the maximum runoff is observed during the early storms after the
408 prescribed fire, the first months being the most critical period for runoff production
409 (González-Pelayo et al., 2010; Rubio et al., 2003). In this study, the significant runoff
410 generation observed in this period (about 2 to 4-fold the values measured in the
411 unburned plots) complies with the results of Vega et al. (2005). These authors found
412 increases in runoff between 2 and 5 times the control values in gorse shrublands of
413 Galicia (NW Spain), although the climate of the studied area is wetter compared to
414 Southern Italy. In disagreement with the latter study, González-Pelayo et al. (2010)
415 reported 10-fold runoff after prescribed burning in a Mediterranean shrub ecosystem
416 close to Valencia (Spain).

417 In our study, immediately after the fire, erosion was in the range 0.09 (oak site) to 0.59
418 (chestnut) tons/ha. Throughout one to five years after prescribed burning, other authors
419 reported erosion in the range 0.2-4.1 tons/ha under natural rainfall in Mediterranean
420 shrubland and grassland (Vega et al., 2005). In contrast, according to Shakesby et al.
421 (2015), soil losses at hillslope scale were never higher than 2.41 tons/ha in the first year
422 after the prescribed fire. A large range of soil loss is shown by Neary and Leonard
423 (2021), from 0.1 to 15 tons/ha per year after low-intensity fires.

424 The soil loss in our burned plots was much higher compared to the unburned soils
425 throughout four to five months after burning. Immediately after application, fire made
426 the soil exposed to erosion, particularly in the forests of pine and chestnut, and less in
427 the oak plots. The increase in the erosion rates due to fire is variable from 500% in
428 chestnut to 800% in pine for the first event, while this increase was only 100% in the

429 oak forest. The erosion rates surveyed in the forests of pine and chestnut are higher than
430 the values reported by Soto et al. (1994) and close to those of Soler et al. (1994). The
431 soil loss surveyed in oak forest was two-fold the erosion of the unburned soils, and this
432 value is similar to the increases in burned areas reported by Vega et al. (2005).
433 Therefore, our study has shown that erosion is not minimal following prescribed fires,
434 in contrast with Morris et al. (2013), Coelho et al. (2004), and de Dios Benavides-
435 Solorio and MacDonald (2005), but never remarkable, as found by other research. For
436 instance, according to González-Pelayo et al. (2010), Inbar et al. (1998), Campo et al.
437 (2006), and Cawson et al. (2013), soil losses can increase even by 100 times the erosion
438 of unburned soils after prescribed fire.

439 The worsened hydrological response of burned soils in the experimental plots was
440 mainly ascribed to two effects: (i) the reduced IR of all forest soils; and (ii) the SWR,
441 particularly in pine and oak soils.

442 The findings of our study are supported by the previous study carried out by (Carrà et
443 al., 2021), who have evaluated the IR and SWR in the same forest stands, using a
444 portable rainfall simulator to measure the IR, and the Water Drop Penetration Test
445 (Bisdorn et al., 1993; Letey, 1969; Woudt, 1959) to estimate the SWR. In more detail, in
446 all forest soils the prescribed fire reduced the mean IR compared to the unburned
447 conditions. The increase in SWR may also have played an important role in increasing
448 runoff and erosion immediately after fire in the soils of pine and oak, since the
449 prescribed burning determined a strong repellency. In contrast, in the chestnut soils the
450 prescribed fire did not alter the slight SWR found in unburned plots (Carrà et al., 2021).
451 Presumably, also the litter and vegetation removal by fire may have played an influence
452 on the hydrological response of the burned soils. Since litter and shrub covers were
453 almost completely removed by the fire in the forests of pine and oak, the soil was left
454 bare and thus exposed to the soil detachment due to the overland flow and as well as to
455 rainsplash erosion. These effects of fire were lower in the chestnut forest, where the
456 litter amount over ground was much lower compared to the other soils. Chestnut usually
457 produces less litter than pine and oak, and this is the basic reason why the chestnut litter
458 was shallower, and its recovery was slower compared to the other forest species.

459 The changes in the hydrological response of the burned soils were not permanent, but
460 remained noticeable throughout 3-4 months. Five months after burning, the low
461 capacity of runoff generation that is typical of the unburned soils practically recovered.
462 The same decreasing trend was noticed for the erosion in the pine soils, where, one year

463 after fire, the soil loss became very similar as the unburned plots. Although declining
464 over time, the increased erosion rates, noticed in the forests of chestnut and oak, were
465 still evident, but not significant, after more than one year from fire application. This
466 means that the recovery of the pre-fire hydrological conditions in the burned soils was
467 not complete, although this incomplete recovery does not play significant effects on
468 runoff and erosion rates. According to the previous study by Carrà et al. (2021), this
469 recovery may be ascribed to the increase in the mean IR and to the disappearance of the
470 SWR, both detected one year after fire. Moreover, in our experimental plots, we
471 visually noticed that, progressively over time, the litter and shrub covers were
472 recovering in the burned soils of oak and pine, thanks to the vegetation regeneration. In
473 contrast, in the chestnut soils, litter cover was still limited after one year, as in the soil
474 condition immediately before and after the prescribed burning. Vegetation recovery and
475 litter accumulation during the growing season reduce the impacts of heavy storms
476 during the wet season, preventing high soil loss (Klimas et al., 2020). Herbaceous and
477 shrub vegetation, and litter covers reduce runoff and erosion rates thanks to rainfall
478 interception, soil surface protection, and evapo-transpiration (DeBano et al., 1998;
479 Sayer, 2006; Stoof et al., 2011; Vega et al., 2005; Walsh and Voigt, 1977). Increases in
480 surface roughness due to the vegetation and litter on the soil determine longer time for
481 overland flow takes to begin during a storm (Cawson et al., 2012; Johansen et al., 2001;
482 Leighton-Boyce et al., 2007; Pierson et al., 2009; Stoof et al., 2011; Vega et al., 2005).
483 Overall, regarding the effects of the prescribed fire on the soil hydrology, our study
484 confirms the “classic” post-fire erosion curve (that is characterised by an early single
485 peak immediately after burning), theoretically reported by Shakesby et al. (2015),
486 Shakesby and Doerr (2006), Swanson (1981), with erosion strongly declining in the
487 subsequent period (Klimas et al., 2020). According to the literature, the effects of an
488 individual prescribed burn lasts for a short period, from three months (Stephens et al.,
489 2004) to one year (Bêche et al., 2005; Cawson et al., 2012). Soil loss then declines in
490 the subsequent months after a fire (Neary et al., 2005; Neary and Leonard, 2021), and is
491 extensive in area but small in magnitude (Morris et al., 2014)

492

493 *4.2. Effects of mulching on runoff and erosion*

494

495 The treatment with fern mulch provided an effective soil protection, which was able to
496 improve the hydrological response of burned soils. Mulching is effective in reducing

497 runoff and erosion rates, since the mulch layer provides a cover that reduces raindrop
498 impact, prevents soil sealing (Lucas-Borja, 2021), promotes infiltration (Bombino et al.,
499 2021, 2019), and decrease runoff velocity (Lal, 1976; Prats et al., 2016). Moreover, the
500 mulch cover synergistically acts with the remaining litter after burning (Vega et al.,
501 2005) towards a reduction in the hydrological response of the burned soils to heavy
502 seasonal storms.

503 However, it should be noticed that the response of the experimental soils was different
504 among the studied forest species in the short term, but very similar between the two
505 monitored hydrological variables. More specifically, fern mulching was particularly
506 effective in reducing the runoff generation capacity immediately after the prescribed fire
507 in both plots of pine and chestnut. Here, reductions in runoff coefficients and erosion by
508 70-80% were achieved compared to the burned soils. Conversely, this reduction was
509 much lower (25-30%) in oak plots. The effectiveness of fern mulching in our study is
510 higher compared results with Prats et al. (2015, 2014, 2013, 2012), Groen and Woods
511 (2008) and Robichaud et al. (2013). The first authors reported runoff reductions
512 between 40 and 60% produced by mulching with forest residues or hydro-mulching
513 during the first year. Groen and Woods (2008) and Robichaud et al. (2013) achieved
514 decreases in runoff between 30 and 60% using straw mulch under rainfall simulations
515 and small paired catchments, respectively.

516 In our study, the beneficial effects of the mulching treatment in the short term were not
517 generally due to the changes in the hydraulic properties of the soils (namely IR and
518 SWR). This contrasts the statement by Lal (1976), who reports that a mulch layer
519 increases water infiltration and surface storage, and improves soil structure and porosity
520 (Prats et al., 2015). Carrà et al. (2021) reported that, in the same forest stands, the mean
521 IR slightly increased in the soils of chestnut and oak, but did not vary in pine forests.
522 According to the same authors, the SWR was not affected by mulching, in line with
523 (Prats et al., 2015). This result is expected, since the vegetal residues require time to be
524 incorporated into the soil and to play effects on soil hydrology (Bombino et al., 2021,
525 2019). Instead, mulching was effective at providing soil with a cover of vegetal
526 residues, as shown by the decreases in bare soil percentage and the progressive
527 establishment of litter (except in chestnut) and shrubs compared to the burned soils.

528 The improvement in the hydrological response of the burned forests due to mulching
529 was losing importance over time, since the pre-fire soil hydrology (runoff coefficients
530 and erosion rates) just recovered some months after burning. However, in soils of pine

531 and chestnut, the runoff generation capacity was even lower compared to the unburned
532 plots, and the same was observed for erosion in the chestnut forest. This means that the
533 soil treatment with mulching may also be effective throughout several months after fire,
534 since the vegetal residues are incorporated into the soil, where organic matter increases
535 and plays beneficial effects on soil macroporosity and infiltration capacity (Bombino et
536 al., 2021, 2019; Lucas-Borja et al., 2019b; Shabanpour et al., 2020). As a matter of fact,
537 one year after fire, the study by Carrà et al. (2021) demonstrated that the infiltration
538 capacity of soils mulched with fern noticeably increased over time, particularly in the
539 soils of chestnut and oak, and less in the pine forest in all soil conditions. However, the
540 incomplete recovery of the pre-fire infiltration did not significantly alter the runoff and
541 erosion rates compared to the unburned soils, and it may be presumable that this
542 recovery will complete in the short term (Carrà et al., 2021).

543 One year after fire, the litter cover recovered in the forests of oak and pine. However,
544 the area with bare soil was higher compared to the soil condition detected immediately
545 after the prescribed burning, since the mulch cover progressively disappeared due to
546 wind and degradation of the vegetal material. A comparative analysis of the organic
547 matter content among the different soil conditions - not carried out in this study, since it
548 was beyond its hydrological focus - could have quantified the amount of degraded
549 mulch residues incorporated into the soil over time.

550

551 **5. Conclusions**

552

553 This study has evaluated runoff and erosion in soils of three Mediterranean forests after
554 a prescribed fire and mulching treatment, and the results help in replying to the three
555 research questions supporting the investigation.

556 First, immediately after the prescribed fire, runoff and erosion significantly increase in
557 all forest plots compared to the unburned soils. However, these increases (by 150% to
558 375% for the runoff coefficients, and by 100% to 800% for the soil losses) are much
559 lower compared to the highest values reported in some studies.

560 Secondly, the window of disturbance after fire is limited to three-four months after fire,
561 and, after five months, the pre-fire runoff generation and erosion the soils are practically
562 restored; if the runoff and erosion are still higher compared to the unburned soils, these
563 changes are not significant.

564 Thirdly, the mulch application using fern residues, which is widely available in
565 Mediterranean forest and is more advisable compared to the most common use of straw,
566 is effective at limiting the increase in the hydrological response observed in the burned
567 soils. This has been demonstrated by reductions in runoff coefficients and soil losses by
568 70-80% (except for oak soils, -25-30% for both runoff and erosion) in the experimental
569 sites.

570 The changes in soil hydrology due to the prescribed fire are due to the reductions in IR,
571 SWR (particularly in soils of pine and oak), and litter and vegetation removal. The soil
572 cover due to mulching is effective and its influence on water infiltration and repellency
573 in the burned soils is very limited. The increases in these hydraulic properties gain
574 importance over time and become beneficial one year after fire, even determining in
575 some cases higher infiltration, and lower runoff and erosion compared to the unburned
576 soils.

577 Further research is needed (i) to validate the results of this study achieved in plots
578 through upscaling to hillslopes or better catchments, and (ii) to explore the influence of
579 the physico-chemical properties (particularly the organic matter content) on the soil
580 hydrology under burned (with and without treatments) conditions.

581 Overall, the results of this investigation can support the tasks of landscape managers to
582 identify proper fuel management practices for wildfire risk reduction (such as the
583 prescribed fire), and of hydrologists to identify cheap and effective techniques of
584 ecological engineering (such as the mulching with fern) in the Mediterranean forests.

585

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596

597

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857

858 **Supplementary material**

859

860 Table 1SM - Runoff volume and its sediment concentration measured in plots after prescribed fire and soil mulching using fern (Samo, Calabria,
861 Southern Italy).

862

Event date	Runoff volume (mm)						Sediment concentration (g/l)					
	<i>Unburned soil</i>		<i>Burned soil</i>		<i>Burned and mulched soil</i>		<i>Unburned soil</i>		<i>Burned soil</i>		<i>Burned and mulched soil</i>	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
<i>Pine</i>												
15 Jul 2019	4.69	1.74	22.31	1.35	6.63	1.16	1.20	0.34	2.35	0.36	1.64	0.37
9 Oct 2019	0.00	0.00	11.03	3.74	4.37	0.33	0.00	0.00	1.47	0.14	0.26	0.02
11 Nov 2019	10.22	4.80	11.12	0.53	10.35	0.80	0.47	0.45	0.21	0.13	0.18	0.02
23 Nov 2019	6.18	4.78	7.01	1.02	5.41	1.73	0.11	0.12	0.19	0.10	0.03	0.02
5 Dec 2019	7.85	6.59	8.44	1.02	8.91	2.40	0.00	0.00	0.07	0.05	0.00	0.00
24 Mar 2020	13.06	11.16	19.77	5.98	8.81	0.60	0.02	0.02	0.03	0.02	0.03	0.01
<i>Chestnut</i>												
15 Jul 2019	4.69	0.68	22.30	4.21	6.61	1.69	1.65	0.54	2.32	0.18	2.17	0.24
9 Oct 2019	8.44	1.16	16.98	5.44	3.00	1.23	1.86	0.59	2.08	1.14	0.58	0.26

11 Nov 2019	13.45	8.25	16.93	9.04	4.64	1.93	0.27	0.05	0.43	0.13	0.19	0.04
23 Nov 2019	8.39	4.32	12.49	8.29	2.51	0.41	0.30	0.03	0.55	0.11	0.10	0.02
5 Dec 2019	11.10	6.60	13.03	11.86	3.24	0.71	0.10	0.00	0.07	0.06	0.00	0.00
24 Mar 2020	18.13	12.92	22.11	12.07	2.98	0.29	0.16	0.11	0.25	0.12	0.13	0.05
14 Jul 2020	3.37	1.28	3.85	1.72	1.25	0.37	0.00	0.00	0.00	0.00	0.00	0.00
<i>Oak</i>												
15 Jul 2019	12.55	2.90	31.34	2.29	22.98	3.69	1.58	0.15	1.48	0.37	1.51	0.09
9 Oct 2019	0.00	0.00	10.00	3.13	3.27	2.83	0.00	0.00	0.90	0.26	0.51	0.89
11 Nov 2019	16.35	3.11	20.64	3.05	17.81	1.68	0.31	0.06	0.34	0.13	0.32	0.06
23 Nov 2019	7.70	2.80	15.86	6.84	9.66	0.17	0.59	0.22	1.12	0.96	0.89	0.29
5 Dec 2019	11.01	1.30	21.11	10.64	16.52	0.86	0.40	0.17	0.48	0.20	0.40	0.09
24 Mar 2020	16.36	6.01	22.11	5.32	18.78	1.20	0.32	0.06	0.37	0.05	0.29	0.03

863

Prescribed fire and soil mulching with fern in Mediterranean forests: Effects on surface runoff and erosion

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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:

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