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

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Abstract:	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.
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COVER LETTER

Reggio 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 undburned 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 Mediterranen 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.

Revised Manuscript (changes marked) Click here to view linked References

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

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Abstract

Prescribed burning is increasingly used to reduce the wildfire risk, and the need to limit runoff and erosion after the fire suggests treating burned soils with mulching. To this aim, fern residues may be more advisable compared to the commonly used straw, since ~~this material~~fern 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 after burning. Subsequently, the pre-fire runoff and erosion rates of the burned soils were practically ~~restored~~recovered, and the hydrological changes were not significant compared to the unburned soils. In the short term after the 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 the runoff coefficients

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

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

1. Introduction

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

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

In order to limit the negative impacts of high-severity fires, preventing strategies have been adopted since long time (Ferreira et al., 2015). Among these strategies, prescribed fire - the planned use of low-intensity fire to achieve very different goals given certain weather, fuel and topographic conditions (Fernandes et al., 2013) - is considered as a primary and integrated option to reduce the wildfire risk in forests (Alcañiz et al., 2018; Klimas et al., 2020).~~remove or reduce the fuel that can generate a high-intensity fire (Vega et al., 2005; Alcañiz et al., 2018).~~ The low-intensity f~~F~~ire, which is applied 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 the summer or other dry periods. Since the fuel for wildfires is regenerating after the prescribed fire, repeated applications are needed to control the wildfire risk over time. Moreover, the ~~P~~prescribed fire, which has low-severity and burn patchiness (Cawson et al., 2012; Pereira et al., 2021), avoids high temperature in soil and tree crown burning, which are the most adverse effects of wildfire on soil and plants. In addition, prescribed fire supports regeneration of some plant species (Scharenbroch et al., 2012; Williams et al., 2012; Francos and Úbeda, 2021). Litter, herbs and shrubs regenerate after the prescribed fire, and this prevents erosion in the treated forest. However, this renewed vegetal cover is insufficient to recover the pre-fire erosion rates, and thus post-fire management actions are needed. Increases in runoff and erosion after prescribed fires are lower compared to wildfires, but these risks are still present (Morris et al., 2013; Shakesby et al., 2015). Runoff and erosion increases have been observed after prescribed fires in different ecosystems, such as heathlands, shrublands and gorse (Vega et al., 2005). In the Mediterranean forests, these increases may be even more intense compared to other rainstorms (Fortugno et al., 2017), since ~~and~~ the soils are generally shallow and show ~~with~~ low aggregate stability, and organic matter and nutrient contents (Cantón et al., 2011). Due to the combination of these climate and soil characteristics, the Mediterranean forests ~~may be~~are more ~~exposes~~ exposed to excessive runoff and soil erosion rates compared to other ~~-~~ecosystems (Zema et al., 2020a;~~,~~ 2020b). Therefore, there is a need for an improved knowledge about soil hydrology in Mediterranean fire-prone forests, also considering that both wildfires and rainstorms are thought to become more frequent and intense according to the forecasted climate scenarios (Badia and Marti, 2008). However, despite an ample literature about the impacts of fire on soil hydrology, the studies ~~about~~ on the hydrological effects of prescribed fire are not exhaustive and often contrasting (Cawson et al., 2012; Shakesby et al., 2015). 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 the 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.

In order to reduce the soil's susceptibility to runoff and erosion ~~to~~ after a wildfire, several treatments have been proposed and their effectiveness has been verified in many environmental contexts (Lucas-Borja, 2021; Zema, 2021). Among the ecological engineering techniques, which use plant ~~vegetative~~ residues for soil conservation, mulching is one of the most common post-fire management options (Lucas-Borja et al., 2019a; Prosdocimi et al., 2016). The objective of mulching is protecting soil with a ground cover and improving the soil quality, if used properly and at the correct time (Prosdocimi et al., 2016; Zituni et al., 2019). However, post-fire mulching can also have negative effects. In some cases, mulching reduces the soil hydraulic conductivity under unsaturated conditions compared to the untreated soils, particularly in the ~~drier~~ driest season (Lucas-Borja et al., 2018). Mulching material is selected based on its availability, resistance to degradation, weed spreading risk and other factors (Parhizkar et al., 2021; Prats et al., 2015). Straw is often used as mulch cover in fire-affected areas (Bontrager et al., 2019; Keizer et al., 2018), but its residues can be displaced by wind in some areas, leaving slopes bare, or ~~accumulated~~ accumulating in thick layers in other areas, with possible reductions in the post-fire emergence of vegetation ~~emergence~~ (Robichaud et al., 2020). Moreover, agricultural straw may contain seeds, chemicals and parasites, which can be the sources of non-native vegetation and plant diseases. Forest residues (e.g., wood strands, chips or shreds) or dead plants may replace straw, because these substrates do not carry non-native seeds or chemical residues, and are more resistant to wind displacement (Robichaud et al., 2020). In Mediterranean forest floor, fern - *Pteridium aquilinum* (L.) Kuhn - is widely available, and this ~~(which~~ avoids the transport costs~~need~~ from other locations~~)~~. ~~and its lignin content is lower compared other agro-forest residues (which allows a fast degradation into soil).~~ Therefore, its use as mulching material in fire-affected areas is preferable to straw. However, to~~at~~ the ~~best~~ authors' best knowledge, no evaluations about the use of fern to protect the burned soil from runoff and erosion impacts are available in literature. Therefore, the effectiveness of fern mulching to restore the hydrological properties of soils should be assessed, and particularly in the short-term after fire, when the soil is left bare and the ~~soil~~ changes in the soil properties (e.g., reduced infiltration, soil water repellency and ash cover) can be significant compared to the unburned and untreated~~affected~~ areas (Cawson et al., 2012; Francos and Úbeda, 2021; Klimas et al., 2020; Wittenberg and Pereira, 2021). A previous study, carried out in the same environment using a rainfall simulator, showed that soil mulching with fern did not increase ~~water infiltration~~the water infiltration rates (IR) and did not alter soil water repellency (SWR) of the burned soils ~~in the measurement point~~at the point scale immediately after a prescribed fire. However, ~~O~~one year after the soil treatment, the ~~soil hydraulic conductivity~~ IR ~~-~~noticeably increased and ~~repellency~~ the SWR completely disappeared (Carrà et al., 2021).

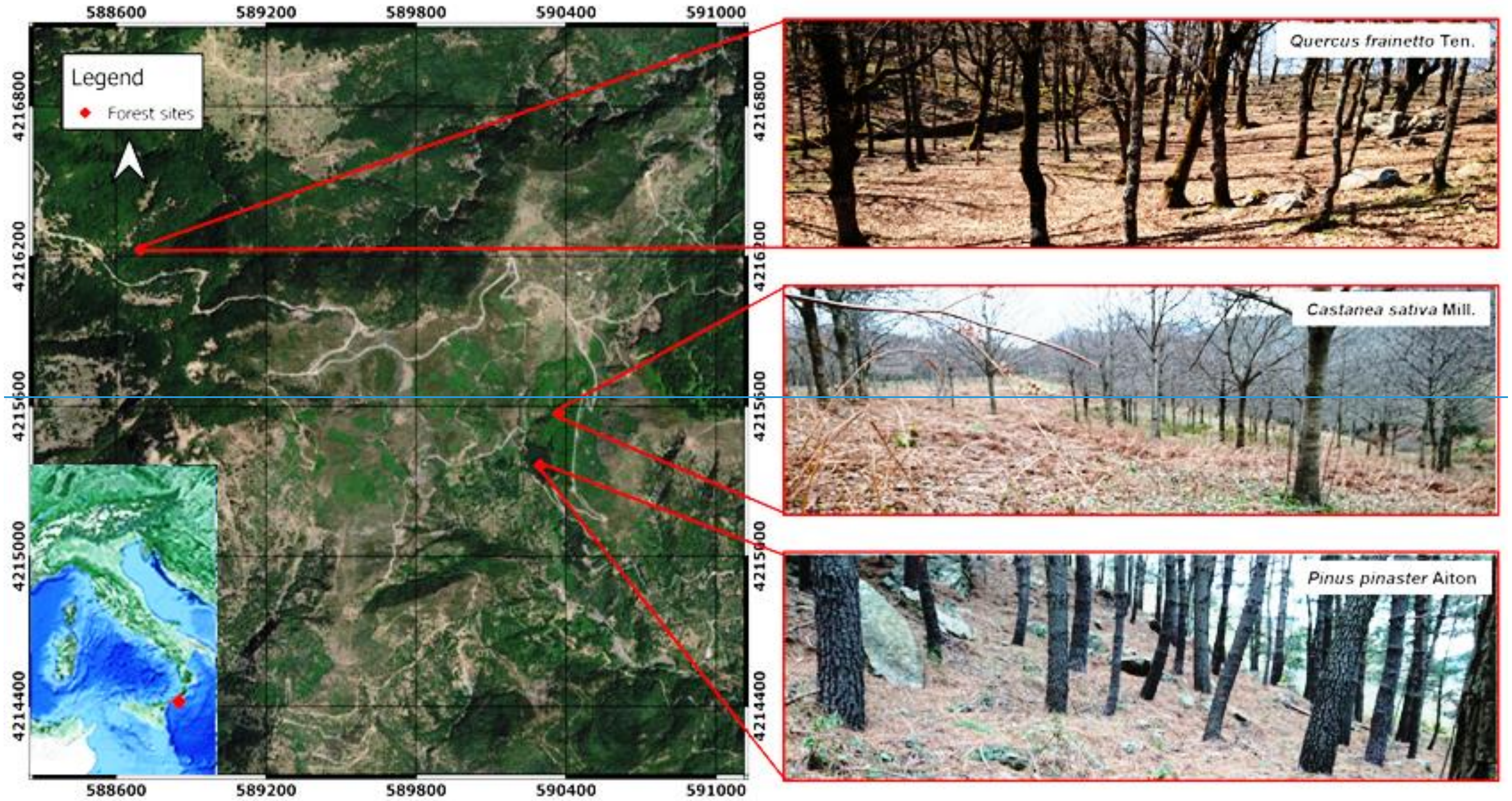
To fill the research gaps and extend the previous investigation to the plot scale, this study has evaluated the hydrological response of soils in three forest stands of Calabria (Southern Italy) after a prescribed fire, with or without a ~~and~~ mulching treatment with fern, in comparison to the undisturbed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

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

2. Material and methods

2.1. Study area

The study was carried out in three forest sites (municipality of Samo, Calabria, Southern Italy) between 600 and 900 m above the sea level (Figure 1 and Table 1). ~~, of which: (i)~~ T~~t~~he first area ("Calamacia") was a pine (*Pinus pinaster* Aiton) stand reforested in 1984. The~~; (ii) the~~ second site ("Rungia") wa~~i~~s a natural oak stand (*Quercus frainetto* Ten.). T~~; and (iii) t~~he third zone ("Orgaro") was a chestnut stand (*Castanea sativa* Mill., about 29-year old). No management actions were carried out in the three forest stands (. Table 1)) reports the main characteristics (coordinates, altitude and soil slope) of the experimental site, while the main characteristics of tree and shrub species are depicted in Table 2.


588600
589200
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4216800
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4214400
Legend
Forest sites
Quercus frainetto Ten.
Castanea sativa Mill.
Pinus pinaster Aiton

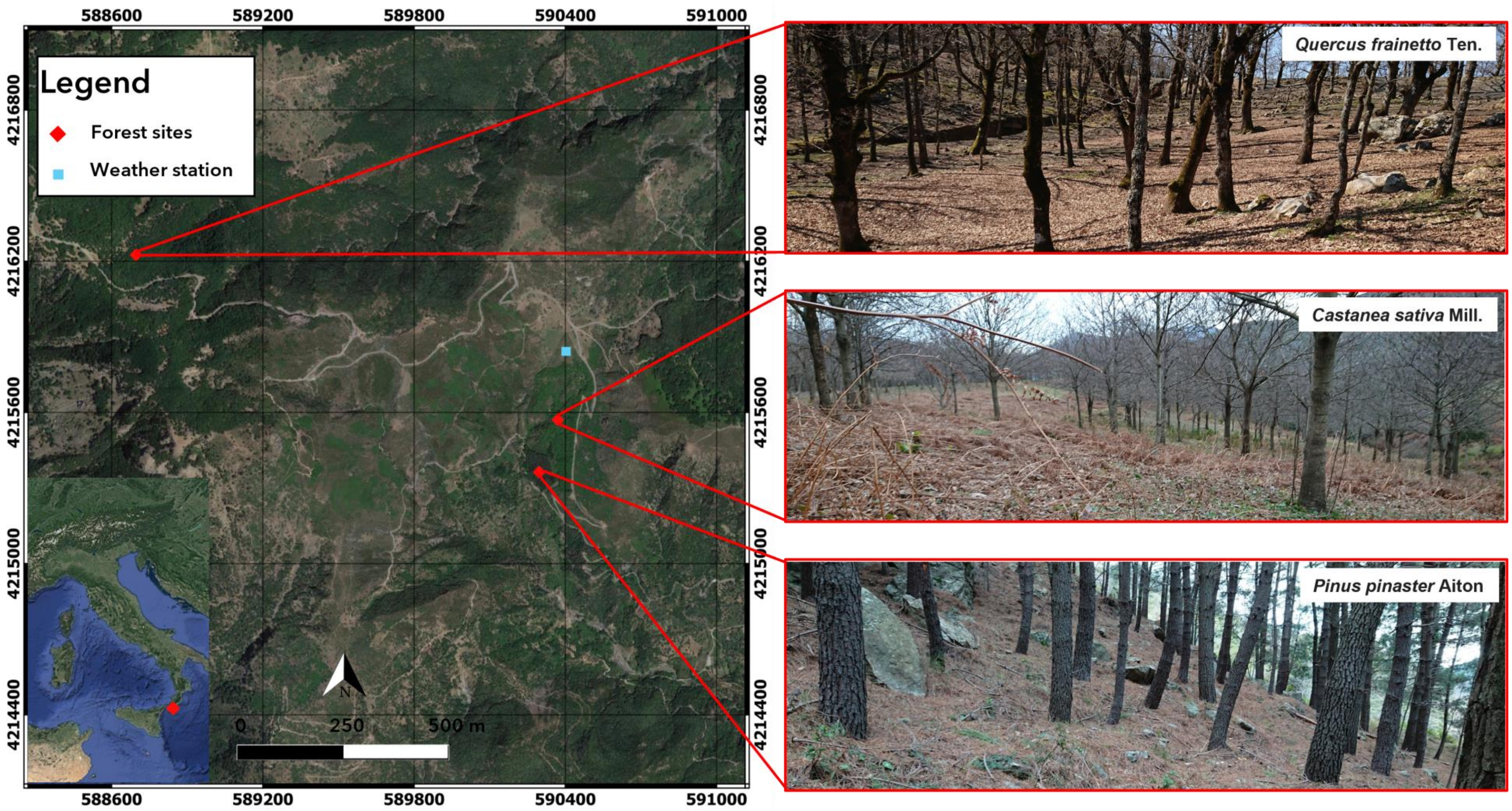

Figure 1 - Location of the experimental site (Samo, Calabria, Southern Italy).

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

Characteristics		**Site**		
		Calamacia	*Rungia*	*Orgaro*
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 (*Pinus pinaster* Aiton)	Oak (*Quercus frainetto* Ten.)	Chestnut (*Castanea sativa* Mill.)
	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
-		*Quercus ilex* L., *Rubus ulmifolius* S.~~, *Bellis perennis* L.~~	*Cyclamen hederifolium*~~, *Bellis perennis* L.~~	*Rubus ulmifolius* S., *Pteridium aquilinum L.*~~, *Bellis perennis* L.~~
Litterfall layer depth (cm)		11.7 ± 4.6	12.2 ± 3.9	6.1 ± 4

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

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

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

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 (*Pinus pinaster* Aiton)	950 ± 86.4	28.3 ± 9.4	20.5 ± 1.4	67.9 ± 6.5	11.7 ± 4.6	*Quercus ilex* L., *Rubus ulmifolius* S., *Bellis perennis* L.
Rungia	oak (*Quercus frainetto* Ten.)	225 ± 44.7	40.7 ± 8.9	18.2 ± 1.9	31.1 ± 3.6	12.2 ± 3.9	*Cyclamen hederifolium*, *Bellis perennis* L.
Orgaro	chestnut (*Castanea sativa* Mill.)	725 ± 89.1	20.2 ± 5.6	9.6 ± 1.2	24.3 ± 4.4	6.1 ± 4	*Rubus ulmifolius* S., *Pteridium aquilinum* L., *Bellis perennis* L.

The climate of the area is typical of the semi-arid environment ("Csa" class, "Hot-summer Mediterranean" climate, according to Koppen classification (Kottek et al., 2006). Winters are mild and rainy, while summers are warm and dry. The mean annual precipitation and temperature are 1102~~.3~~ mm and 17.4 °C, respectively. The minimum temperature is - 4.3 °C, while the maximum is 43.1 °C (weather station of Sant'Agata del Bianco~~ (RC)~~, geographical coordinates 4217548 N, 595159 E, period of 2000-2020).

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

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

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	
		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	loamy sand
		burned	11.3 ± 1.53	8.7 ± 0.58	80.2 ± 1.04	

2.2. Prescribed fire operations and mulching application

The prescribed fire was carried outapplied in early June 2019 with the support of the Environmental Regional Agency ("Calabria Verde") and the surveillance of the National Corp of Firefighters (Figure 2a).

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

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

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

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

(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. T~~; t~~his 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 ~~soils~~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).

2.4. Plot construction

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

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

2.5. Monitoring of the hydrological variables

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

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

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

2.7. Statistical analyses

One-way ANOVA with repeated measures (at each rainfall-runoff event) was applied to the runoff volume and soil loss (response variables) separately for the three forest ~~species~~stands, assuming as factor the soil condition (unburned, burned and not treated, and burned and mulched). The pairwise comparison by Tukey's test (at $p < 0.05$) was also used to evaluate the statistical significance of the differences in the response variables. In order to satisfy the assumptions of the statistical tests (homogeneity~~equality~~ of variance and normal distribution), the data were subjected to normality test or were square root-transformed whenever necessary. All the statistical tests were carried out by with the XLSTAT software (release 2019.1, Addinsoft, Paris, France).

3. Results

3.1. Rainfall characterization

Throughout the monitoring period, 516 rainfall events with a total depth of 1120 were recorded at the rain gauging station. Of these events, only seven were classified as erosive events and then monitored~~ (that is, with depth over 13 mm), according to Wischmeier and Smith (1978)~~. The height of these events was in the range of 22.4 (14 July 2020) - 156 (11 March 2020) mm, while their duration varied between 7 (14 July 2020) and 41 (11 November 2019) hours. The latter event ~~e latter ~~was characterized by the maximum absolute intensity~~the most intense event (mean intensity~~ (~~of ~~26.2 mm/h), while ~~the maximum intensity was recorded for ~~the event of 5 December 2019 had the highest mean intensity ~~23 November 2019~~(4.90 mm/h)~~ (Table 5)~~. One event (dated 24 July 2020) produced runoff and erosion only in the chestnut plots (Table 4).
The spatial variability of the precipitation among the three forest sites was very low (< 5%) for all the monitored events. The net rainfall (due to the interception) was between 4-10% (pine and chestnut forests) and 6-12% (oak site) of the total precipitation (Table 4~~5~~).

Table 4~~5~~ - Main hydrological variables of erosive rainfall events monitored in the experimental site (Samo, Calabria, Southern Italy).

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.

3.2. Runoff

The runoff volumes measured at the experimental plots are reported in Table 1SM of the Supplementary Materials. ~~In the unburned plots, the maximum runoff (from 13.1 ± 11.2 mm in the pine forest to 18.1 ± 12.9 mm in chestnut forest) was measured always after the rainfall with the highest height (156 mm, 24 March 2020). In oak forest, a high runoff (16.4 ± 3.11 mm) was also collected after the event with the highest mean intensity (26.2 mm/h on 11 November 2019, 143 mm in 41 hours). In one event (9 October 2019, 50 mm), having the lowest height among the erosive rainfalls, no runoff was collected in the unburned chestnut and oak forests (Table 6).~~

~~Conversely, the highest runoff volume in the burned plots was always collected after the first of the monitored events. More specifically, on 15 July 2019 (one month after the prescribed fire), the runoff was 22.3 ± 1.35 mm in the chestnut forest, 22.3 ± 4.21 mm in the pine stand, and 31.3 ± 2.29 in oak plots. The first rainfall event produced the highest runoff also in the burned and mulched plots of chestnut and oak forests (6.61 ± 1.16 mm and 23 ± 3.69 mm, respectively), while in the pine plots the maximum runoff (10.4 ± 0.80 mm) was measured after the second event (11 November 2019, 143 mm of rainfall) (Table 6).~~

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

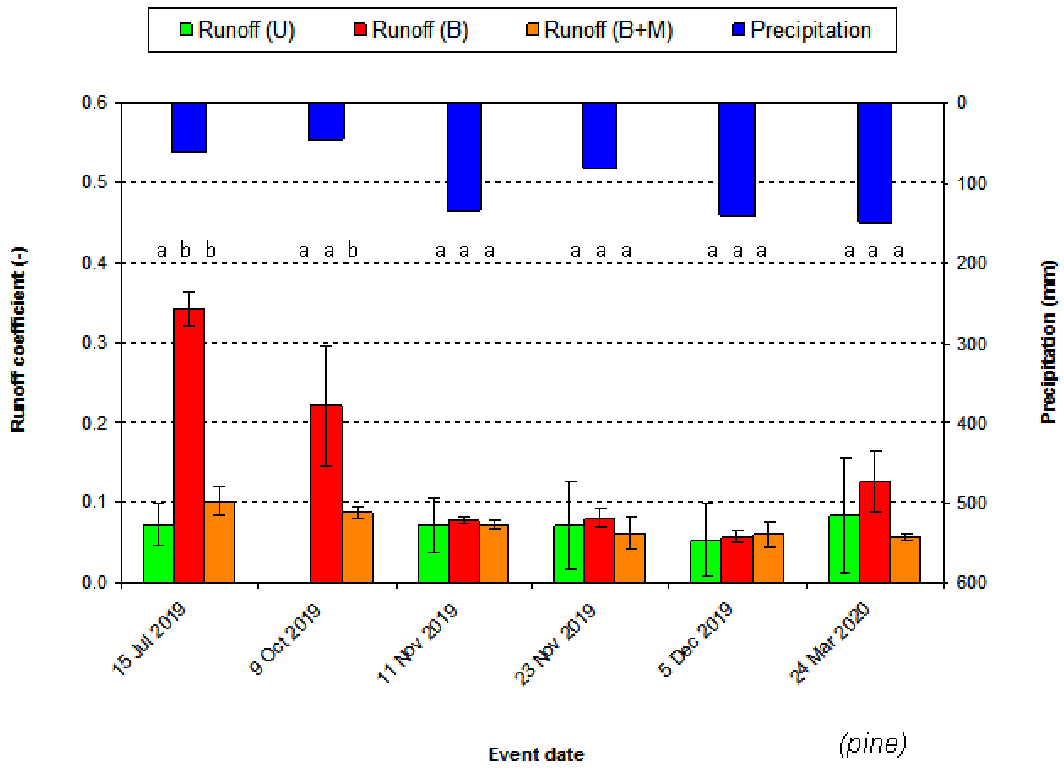
In contrast, immediately after the prescribed fire, the runoff coefficient suddenly increased in all forest plots (up to a maximum of ~~0.34 ± 0.02, pine, 0.34 ± 0.06, chestnut, and even~~ 0.48 ± 0.04~~,~~ in the oak forest). In the ~~pine and chestnut~~ plots of pine and chestnut, a high runoff coefficient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

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

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

Event date	**Runoff volume (mm)**						**Sediment concentration (g/l)**					
	Unburned soil		*Burned soil*		*Burned and mulched soil*		*Unburned soil*		*Burned soil*		*Burned and mulched soil*	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Pine												
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
Chestnut												
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~~
~~*Oak*~~												
~~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~~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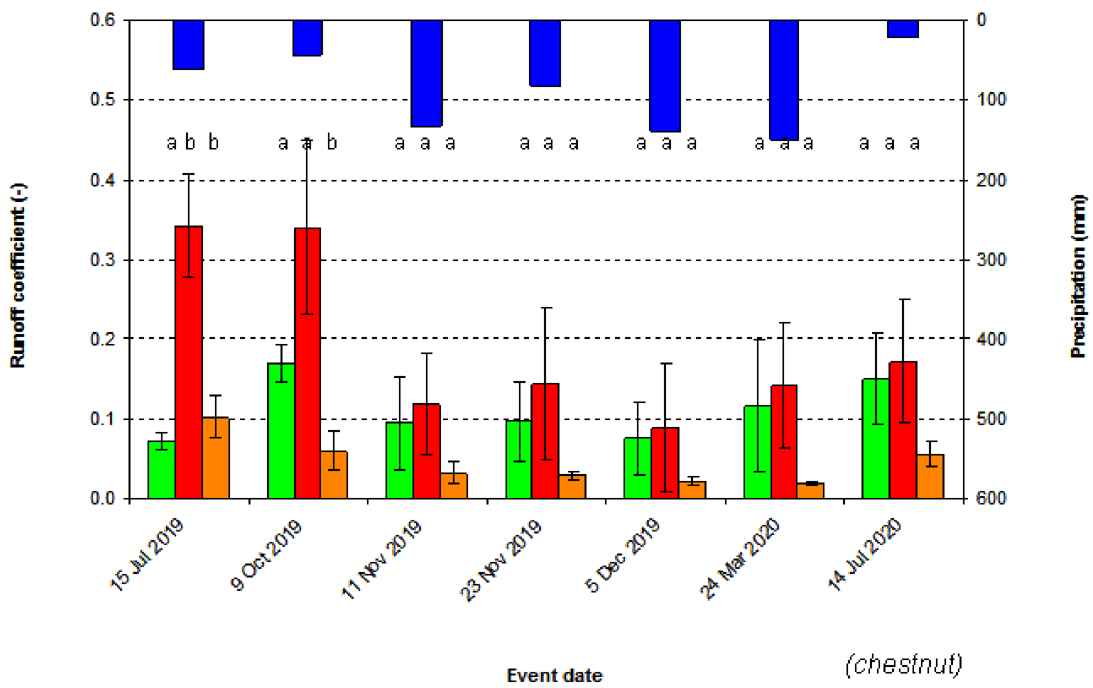
Runoff (B)
Runoff (B+M)
Precipitation
Runoff coefficient (-)
Precipitation (mm)
15 Jul 2019
9 Oct 2019
11 Nov 2019
23 Nov 2019
5 Dec 2019
24 Mar 2020
Event date
(pine)


Runoff coefficient (-)
Precipitation (mm)
15 Jul 2019
9 Oct 2019
11 Nov 2019
23 Nov 2019
5 Dec 2019
24 Mar 2020
14 Jul 2020
Event date
(chestnut)

386

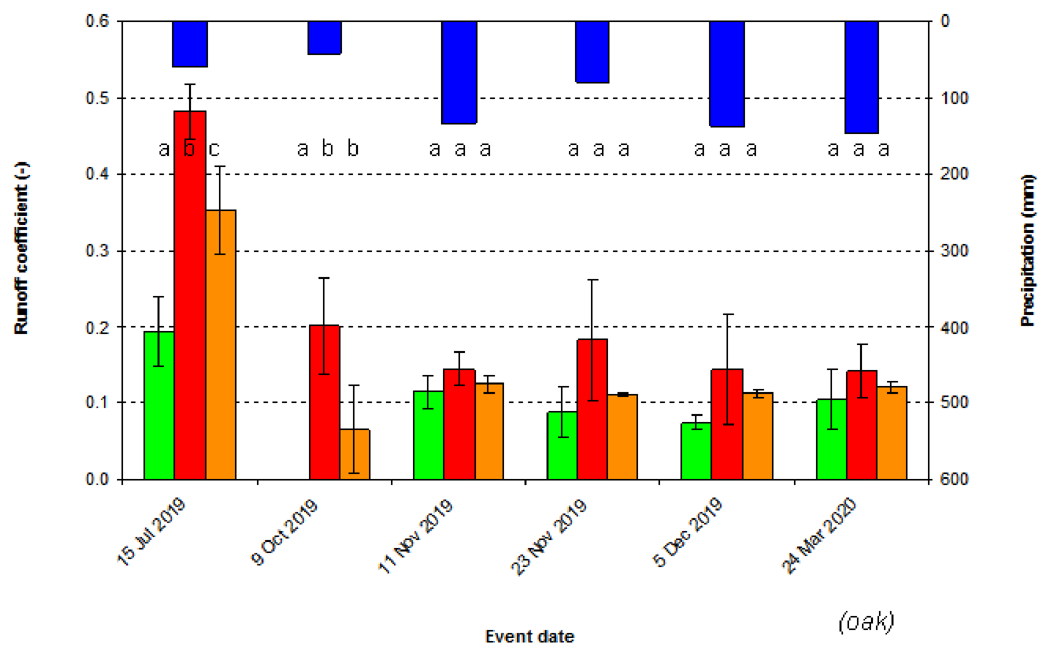


Figure 4 - Precipitation and runoff coefficients measured in plots after prescribed fire and soil mulching using fern (Samo, Calabria, Southern Italy).

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

3.3. Erosion

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

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

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

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

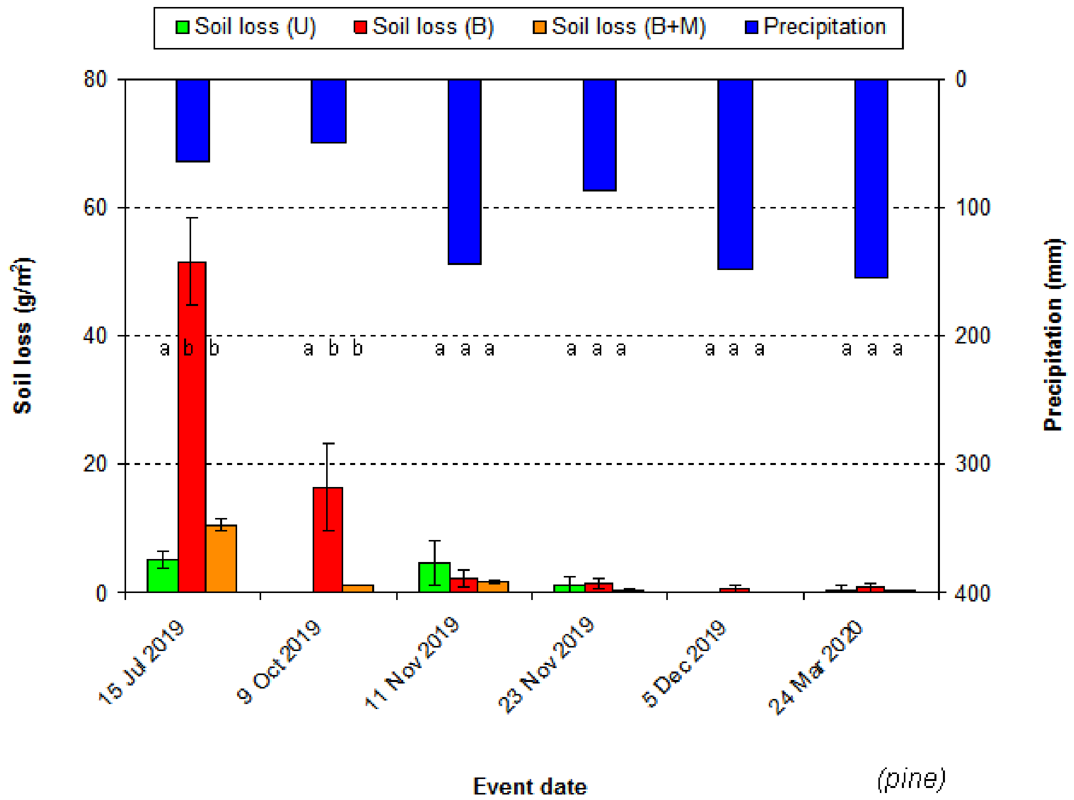
As expected, the soil loss~~, estimated as the product of the runoff volume collected in the tanks by the corresponding sediment concentration,~~ was of low amount in the unburned plots. ~~(up to 5.31 ± 1.40 g/m^2 in pine forest, and 7.37 ± 2.72 g/m^2 in oak, both~~ The maximum erosion was estimated ~~in~~ after the first event ~~of 15 Jul 2019, 65 mm and 22.2 mm/h~~ in the forests of pine and oak (5.31 ± 1.40 and 7.37 ± 2.72 g/m^2, respectively), while the rainfall event that produced the highest soil loss (~~, and~~ 15.34 ± 3.21 g/m^2~~-~~) in the chestnut soil was the ~~in chestnut, the latter after the~~ second event ~~of 9 Oct 2019, 50 mm and 14.6 mm/h)~~ (Figure 5).

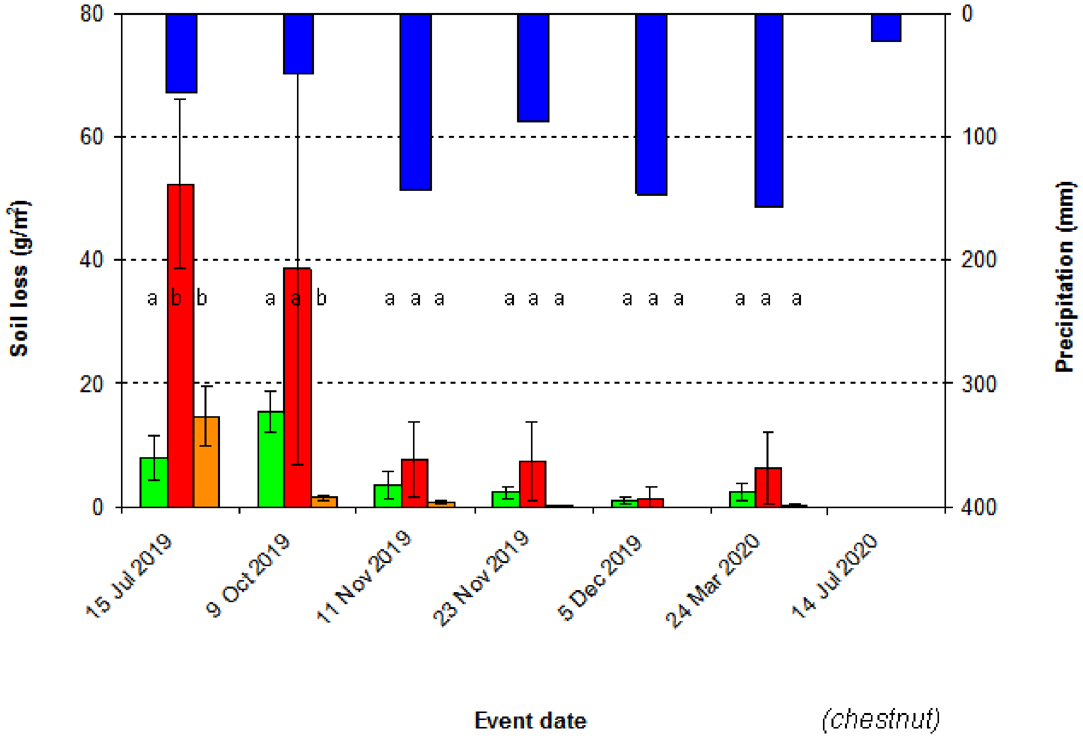
For these two rainfall events, erosion increased very much in burned soils of all forests, and mainly in the ~~pine and chestnut~~ soils of pine and chestnut. In these plots, the maximum values of soil loss, equal to 51.61 ± 6.92 and 52.26 ± 13.67 g/m^2~~-~~, ~~(first event~~

of 15 Jul 2019, 65 mm and 22.2 mm/h) were detected after the first event., while i In the oak soils, erosion was noticeably lower, 15.12 ± 2.87 g/m^2 (although higher compared to the unburned plots). However, mulching was effective to reduce these soil losses, and the whose maximum values (14.58 ± 4.80 g/m^2) was detected in chestnut forestere equal to 10.62 ± 0.99 g/m^2 (pine forest), 14.58 ± 4.80 g/m^2 (chestnut), and 11.53 ± 2.23 g/m^2 (oak). The highest erosion in the mulched soils was , always estimated after the first eventrainfalls (15 Jul 2019) (Figure 5).

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

Covering soil with fern mulch was able to reduce erosion compared to the burned plots, and this beneficial effect was mainly observed in the pine and chestnut forests of pine and chestnut, and less in the oak soils compared to fire-affected plots. The In more detail, maximum soil losses (1.87 ± 0.33 g/m^2, pine) was observed after the third eventere equal to 1.87 ± 0.33 and 0.81 ± 0.16 g/m^2 (both surveyed in the third event of 11 Nov 2019, 143 mm and 26.2 mm/h), respectively, while the erosion was always over 5.40 ± 0.81 g/m^2 in oak plots (event of 24 Mar 2020, 156 mm and 13.8 mm/h). In the pine and mainly chestnut plots of pine and chestnut, for all monitored events the estimated soil losses for all monitored events were even lower in comparison to the unburned soils. , while the pre-fire erosion rates were restored Iin the oak forests, the pre-fire erosion rates only recovered only for two events precipitations (the fourth and the sixth events23 Nov 2019 and 24 Mar 2020) (Figure 5).


Soil loss (U)
Soil loss (B)
Soil loss (B+M)
Precipitation
Soil loss (g/m²)
Precipitation (mm)
80
60
40
20
0
0
100
200
300
400
a b b
a b b
a a a
a a a
a a a
a a a
15 Jul 2019
9 Oct 2019
11 Nov 2019
23 Nov 2019
5 Dec 2019
24 Mar 2020
Event date
(pine)


Soil loss (g/m²)
Precipitation (mm)
80
60
40
20
0
0
100
200
300
400
a b b
a a b
a a a
a a a
a a a
a a a
15 Jul 2019
9 Oct 2019
11 Nov 2019
23 Nov 2019
5 Dec 2019
24 Mar 2020
14 Jul 2020
Event date
(chestnut)

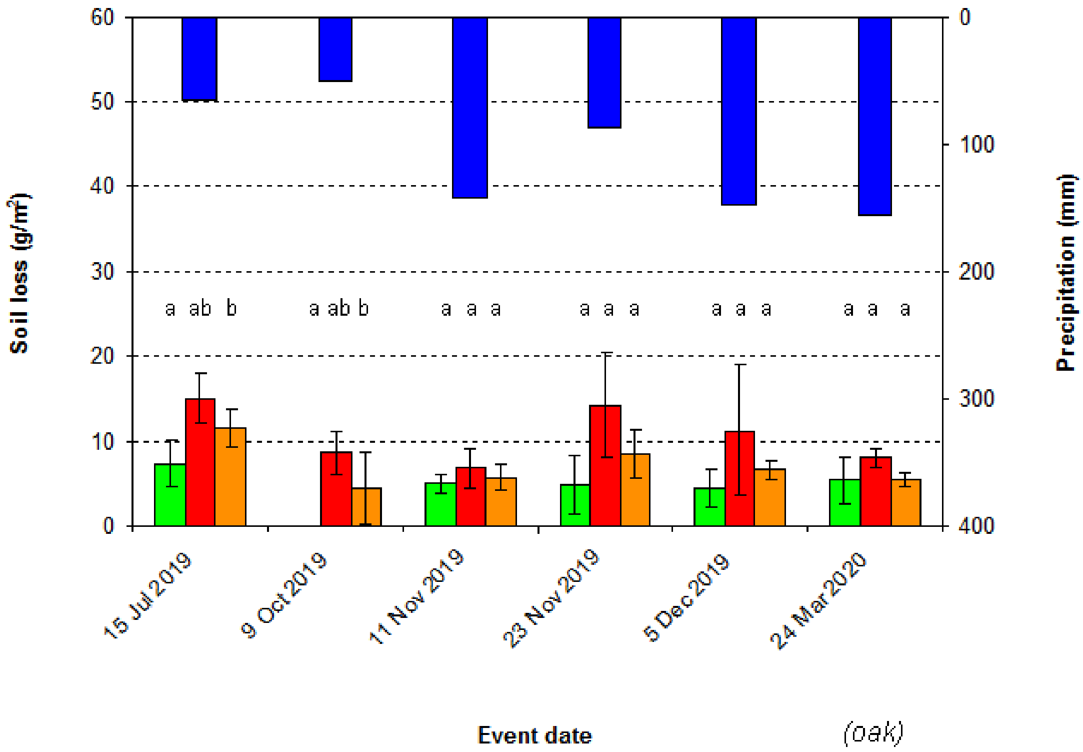


Figure 5 - Precipitation and soil loss measured in plots after prescribed fire and soil mulching using fern (Samo, Calabria, Southern Italy).

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

4. Discussion

4.1. Effects of prescribed fire on runoff and erosion

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

All forest soils showed low runoff coefficients (not higher than 0.20), which means that, also after very intense storms (100-150 mm, having return interval estimated in 3-5 years in this area), the runoff generation capacity of these soils is basically limited. This is mainly due to the high water losses occurring in forest environments, on which high soil infiltration (mainly due to the noticeable organic matter content), tree canopy interception (especially in the broadleaf tree species), water retention by litter and understory, and evapo-transpiration rates are beneficial, e.g., ~~(~~Imeson et al. (~~,~~1992), ~~;~~ Llorens et al. (~~,~~2011), ~~;~~ and Nadal- Romero et al. (~~,~~2016). The low runoff generation measured in the undisturbed soils also limited the erosion rates, whose maximum value was 0.15 tons per hectare (in the chestnut forest) for the most intense rainstorm. Cumulating all the ~~monitored~~ erosive events observed in this study, erosion never exceeded 0.33 tons/ha throughout the monitored year, and this value is well below the tolerance limit of the range ~~between~~ 3 to~~and~~ 11.2 tons/ha per year (Bazzoffi, 2009; Wischmeier and Smith, 1978).

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

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

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

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

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

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

In more detail, in all forest soils ~~regarding the water infiltration measurements,~~ the prescribed fire reduced the mean IR ~~in the soils of all forest species~~ compared to the unburned conditions. The increase in SWR may also have played an important role in increasing runoff and erosion immediately after fire in the ~~pine and oak~~ soils of pine and oak, since the prescribed burning determined a strong repellency. In contrast, ~~While~~ in the chestnut soils the prescribed fire did not alter the slight ~~repellency~~ SWR found in unburned plots~~, burning determined a strong repellency in both pine and oak soils, with or without mulch cover~~ (Carrà et al., 2021).

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

The changes in the hydrological response of the burned soils were not permanent, but remained noticeable throughout 3-4 months. Five months after burning, the low ~~pre-fire~~ capacity of runoff generation that is typical of ~~capacity of~~ the unburned soils ~~was~~ practically recovered~~stored~~. T~~, and t~~he same decreasing trend was noticed for the erosion in the pine soils, ~~(~~ where, one year after fire, the soil loss became very similar as the ~~control~~ unburned plots~~)~~. Although ~~declined~~ declining over time ~~in all forest plots~~, the increased erosion rates, noticed in the ~~chestnut and oak~~ forests of chestnut and oak, ~~are~~ were still evident, but ~~-~~not significant, after more than one year ~~elapsed~~ from fire application~~, but, in any case, these changes in soil hydrology were not significant~~. This means that the recovery of the pre-fire hydrological conditions in the burned soils ~~is~~ was not complete, although this incomplete recovery does not play significant effects on runoff and erosion rates. According to the previous study by ~~(~~Carrà et al. (~~,~~ 2021), this recovery may be ascribed to the increase in the mean IR and to the disappearance of the SWR ~~disappearance~~, both detected one year after fire. ~~SWR disappeared in few months, losing importance on hydrology of burned soils, which became non-repellent.~~

Moreover, in our experimental plots, we visually noticed that, progressively over time, the litter and shrub covers were recovering in the burned soils ~~in oak and pine stands~~of oak and pine, thanks to the vegetation regeneration ~~over the burned soils~~. In contrast, in the chestnut soils, litter cover was still limited after one year, as in the soil condition immediately before and after the prescribed burning. Vegetation recovery and litter accumulation during the growing season reduce ~~d~~ the impacts of heavy storms during the wet season ~~in forests~~, preventing high soil loss (Klimas et al., 2020). Herbaceous and shrub vegetation, and ~~leaf~~ litter covers reduce runoff and erosion rates thanks to rainfall interception, soil surface protection, and evapo-transpiration (DeBano et al., 1998; Sayer, 2006; Stoof et al., 2011; Vega et al., 2005; Walsh and Voigt, 1977). Increases in surface roughness due to the vegetation and litter on the soil determine longer time for overland flow takes to begin during a storm (Cawson et al., 2012; Johansen et al., 2001; Leighton-Boyce et al., 2007; Pierson et al., 2009; Stoof et al., 2011; Vega et al., 2005).

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

4.2. Effects of mulching on runoff and erosion

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

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

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

The improvement ~~of~~ in the hydrological response of the burned forests due to mulching was losing importance over time, since the pre-fire soil hydrology (runoff coefficients and erosion rates) ~~was restored~~ just recovered some months after burning. However, in ~~pine and chestnut~~ soils of pine and chestnut, the runoff generation capacity was even lower compared to the unburned plots, and the same was observed for erosion in the chestnut forest. This means that the soil treatment with mulching may also be effective throughout ~~also~~ several months after fire, since the vegetal residues ~~have been~~are incorporated into the soil, where organic matter increases and plays beneficial effects on soil macroporosity and infiltration capacity (Bombino et al., 2021, 2019; Lucas-Borja et al., 2019b; Shabanpour et al., 2020). As a matter of fact, one year after fire, the study by ~~(~~Carrà et al. (~~,~~2021) demonstrated that the infiltration capacity of soils mulched with fern noticeably increased over time, particularly in the soils of chestnut and oak, and less in the pine forest~~soils~~ ~~among~~ in all soil conditions. However, the incomplete recovery of the pre-fire infiltration ~~values of IR~~ did not significantly alter the runoff and erosion rates compared to the unburned soils, and it may be ~~presumably~~ presumable that this recovery will complete in the short term (Carrà et al., 2021).

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

5. Conclusions

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

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

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

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

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

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

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

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Supplementary material

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

Event date	**Runoff volume (mm)**						**Sediment concentration (g/l)**					
	Unburned soil		*Burned soil*		*Burned and mulched soil*		*Unburned soil*		*Burned soil*		*Burned and mulched soil*	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Pine												
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
Chestnut												
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
Oak												
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

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

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Abstract

Prescribed burning is increasingly used to reduce the wildfire risk, and the need to limit runoff and erosion after the fire suggests treating burned soils with mulching. To this aim, fern residues may be more advisable compared to the commonly used straw, since fern 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 after burning. Subsequently, the pre-fire runoff and erosion rates of the burned soils were practically recovered, and the hydrological changes were not significant compared to the unburned soils. In the short term after the 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 the runoff coefficients

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

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

1. Introduction

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

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

In order to limit the negative impacts of high-severity fires, preventing strategies have been adopted since long time (Ferreira et al., 2015). Among these strategies, prescribed fire - the planned use of low-intensity fire to achieve very different goals given certain weather, fuel and topographic conditions (Fernandes et al., 2013) - is considered as a primary and integrated option to reduce the wildfire risk in forests (Alcañiz et al., 2018; Klimas et al., 2020). The low-intensity fire, which is applied 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 the summer or other dry periods. Since the fuel for wildfires is regenerating after the prescribed fire, repeated applications are needed to control the wildfire risk over time. Moreover, the prescribed fire, which has low-severity and burn patchiness (Cawson et al., 2012; Pereira et al., 2021), avoids high temperature in soil and tree crown burning, which are the most adverse effects of wildfire on soil and plants. In addition, prescribed fire supports regeneration of some plant species (Scharenbroch et al., 2012; Williams et al., 2012; Francos and Úbeda, 2021). Litter, herbs and shrubs regenerate after the prescribed fire, and this prevents erosion in the treated forest. However, this renewed vegetal cover is insufficient to recover the pre-fire erosion rates, and thus post-fire management actions are needed. Increases in runoff and erosion after prescribed fires are lower compared to wildfires, but these risks are still present (Morris et al., 2013; Shakesby et al., 2015). Runoff and erosion increases have been observed after prescribed fires in different ecosystems, such as heathlands, shrublands and gorse (Vega et al., 2005). In the Mediterranean forests, these increases may be even more intense compared to other rainstorms (Fortugno et al., 2017), since the soils are generally shallow and show low aggregate stability, and organic matter and nutrient contents (Cantón et al., 2011). Due to the combination of these climate and soil characteristics, the Mediterranean forests are more exposed to excessive runoff and soil erosion rates compared to other ecosystems (Zema et al., 2020a; 2020b). Therefore, there is a need for an improved knowledge about soil hydrology in Mediterranean fire-prone forests, also considering that both wildfires and rainstorms are thought to become more frequent and intense according to the forecasted climate scenarios (Badia and Marti, 2008). However, despite an ample literature about the impacts of fire on soil hydrology, the studies on the hydrological effects of prescribed fire are not exhaustive and often contrasting (Cawson et al., 2012; Shakesby et al., 2015). 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 the 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.

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

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

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

2. Material and methods

2.1. Study area

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

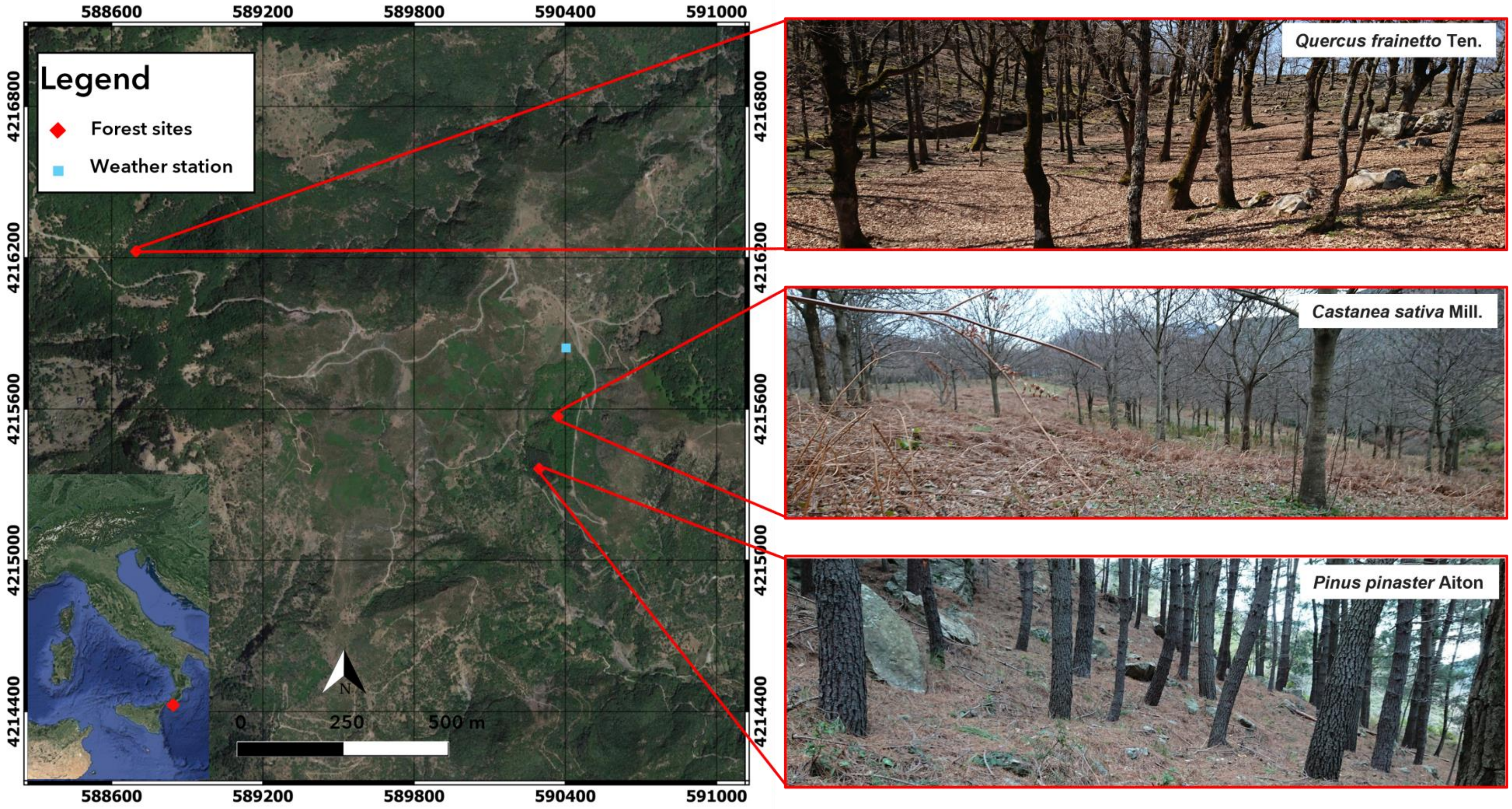


Figure 1 - Location of the experimental site (Samo, Calabria, Southern Italy).

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

Characteristics		**Site**		
		Calamacia	*Rungia*	*Orgaro*
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 (*Pinus pinaster* Aiton)	Oak (*Quercus frainetto* Ten.)	Chestnut (*Castanea sativa* Mill.)
	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
-		*Quercus ilex* L., *Rubus ulmifolius* S.	*Cyclamen hederifolium*	*Rubus ulmifolius* S., *Pteridium aquilinum L.*
Litterfall layer depth (cm)		11.7 ± 4.6	12.2 ± 3.9	6.1 ± 4

The climate of the area is typical of the semi-arid environment ("Csa" class, "Hot-summer Mediterranean" climate, according to Koppen classification (Kottek et al., 2006). Winters are mild and rainy, while summers are warm and dry. The mean annual precipitation and temperature are 1102 mm and 17.4 °C, respectively. The minimum temperature is - 4.3 °C, while the maximum is 43.1 °C (weather station of Sant'Agata del Bianco, geographical coordinates 4217548 N, 595159 E, period of 2000-2020).

All soils are loamy, except the unburned area of the pine forest, which is sandy loam (Table 2).

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

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	loamy sand
Rungia	oak	unburned	12.7 ± 1.53	9.7 ± 0.58	77.7 ± 1.15	
		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	

2.2. Prescribed fire operations and mulching application

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

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

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

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

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

(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).

2.4. Plot construction

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

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

2.5. Monitoring of the hydrological variables

The hydrological measurements started immediately after site installation (mid-June 2019) and were carried out throughout 15 months (until mid-September 2020).
A weather station with a tipping bucket rain gauge (measuring sub-hourly data) was installed at a maximum distance of 1 km from the experimental sites, to measure precipitation height, storm duration, and rainfall intensity. The mean rainfall intensity was the total rainfall divided by the storm duration. Moreover, an additional rain gauge (measuring only the rainfall height) was installed in each forest site, in order to estimate the rainfall intercepted by the tree canopy, and to check the spatial variability of the rainfall measured by the main weather station.
The surface runoff and sediment concentration after precipitation were measured following the procedures suggested by Lucas-Borja et al. (2019b) and Bombino et al. (2021). Only the runoff volumes produced by rainfalls over 13 mm, which can be considered as "erosive events", according to (Wischmeier and Smith, 1978), were monitored. The collecting tanks were emptied and cleaned after each precipitation - erosive or not - event. To summarize, the runoff water in the tank was stirred to achieve a good suspension, and three separate samples of the suspension was collected, totalling about 0.5 litres. The samples were brought to the laboratory, and oven-dried at 105 °C for 24 hours. After drying, the sediments were weighted and referred to the sample volume, in order to calculate the sediment concentration. The soil loss produced by the rainfall-runoff event was estimated by the product of the runoff volume by the sediment concentration. The runoff coefficients were also calculated as the ratio of runoff to rainfall.

2.7. Statistical analyses

One-way ANOVA with repeated measures (at each rainfall-runoff event) was applied to the runoff volume and soil loss (response variables) separately for the three forest stands, assuming as factor the soil condition (unburned, burned and not treated, and burned and mulched). The pairwise comparison by Tukey's test (at $p < 0.05$) was also used to evaluate the statistical significance of the differences in the response variables. In order to satisfy the assumptions of the statistical tests (homogeneity of variance and normal distribution), the data were subjected to normality test or were square root-transformed whenever necessary. All the statistical tests were carried out by with the XLSTAT software (release 2019.1, Addinsoft, Paris, France).

3. Results

3.1. Rainfall characterization

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

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

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

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

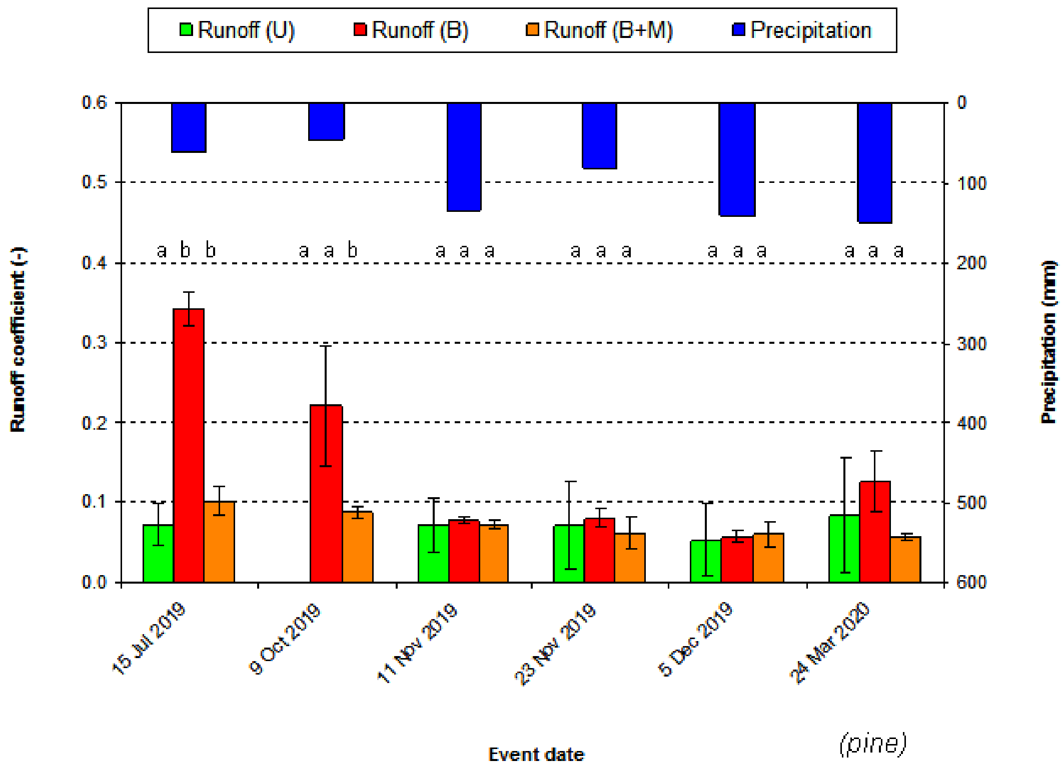
Note: recorded at the rain gauge station under tree canopy in each forest.

3.2. Runoff

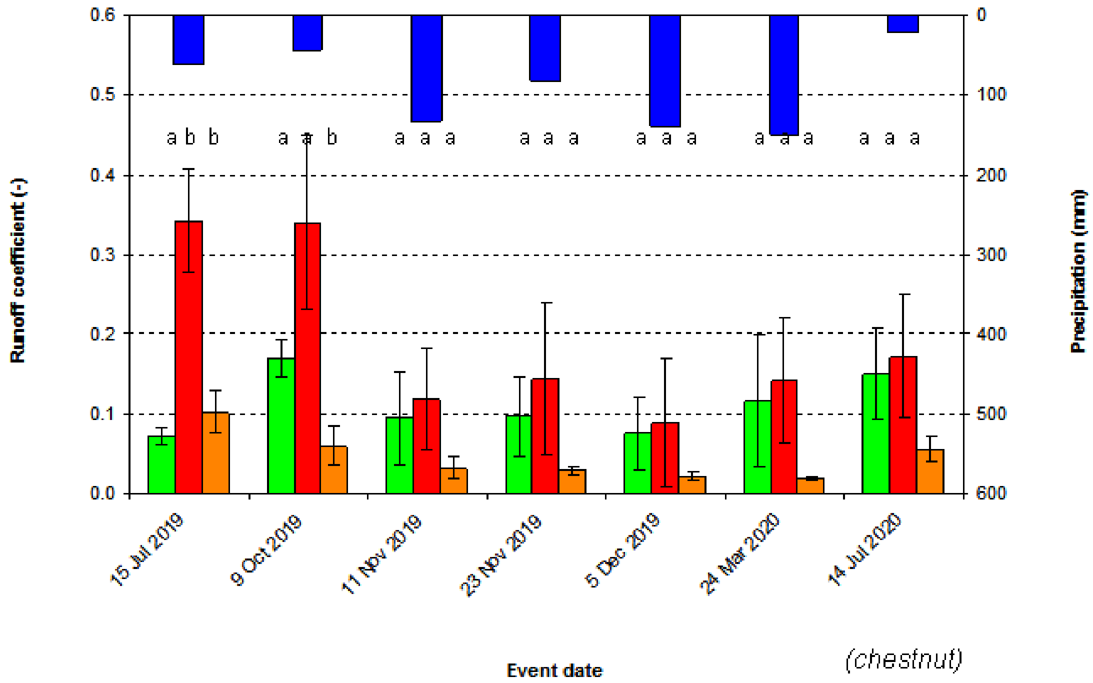
The runoff volumes measured at the experimental plots are reported in Table 1SM of the Supplementary Materials. These measurements coupled to the rainfall records were the base for the evaluation of the hydrological response of the three soil conditions to burning and post-fire mulching in terms of runoff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

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

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



Runoff (U)
Runoff (B)
Runoff (B+M)
Precipitation
Runoff coefficient (-)
Precipitation (mm)
a b b
a a b
a a a
a a a
a a a
a a a
15 Jul 2019
9 Oct 2019
11 Nov 2019
23 Nov 2019
5 Dec 2019
24 Mar 2020
Event date
(pine)



Runoff coefficient (-)
Precipitation (mm)
a b b
a a b
a a a
a a a
a a a
a a a
a a a
15 Jul 2019
9 Oct 2019
11 Nov 2019
23 Nov 2019
5 Dec 2019
24 Mar 2020
14 Jul 2020
Event date
(chestnut)

335

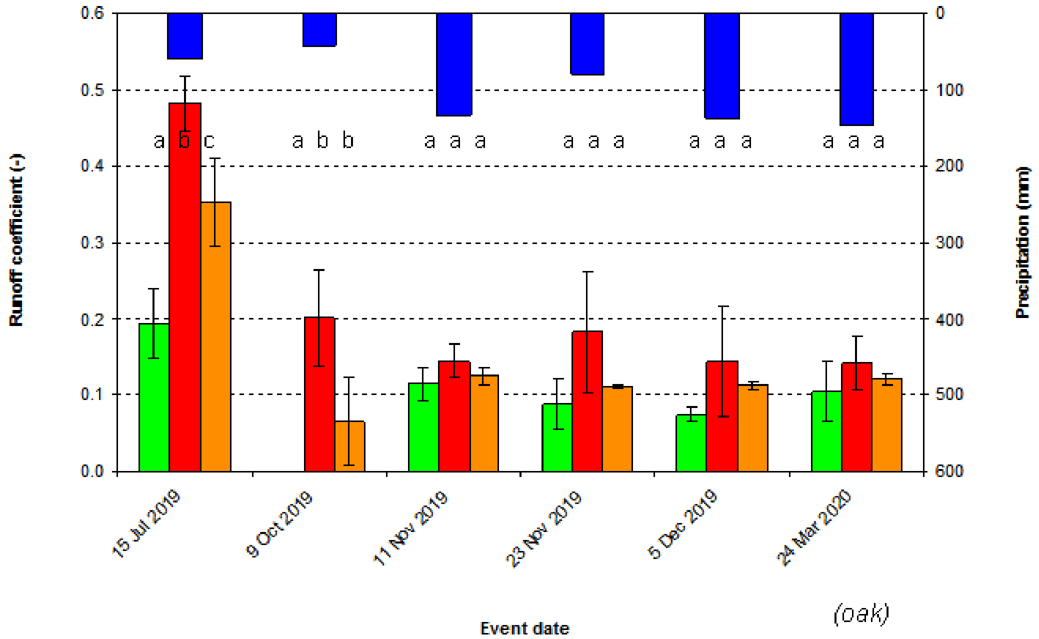


Figure 4 - Precipitation and runoff coefficients measured in plots after prescribed fire and soil mulching using fern (Samo, Calabria, Southern Italy).

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

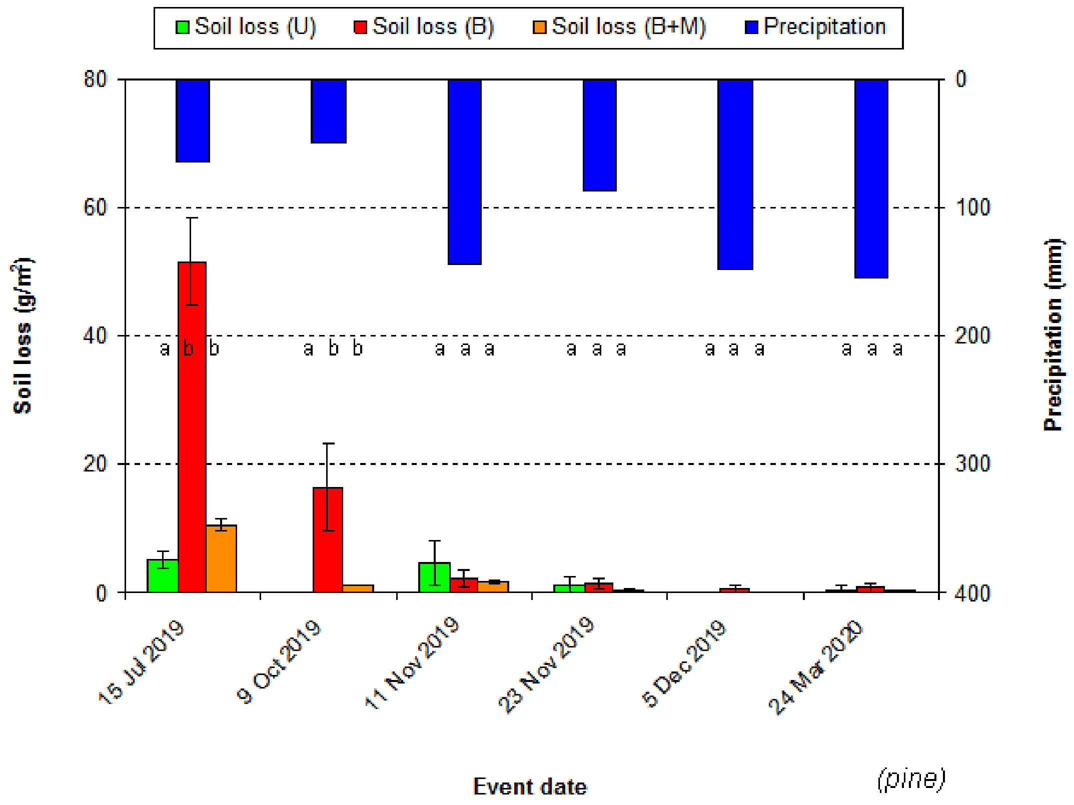
3.3. Erosion

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

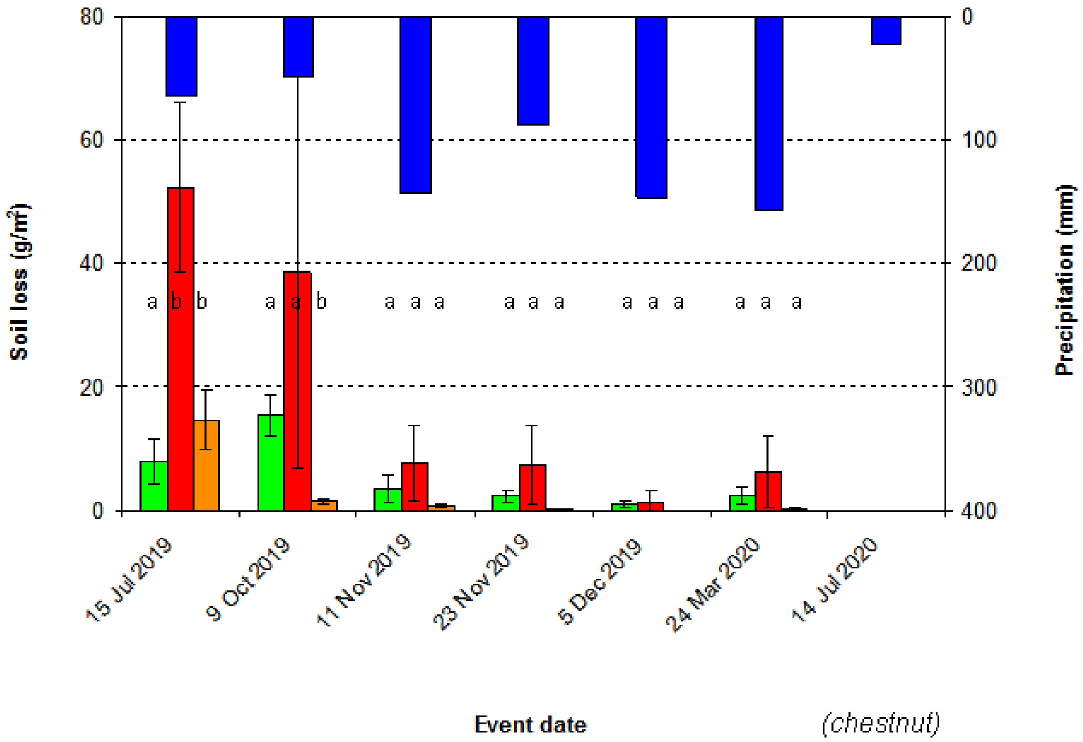
As expected, the soil loss was of low amount in the unburned plots. The maximum erosion was estimated after the first event in the forests of pine and oak (5.31 ± 1.40 and 7.37 ± 2.72 g/m^2, respectively), while the rainfall event that produced the highest soil loss (15.34 ± 3.21 g/m^2) in the chestnut soil was the second event (Figure 5).

For these two rainfall events, erosion increased very much in burned soils of all forests, and mainly in the soils of pine and chestnut. In these plots, the maximum values of soil loss, equal to 51.61 ± 6.92 and 52.26 ± 13.67 g/m^2, were detected after the first event. In the oak soils, erosion was noticeably lower, 15.12 ± 2.87 g/m^2 (although higher compared to the unburned plots). However, mulching was effective to reduce these soil losses, and the maximum value (14.58 ± 4.80 g/m^2) was detected in chestnut forest. The highest erosion in the mulched soils was always estimated after the first rainfall (Figure 5).

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



Soil loss (U)
Soil loss (B)
Soil loss (B+M)
Precipitation
Soil loss (g/m²)
Precipitation (mm)
80
60
40
20
0
0
100
200
300
400
a b b
a b b
a a a
a a a
a a a
a a a
15 Jul 2019
9 Oct 2019
11 Nov 2019
23 Nov 2019
5 Dec 2019
24 Mar 2020
Event date
(pine)



Soil loss (g/m²)
Precipitation (mm)
80
60
40
20
0
0
100
200
300
400
a b b
a a b
a a a
a a a
a a a
a a a
15 Jul 2019
9 Oct 2019
11 Nov 2019
23 Nov 2019
5 Dec 2019
24 Mar 2020
14 Jul 2020
Event date
(chestnut)

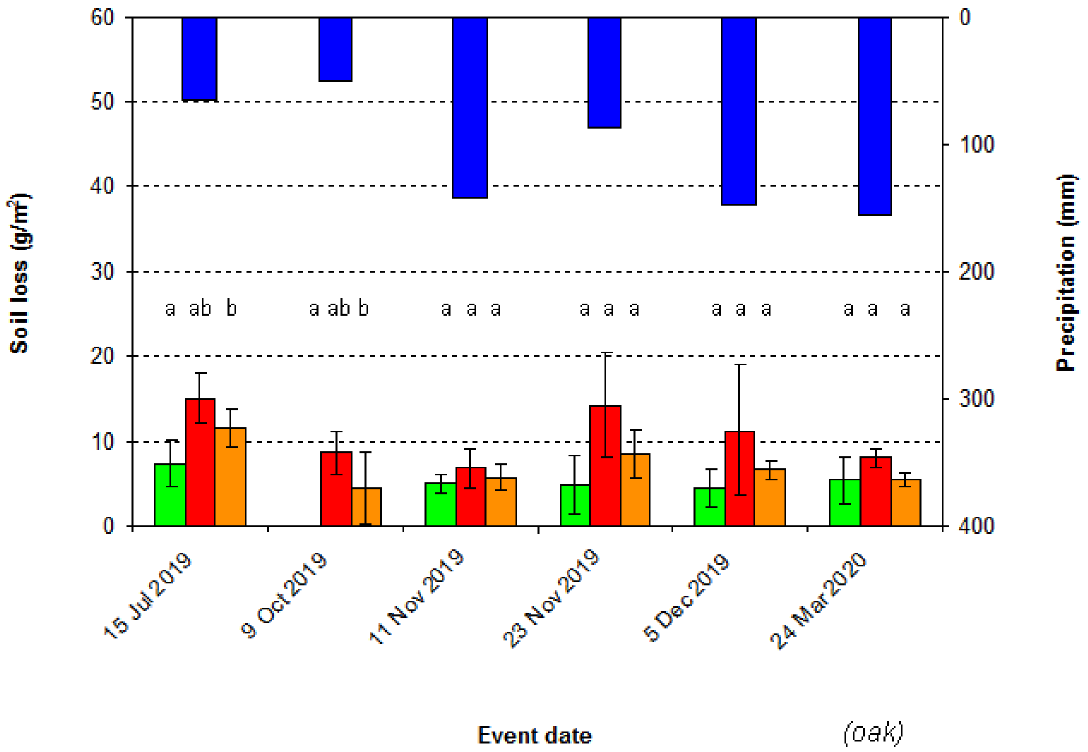


Figure 5 - Precipitation and soil loss measured in plots after prescribed fire and soil mulching using fern (Samo, Calabria, Southern Italy).

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

4. Discussion

4.1. Effects of prescribed fire on runoff and erosion

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

Cumulating all the erosive events observed in this study, erosion never exceeded 0.33 tons/ha throughout the monitored year, and this value is well below the tolerance limit of the range 3 to 11.2 tons/ha per year (Bazzoffi, 2009; Wischmeier and Smith, 1978).

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

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

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

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

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

The findings of our study are supported by the previous study carried out by (Carrà et al., 2021), who have evaluated the IR and SWR in the same forest stands, using a portable rainfall simulator to measure the IR, and the Water Drop Penetration Test (Bisdom et al., 1993; Letey, 1969; Woudt, 1959) to estimate the SWR. In more detail, in all forest soils the prescribed fire reduced the mean IR compared to the unburned conditions. The increase in SWR may also have played an important role in increasing runoff and erosion immediately after fire in the soils of pine and oak, since the prescribed burning determined a strong repellency. In contrast, in the chestnut soils the prescribed fire did not alter the slight SWR found in unburned plots (Carrà et al., 2021).

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

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

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

4.2. Effects of mulching on runoff and erosion

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

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

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

The improvement in the hydrological response of the burned forests due to mulching was losing importance over time, since the pre-fire soil hydrology (runoff coefficients and erosion rates) just recovered some months after burning. However, in soils of pine and chestnut, the runoff generation capacity was even lower compared to the unburned plots, and the same was observed for erosion in the chestnut forest. This means that the soil treatment with mulching may also be effective throughout several months after fire, since the vegetal residues are incorporated into the soil, where organic matter increases and plays beneficial effects on soil macroporosity and infiltration capacity (Bombino et al., 2021, 2019; Lucas-Borja et al., 2019b; Shabanpour et al., 2020). As a matter of fact, one year after fire, the study by Carrà et al. (2021) demonstrated that the infiltration capacity of soils mulched with fern noticeably increased over time, particularly in the soils of chestnut and oak, and less in the pine forest in all soil conditions. However, the incomplete recovery of the pre-fire infiltration did not significantly alter the runoff and erosion rates compared to the unburned soils, and it may be presumable that this recovery will complete in the short term (Carrà et al., 2021).

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

5. Conclusions

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

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

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

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

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

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

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

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Supplementary material

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

Event date	**Runoff volume (mm)**						**Sediment concentration (g/l)**					
	Unburned soil		*Burned soil*		*Burned and mulched soil*		*Unburned soil*		*Burned soil*		*Burned and mulched soil*	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Pine												
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
Chestnut												
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
Oak												
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

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

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Declaration of interests

X 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.

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