Hydrological and Erosive Effects of Prescribed Fire and Mulching with Fern Residues in a Mediterranean Pine Forest

Hydrological effects of prescribed fire and mulching with fern residues in a Mediterranean pine forest

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Abstract. This study has evaluated the short-term effects of prescribed fire and post-fire mulching using fern on soil hydrology in a pine forest of Southern Italy. Water infiltration (by rainfall simulations) and soil water repellency (SWR) were estimated immediately and one year after fire. Surface runoff volume and soil loss have been measured in experimental plots under natural precipitations throughout one year. The prescribed fire reduced the infiltration rates compared to the unburned soils. Mulching was not able to contrast this reduction, which, however, vanished over time. Immediately after the fire, the runoff (+375%) and erosion (+900%) significantly increased. The pre-fire runoff and erosion rates restored after about five months. Soil mulching with fern was effective to limit these increases (reductions in the runoff coefficients and soil losses by 60 to 90%, respectively). The prescribed fire induced SWR, which disappeared after one year. Overall, in a Mediterranean pine forest, post-fire management actions with a cheap mulch materials, as fern residues, are needed to control the negative hydrological impacts of prescribed fires in the short term.

Keywords: Water infiltration, soil water repellency, surface runoff, soil erosion, soil hydrological response, post-fire management.

1 Introduction

Prescribed fire, the planned use of low-intensity fire to remove or reduce the fuel that can generate high-severity fires, is considered as a primary option to reduce the wildfire risk in forests. However, this technique removes forest litter and vegetation, leaving the soil bare in the so-called "window of disturbance" of forest soils (Prosser and Williams, 1998) that lasts from some months to one year after fire application. Moreover, in spite of the low temperature of soil during heating, some changes in soil properties may be noticed (for instance, reductions in organic matter content and soil aggregate stability) (Alcañiz et al., 2018), and soil hydrophobicity may be induced (DeBano, 1981). The latter effects of prescribed fire may result in reduced water infiltration, and, therefore, in increased runoff and erosion. In the Mediterranean forests, these increases may be even more intense, since the soils are generally shallow and show low aggregate stability. Despite an ample literature about the impacts of fire on soils, the studies on the hydrological effects of prescribed fire are not exhaustive and often contrasting (Cawson et al., 2012). Increases in runoff and erosion by two orders of magnitude may be observed compared to unburned areas (Cawson et al., 2013). In contrast, minimal erosion after prescribed fire is sometime recorded (Keesstra et al., 2014; Morris et al., 2014).

In order to reduce the soil's susceptibility to runoff and erosion after a wildfire, several treatments have been proposed (Zema, 2021). Soil mulching is one of the most common post-fire management options (Lucas-Borja et al., 2019), since the mulch protects the soil and improves its quality. Agricultural straw is often used as mulch cover in fire-affected areas, but its residues can be displaced by wind in some areas, leaving the hillslopes bare, or accumulated in other areas, with possible reductions in the post-fire emergence of vegetation (Robichaud et al., 2020). Moreover, straw may contain seeds, chemicals and parasites, which can be the sources of non-native vegetation and plant diseases. Fern - *Pteridium aquilinum* (L.) Kuhn – is widely available in forests, does not do not carry non-native seeds or chemical residues, and is more resistant to wind displacement (Robichaud et al., 2020). Therefore, its residues as mulching material in burned forests may be 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. To fill these research gaps, this study has evaluated the hydrological response of soils in a forest of Calabria (Southern Italy) after a prescribed fire, with or without a mulching treatment with fern residues, in comparison to the unburned soils. More specifically, water infiltration has been estimated in rainfall simulations, and surface runoff and soil loss were measured after natural precipitations throughout one year after fire.

2 Material and methods

2.1 Study area

The study was carried out in a pine forest site close to the municipality of Samo (Calabria, Southern Italy, Fig. 1). 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). The minimum temperature is -4.3 °C, while the maximum is 43.1 °C The altitude ranges between 650 and 700 m a.s.l. and the local slope is 20.0 ± 0.82%. The texture of soil burned by prescribed fire was loamy sand, while the unburned area was sandy loam. The main tree and shrub species are Pine (*Pinus pinaster* Aiton) and *Quercus ilex* L., *Rubus ulmifolius* S., respectively.

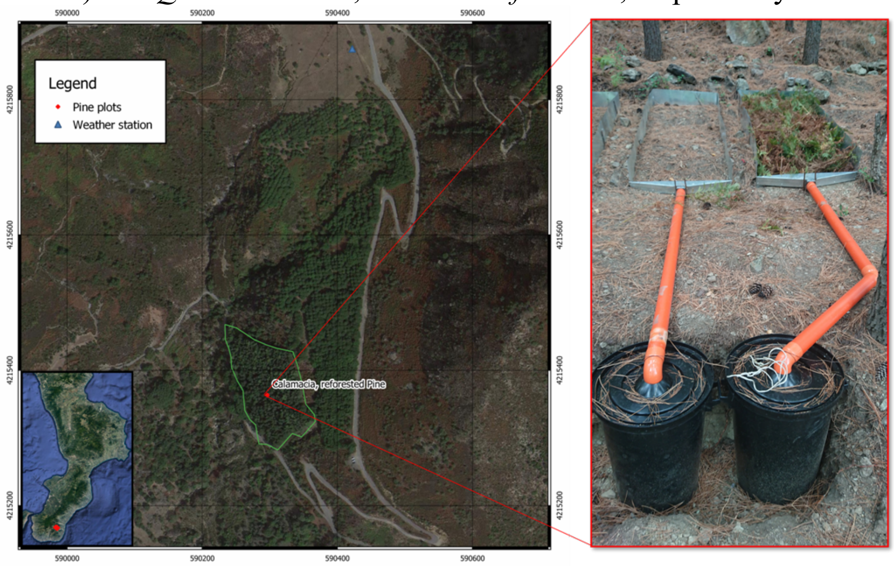


Fig. 1. Location of the experimental site (Samo, Calabria, Italy).

2.2 Prescribed fire operations and mulching application

In early June 2019 the prescribed fire was applied in the forest site by the Environmental Regional Agency under proper weather conditions (no wind and or humidity over 50%). The mean soil temperature, measured by thermocouples, was about 25 °C with a peak of 29 °C. Immediately after the prescribed fire, a part of the burned areas was covered with fern residues as mulch material. The plants were cut in the same forest and manually shredded in small pieces (3-5 cm) at a dose of 200 g/m^2 of dry matter, to form a mulch layer 2 to 3-cm thick.

2.3 Experimental design

In the experimental site, three series of plots were installed on hillslopes. Three plots were located in the unburned soils (considered as control). Six other plots were in the burned area, of which three plots were not treated and three plots were mulched with fern. Overall, the experimental design consisted of three soil conditions (unburned, burned and not treated, and burned and mulched) × three replicates. Each plot was 3-m long and 1-m wide, and covered an area of 3 m^2. In order to prevent the inflow of surface water, the plots were hydraulically isolated using metallic sheets that were inserted below the ground surface. A transverse channel and a longitudinal pipe, installed downstream of each plot, intercepted the flows of water and sediments, which were collected into 100-litre tanks.

2.4 Monitoring of the hydrological variables

The water infiltration rate (IR) was determined using a portable Eijelkamp® rain simulator. The simulator reproduced a rainfall with a height and intensity of 18 mm and 360 mm h^{-1}, respectively, over a surface area of 0.3 m x 0.3 m. The soil water repellency (SWR) was estimated using the Water Drop Penetration Test (WDPT) method (Woudt 1959; Letey 1969), and classified according to the values of WDPT proposed by (Bisdom et al. 1993). Fifteen drops of distilled water were released on the soil surface, using a pipette. The time needed by the drops to penetrate the soil was measured, in order to estimate the WDPT. The SWR was measured at the natural soil water content (SWC) using a probe. The SWR measures differing for a SWC by over 10% were discarded. IR, SWR and SWC were measured immediately after the prescribed fire and at one year in three randomly selected points per plot, and the three measures were then averaged.

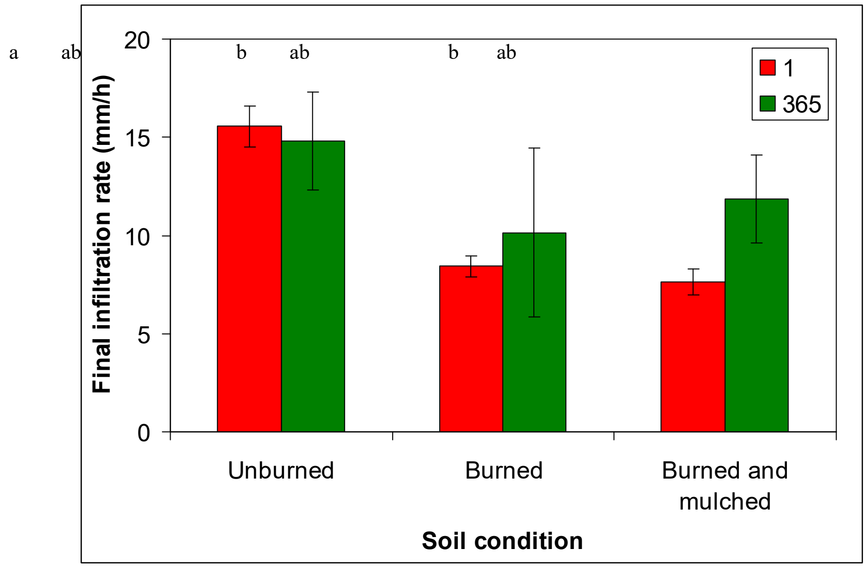
The measurements of surface runoff and soil loss under natural precipitations started immediately after site installation and were carried out throughout until June 2020. Precipitation depth, duration, and intensity were measured by a tipping bucket rain gauge (measuring 5-min data) at a weather station with that was located 1 km from the experimental site. Surface runoff (SR) and sediment concentration were measured after rainfalls over 13 mm, which can be considered as "erosive events" according to (Wischmeier and Smith, 1978). The runoff water in the tank was stirred to achieve a good suspension, and three separate samples were collected, totalling about 0.5 litres. The samples were oven-dried at 105 °C for 24 hours in laboratory. Then, the sediments were weighted and referred to the eroded area, to calculate the soil loss (SL).

2.5 Statistical analyses

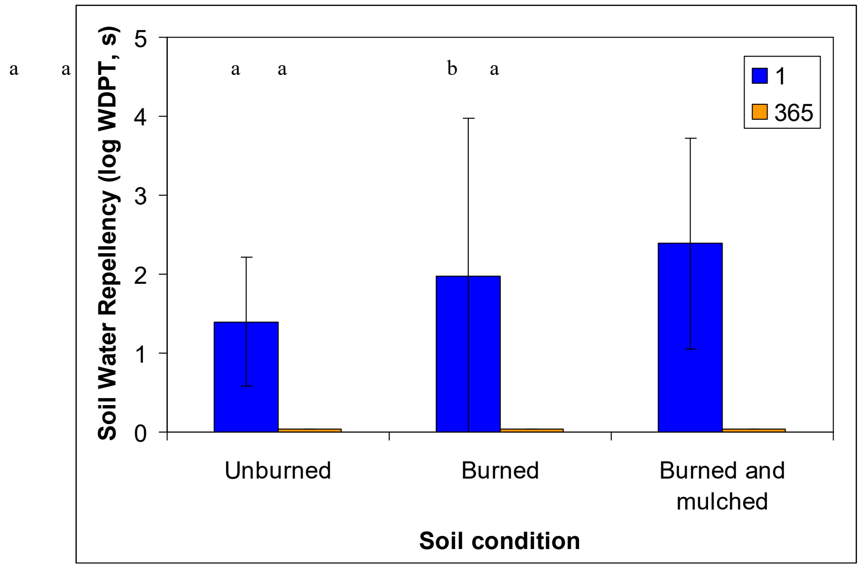
One-way ANOVA with repeated measures (one for each rainfall-runoff event) was applied to IR, SWR, SR, and SL (response variables), assuming as factor the soil condition (unburned, burned and not treated, and burned and mulched). The pairwise comparison by Tukey's test (at $p < 0.05$) was also used to 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.

3 Results and Discussion

Prescribed fire reduced IR by 46% compared to the unburned sites. Mulching was not able to limit this reduction (-51%) (Fig. 2a). Moreover, fire increased the slight SWR of unburned soil, which became strongly repellent (Fig. 2b). The significant reduction in IR is due to the synergistic effects of increased SWR, removal of vegetation and presence of ash that clogs the soil pores (Cawson et al., 2012). One year after the fire, the SWR disappeared and all soils became non-repellent (Fig. 2b). The IR of burned soils slightly increased compared to the value measured one day after the fire (+20%), while this increase was 55% in the mulched soils (Fig. 2a). This shows the positive effect of the post-fire treatment on the hydrological properties of burned soils.



(a)



(b)

Fig 2. Water infiltration rate (a) and soil water repellency (b) after prescribed fire and soil mulching with fern residues in the experimental site (Samo, Calabria, Italy). Note: different letters indicate significant differences in the interaction between soil conditions and time after fire, respectively, after Tukey's test ($p < 0.05$); bars report mean ± std. dev. ($n = 3$).

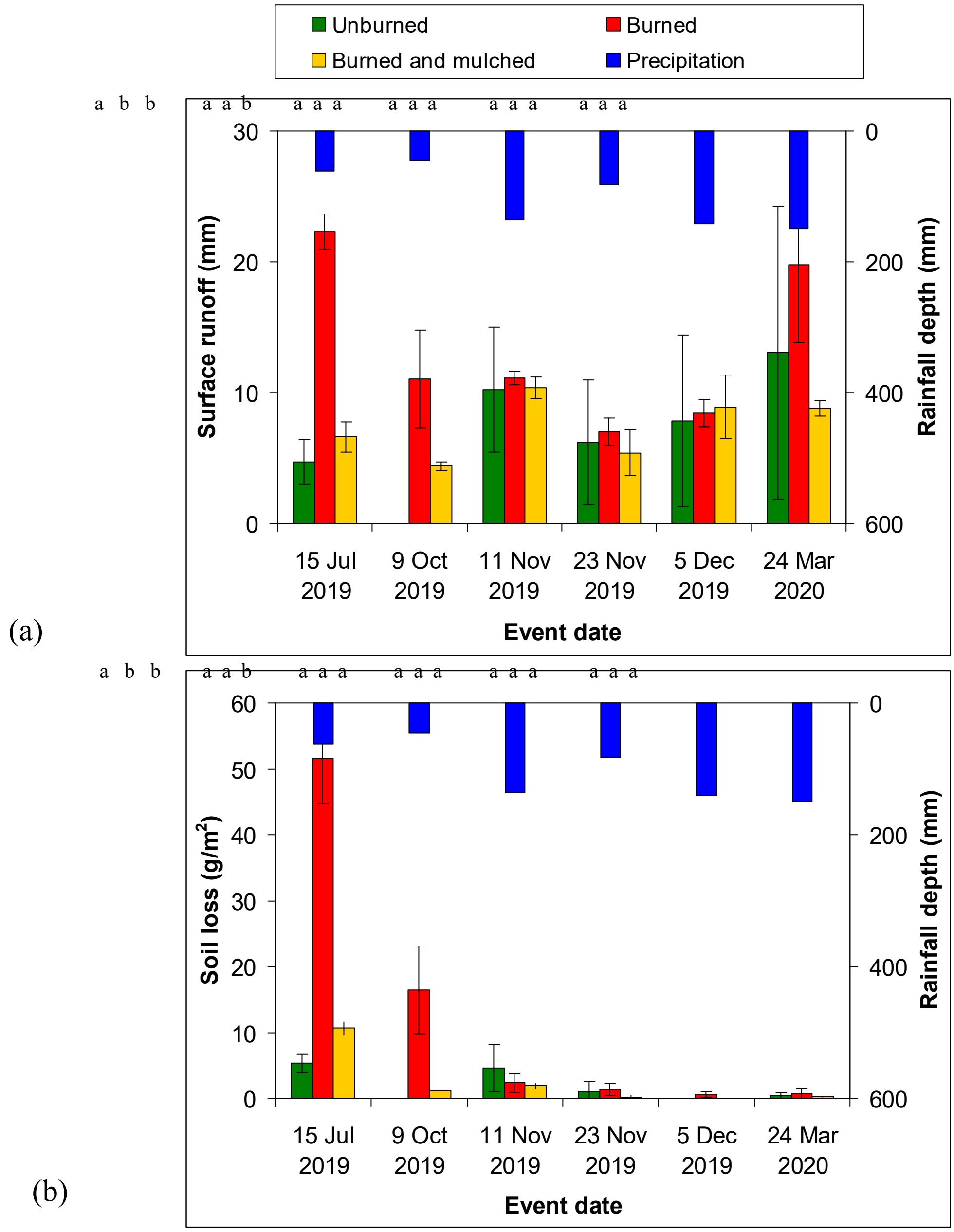


Fig. 3. Precipitation, runoff coefficients (a) and soil loss (b) measured in plots under natural precipitations after prescribed fire and soil mulching with fern residues (Samo, Calabria, Southern Italy). Note: different letters indicate statistically significant differences after Tukey's test ($p < 0.05$).

Throughout the monitoring period, seven rainfalls were classified as erosive events. The depth of these events was in the range of 22.4 - 156 mm, while their duration varied between 7 and 41 hours. The maximum absolute intensity was 26.2 mm/h, while the highest mean intensity was 4.90 mm/h. Runoff and erosion significantly increased after the two rainstorm events occurred immediately after fire. In more detail, compared to the unburned plots, the runoff volume measured in the burned soils increased by over 375% in the first event and from zero to 11 mm in the second rainstorm. About five months after burning, the pre-fire runoff generation capacity practically restored, and surface runoff in the burned soils was similar as in the unburned conditions (Fig. 3a). Soil erosion followed the same pattern as runoff, with increases in burned plots up to 900% on occasion of the first erosive event. Soil erosion progressively decreased over time (Fig. 3b). This means that the negative impacts on the hydrological response in burned soils are limited to four-five months after burning. The first rainfall events, when fire has almost thoroughly removed the vegetation cover and the litter, noticeably increase runoff and erosion (Lucas-Borja et al., 2021). This is in close

accordance with the majority of studies, which showed that prescribed fire generates noticeably more runoff and soil loss compared to the unburned areas in the short term after fire (e.g., (de Dios Benavides-Solorio and MacDonald, 2005; Morris et al., 2014).
In the short term, soil mulching with fern residues was effective at limiting the increase in the hydrological response of the burned soils, surface runoff and soil loss being lower by 60-70% and 80-90%, respectively, compared to the burned and untreated plots. The changes in runoff and erosion rates were associated to the variations in the infiltration rates and water repellency immediately after fire. The recovery of the pre-fire IR and the disappearance of the SWR gained importance over time, and the incorporation of mulch residues became beneficial in driving the short-term hydrological response of the burned soils. The effectiveness of fern mulching on soil hydrology shown in our study is higher compared to other relevant investigations (reductions between 40 to 60% compared to the runoff observed in unburned conditions, e.g. (Prats et al., 2016; Robichaud et al., 2013)).

4 Conclusion

The experimental investigation has shown that, in a Mediterranean pine forest, post-fire management actions, such as the soil cover with a fern residues, are needed to control the short-term increases in surface runoff and soil erosion after prescribed fires. Further research is needed (i) to validate the results at the plot scale through upscaling to hillslopes or better catchments, and (ii) to explore the influence of the physico-chemical properties of soil on its hydrological response under burned conditions with and without treatments.

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