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

Manuel García Díaz [a], Manuel Esteban Lucas-Borja [a], Javier Gonzalez-Romero [a], Pedro Antonio Plaza-Alvarez [a], Mehdi Navidi [b], Yi-Fan Liu [c], Gao-Lin Wu [c], Demetrio Antonio Zema [d,*]

[a] *Castilla La Mancha University, School of Advanced Agricultural and Forestry Engineering, Department of Agroforestry Technology and Science and Genetics, Campus Universitario s/n, E-02071 Albacete, Spain*

[b] *Faculty of Natural Resources, Forestry Department, Urmia University, Urmia, West Azerbaijan, Islamic Republic of Iran*

[c] *State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Water and Soil Conservation, Northwest A&F University, Yangling, Shaanxi 712100, China*

[d] *Mediterranean University of Reggio Calabria, Department AGRARIA, Località Feo di Vito, I-89122 Reggio Calabria, Italy.*

A R T I C L E I N F O

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A B S T R A C T

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

1. Introduction

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

In forests affected by wildfires, the vegetation is completely removed and the soil is left bare and thus exposed to rainsplash, surface runoff and erosion (Bodí et al., 2012; Shakesby and Doerr, 2006a, 2006b). Moreover, the wildfire heavily alter the chemical properties of soils, such as the pH, electrical conductivity, and contents of organic matter and nutrients (Alcañiz et al., 2018; Certini, 2005; Zavala et al., 2014). Moreover, the physical characteristics of burned areas, such as soil water repellency and aggregate stability, are also impacted (Arcenegui et al., 2008; Varela et al., 2010; Zema et al., 2021a, 2021b). The changes in

* Corresponding author.
E-mail address: dzema@unirc.it (D.A. Zema).

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vegetation cover and soil properties can be long lasting (Shakesby and Doerr, 2006a, 2006b; L. M. Zavala et al., 2014), and the soils burned by high-intensity fires may need several years or even decades to restore their pre-fire properties (Certini, 2005; Glenn and Finley, 2010).

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

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

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

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

To fill these research needs (comparative studies on Mediterranean burned forests treated with post-fire management techniques, and evaluation of mulching effectiveness on the hydrology of burned forests using two cover residues), this study has evaluated the hydrological behaviour of soil mulched with straw or wood chips after a wildfire in a pine forest of Central-Eastern Spain. More specifically, water infiltration, surface runoff and soil loss were measured on unburned, and burned and mulched soils using a small portable rainfall simulator together with the soil covers (vegetation, rock, mulch, and bare soil). We hypothesize that: (i) mulching is in general able to reduce runoff and erosion compared to the control soils; and (ii) this technique is more effective on the steep slopes in these semi-arid areas. Finally, the comparison between two different vegetal materials for mulching should give indications about the more advisable technique for soil conservation in burned areas.

2. Materials and methods

2.1. Study area

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

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

2.2. Experimental design

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

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

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

2.3. Hydrological simulations

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

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

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

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

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

2.4. Measurement of soil covers

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

2.5. Statistical analysis

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

3. Results

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

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

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

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

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

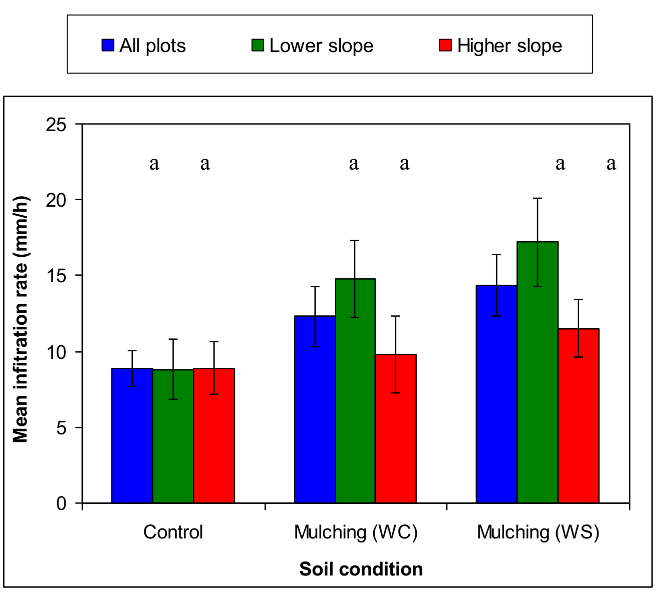

Fig. 1. Water infiltration rate (mean ± std. error) measured by a portable rainfall simulator under three conditions (control, mulched with wood chips, WC, or wheat straw, WS) and two slopes of forest soils (Liétor, Castilla La Mancha, Spain). Different letters indicate significant differences among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

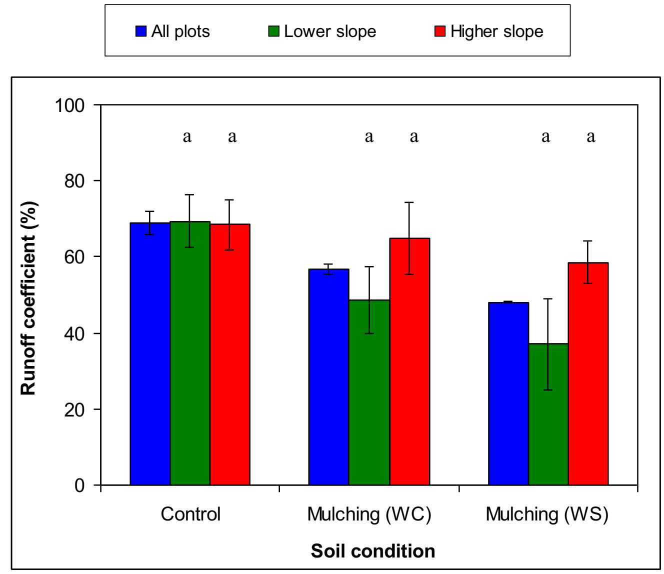

Fig. 2. Runoff coefficients (mean ± std. error) measured by a portable rainfall simulator under three conditions (control, mulched with wood chips, WC, or wheat straw, WS) and two slopes of forest soils (Liétor, Castilla La Mancha, Spain). Different letters indicate significant differences among soil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

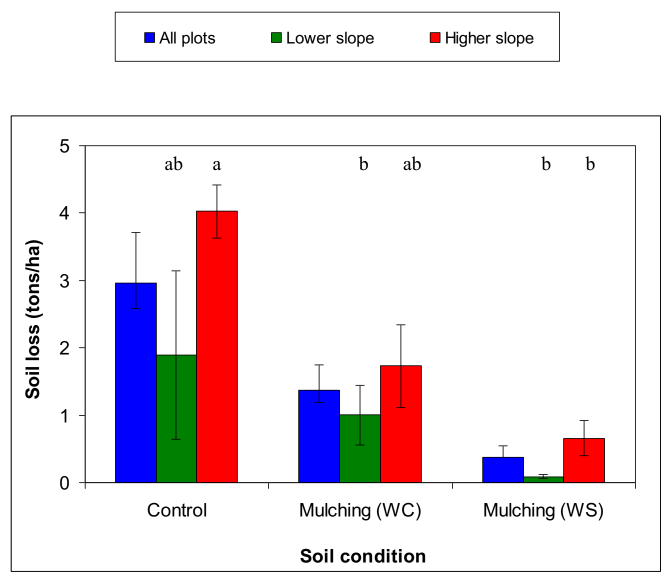

Fig. 3. Soil losses (mean ± std. error) measured by a portable rainfall simulator under three conditions (control, mulched with wood chips, WC, or wheat straw, WS) and two slopes of forest soils (Liétor, Castilla La Mancha, Spain). Different letters indicate significant differences among soil conditions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

in the soils treated with wood chips, and between 70% (higher slope) and 75% (lower slope) in the plots mulched with straw (Fig. 4).

By regressing using a linear equation each hydrological variable on the different soil covers, low coefficients of regression were found ($r^2 <$ 0.35). More specifically, no evident and significant correlations were found between the runoff coefficients and soil losses on one side, and the soil covers on the other side ($r^2 < 0.52$); the only exception was the regression between the soil loss and the mulch cover in soils with higher slopes ($r^2 = 0.85$, Fig. 5).

4. Discussions

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

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

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

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

In our study, mulching resulted in two important hydrological effects. First and mainly, the mulch cover retains part of the rainwater, which evaporates and thus reduces the hydrological response of the soil.

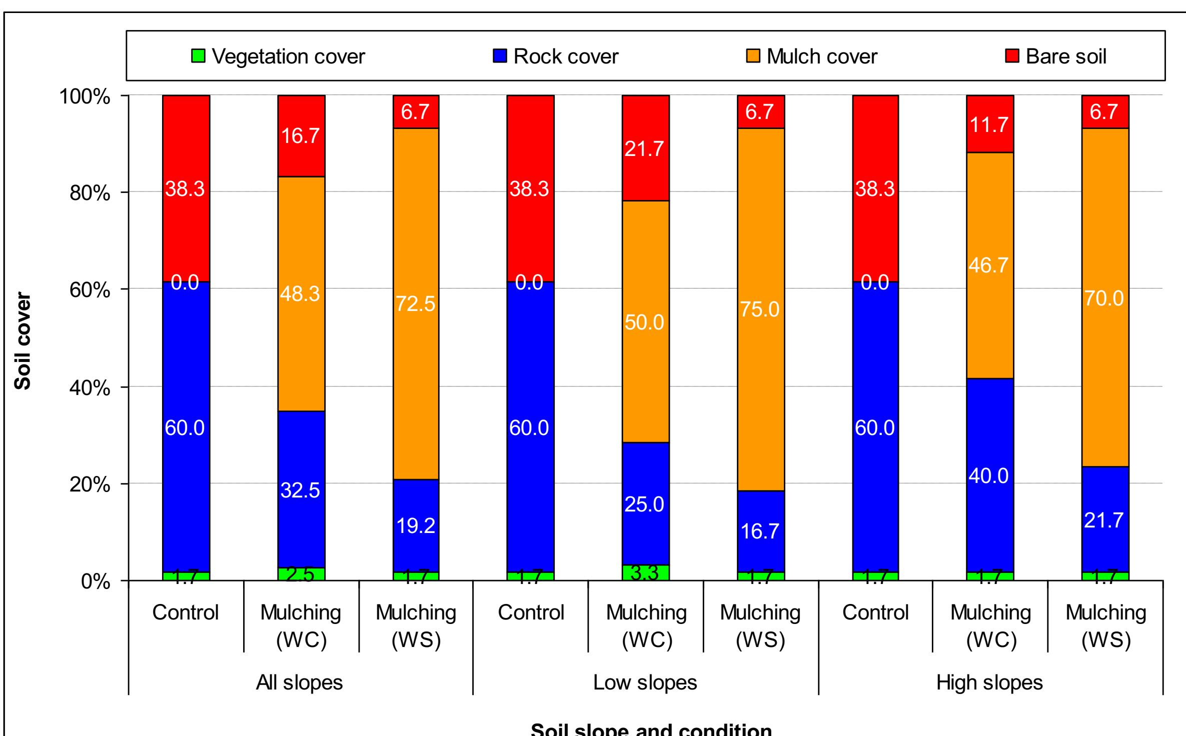

Fig. 4. Soil covers (in % on the total plot area) measured under three conditions (control, mulched with wood chips, WC, or wheat straw, WS) and two slopes in the studied forest (Liétor, Castilla La Mancha, Spain).

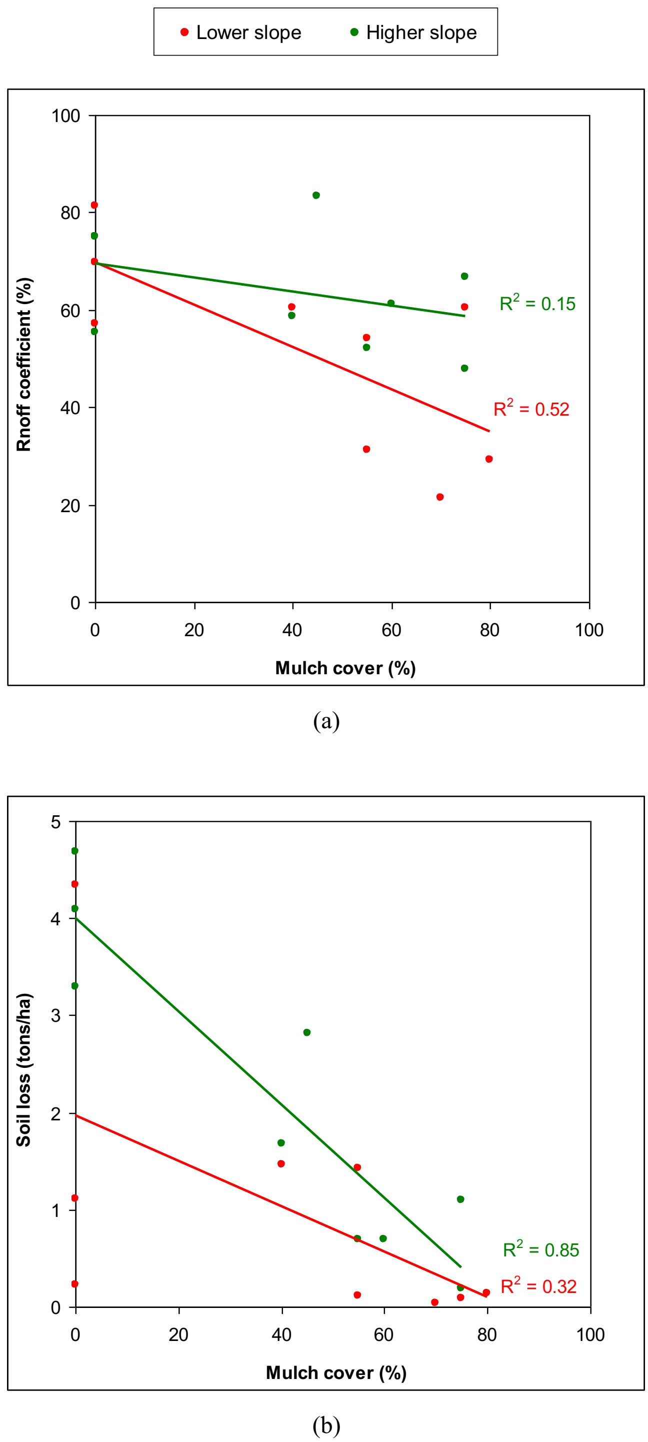

Fig. 5. Correlations between the mean runoff coefficients (a) and soil losses (b), and the mulch cover measured on soils (number of plots = 3) under three conditions (control, mulched with wood chips or wheat straw) and two slopes in the experimental forest (Liétor, Castilla La Mancha, Spain).

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

Secondly, the variations in the hydraulic conductivity, although not being significant, may also be another reason of the differences measured in the soil's hydrological response between the mulched and untreated areas. An increased water infiltration results in a consequent reduction in the runoff rates. As outlined above, a longer time between the time elapsed from mulch application and the hydrological measurements should have evidenced a further decrease in the runoff response of the treated soils, due the mulch degradation and improvement of physical properties of the burned soils.

The general reduction in the hydrological response of the investigated fire-affected areas has demonstrated how and by what extent the presence of a vegetal cover on the burned soil is beneficial to reduce the overland flow after precipitation. Also other authors (e.g., Cerdà and Doerr, 2008; Prats et al., 2012) reported a decrease in the surface runoff with increasing covers of dead or living vegetation as mulch materials.

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

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

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

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

A possible limitation of this study is the only use of simulated rainfall. Compared to the natural precipitation, the kinetic energy of rainfall is lower under artificial conditions and the rainsplash erosion is therefore underestimated; moreover, the runoff detachment due to the overland and rill flows is not evaluated by small devices (Hamed et al., 2002; Loch et al., 2001). However, in this study the erosion rates at the event scale measured for the burned and mulched areas (up to 1–2 tons/ha) are well below the limits of hazardous erosion. Therefore, the difference between the tolerance limits mentioned above and the experimental values is too high to make unrealistic this rough comparison.

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

5. Conclusions

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

CRediT authorship contribution statement

Manuel García Díaz: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Manuel Esteban Lucas-Borja:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Supervision, Project administration. **Javier Gonzalez-Romero:** Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Pedro Antonio Plaza-Alvarez:** Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Mehdi Navidi:** Methodology, Validation, Formal analysis, Writing – review & editing. **Yi-Fan Liu:** Methodology, Validation, Formal analysis, Writing – review & editing. **Gao-Lin Wu:** Methodology, Validation, Formal analysis, Writing – review & editing. **Demetrio Antonio Zema:** Conceptualization, Methodology, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare no known competing financial interests.

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Appendix A. Supplementary data

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