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Original Research Article

Exploring the factors influencing the hydrological response of soil after low and high-severity fires with post-fire mulching in Mediterranean forests

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A B S T R A C T

Despite ample literature, the influence of the individual soil properties and covers on the hydrological response of burned soils of forests has not clearly identified. A clear understanding of the surface runoff and erosion rates altered by wildfires and prescribed fires is beneficial to identify the most suitable post-fire treatment. This study has carried out a combined analysis of the hydrological response of soil and its driving factors in burned forests of Central-Eastern Spain. The pine stands of these forests were subjected to both prescribed fire and wildfire, and, in the latter case, to post-fire treatment with mulching. Moreover, simple multi-regression models are proposed to predict runoff and erosion in the experimental conditions. In the case of the prescribed burning, the fire had a limited impact on runoff and erosion compared to the unburned areas, due to the limited changes in soil parameters. In contrast, the wildfire increased many-fold the runoff and erosion rates, but the mulching reduced the hydrological response of the burned soils, particularly for the first two-three rainfalls after the fire. The increase in runoff and erosion after the wildfire was associated to the removal of the vegetation cover, soil water repellency, and ash left by fire; the changes in water infiltration played a minor role on runoff and erosion. The multi-regression models developed for the prescribed fire were accurate to predict the post-fire runoff coefficients. However, these models were less reliable for predictions of the mean erosion rates. The predictions of erosion after wildfire and mulching were excellent, while those of runoff were not satisfactory (except for the mean values). These results are useful to better understand the relations among the hydrological effects of fire on one side and the main soil properties and covers on the other side. Moreover, the proposed prediction models are useful to support the planning activities of forest managers and hydrologists towards a more effective conservation of forest soils.

1. Introduction

Fire impact many components of forest ecosystems (vegetation, animals, soil, air, surface water and groundwater) (DeBano et al., 1998; Kozlowski, 2012; Lucas-Borja, González-Romero, et al., 2019). Its effects extend to time (up to several years after fire) and space (on large distances downstream of the burned areas); the magnitude of these effects depends on fire severity (Lucas-Borja, González-Romero, et al., 2019; Niemeyer et al., 2020; Pereira et al., 2018). The wildfire completely removes the vegetation and changes the soil properties for a long time (Bento-Goncalves et al., 2012), while the low-severity fire burns only the herbaceous and shrub layers, with limited effects in time and intensity (Alcañiz et al., 2018; Cawson et al., 2012). The burning of vegetation and

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the changes in the soil properties modify the hydrology of forests with possible degradation of soil quality (Zema, 2021). Some of the most hazardous impacts of the forest fires are intense surface runoff and soil loss. The erosion rates may even increase many-fold compared to the unburned soils, also for low-severity fires (Cawson et al., 2013; González-Pelayo et al., 2010; Vega et al., 2005). The increase in flooding and erosion risks after fire is an essential problem for landowners, who must limit land degradation and biodiversity loss. The hydrological and ecological protection of forests against fire is an important issue also for authorities and land managers (Prats et al., 2015). This issue has becoming urgent due to the future climate changes, which will result in increases in fire frequency and damage (Badia & Marti, 2008; Lucas-Borja et al., 2020).

Forests can be protected against fire by adopting several pre-fire and post-fire management techniques (Lucas-Borja, 2021; Zema, 2021). Among the pre-fire actions, the prescribed fire (the planned use of low-severity fire to remove the fuel for wildfires in forest areas (Fernandes et al., 2013) has been applied in several contexts to reduce the wildfire risk (Francos & Úbeda, 2021). Several post-fire management techniques (e.g., afforestation, seeding, mulching, salvage logging, erosion barriers or soil preparation, Pereira et al., 2018; Zema, 2021) have been developed and experimented to limit the hazardous impacts of wildfires on the forest ecosystem (Lucas-Borja, 2021). The hydrological effects of the prescribed fire and post-fire management techniques have been studied in a large variety of environments (e.g., mulching in Iberian Peninsula, Lucas-Borja et al., 2018; log-erosion barriers in Spain, Albert-Belda et al., 2019; Fernández et al., 2019; contour felled log debris in Azerbaijan, Jourgholami et al., 2020). However, in some cases, such studies have only focused on some ecosystem components (e.g., the vegetation cover, soil properties, water runoff and erosion, Bontrager et al., 2019; Lopes et al., 2020; Wagenbrenner et al., 2015). These studies should have rather analysed the complex relationships between the fire and the impacted forest components.

Soil hydrology after fire is a physical process that is governed by several environmental drivers (e.g., vegetation dynamics, soil changes, water and sediment flows). For this reason, it is important to disentangle and quantify the influence of each driver on the various forest components affected by fire (physico-chemical properties of soils, topography, fire history, fuel quantity, vegetation species, weather patterns, etc., Francos et al., 2018; Pereira et al., 2018). The effect of each factor on the hydrologic response of burned soils is still not completely understood, since this effect is variable depending on the site characteristics, vegetation species, and soil types. Therefore, understanding and measuring these effects are important tasks to predict the erosion intensity, and to site and plan the most effective post-fire action to control post-fire hydrology (Robichaud et al., 2013).

A large body of literature that has widely explored the fire impacts on different forest ecosystems (e.g., Cawson et al., 2011; Inbar et al., 2014) on soil hydrology, and Fuentes et al., 2018; Nunes et al., 2018) on vegetation cover. However, few comprehensive studies have analysed the dynamics of the runoff and erosion together with the soil properties, vegetal and ground covers. To the authors' best knowledge, no studies have linked the runoff and erosion rates in burned areas to the changes in a significant ensemble of soil properties and covers after alterations due to fires of different severity. This literature gap is particularly felt in the semi-arid environments. The Mediterranean forests are particularly prone to excessive runoff and soil erosion rates after the fire (Zema, Lucas-Borja, et al., 2020; 2020b), due to heavy and sudden rainstorms as well as shallow and arid soils (Cantón et al., 2011; Fortugno et al., 2017). Only Vieira, Malvar, et al. (2018) applied a multiple regression model analysis to understand how several key factors influence the hydrological response of a burned Mediterranean forest. However, this study was limited to microplots and had a multi-year perspective rather focusing on the short time.

A comprehensive and integrated knowledge of the hydrology of burned areas and the factors that influence soil restoration and vegetation regeneration after the fire can support the identification of the most effective post-fire management technique. For instance, when the erosion rates are high, due to the vegetation burning, a quick restoration of the burned areas with a vegetal cover using mulching, afforestation or seeding is imperative (Certini, 2005; Niemeyer et al., 2020). In contrast, if the hydrological response of a burned soil is enhanced by a decreased infiltration, the post-fire action should prioritize those techniques that restore the pre-fire soil conditions, such as the soil preparation or treatment (Inbar et al., 2014; Zavala et al., 2014).

Another important task for authorities and land managers is the prediction of the runoff and erosion rates in burned forests, particularly when alternative scenarios of post-fire management must be evaluated. Also this task requires a detailed knowledge of the hydrological processes in burned areas with and of their links with soil properties and covers (Prats, Sergio Alegre, et al., 2016). The hydrological models are viable tools for predicting runoff and erosion in burned areas. However, the choice of the most suitable model and its implementation may be difficult and time-consuming (Bezak et al., 2021; Borrelli et al., 2021; Filianoti et al., 2020). In contrast, the simple regression models are often more efficient and their use is simpler, at least for rough and quick evaluations (Lucas-Borja et al., 2020). However, these models must purposely calibrated in the same geomorphological and hydrological context of the burned area. Hydrological modelling of burned, and burned and treated areas has been carried out from several years and in many environmental contexts, e.g., Lopes et al. (2021); Vieira, Malvar, et al. (2018). Less modelling experiences have evaluated the hydrological prediction capacity of multi-regression equations, using soil properties and covers as input parameters.

This study aims to fill two gaps of the literature about the soil hydrology of burned forests: (i) the absence of a combined analysis of the hydrological response of soil and its driving factors; and (ii) the lack of simple analytical models for runoff and erosion predictions. The specific aims of this study are: (i) the identification of the that most influence the surface runoff and soil loss; and (ii) the evaluation of the hydrological prediction capacity of multi-regression models based on a small number of soil properties and covers. We hypothesize that: (i) both prescribed fire and wildfire significantly changes the runoff and erosion rates depending on soil properties and covers as well as fire severity and soil condition (wildfire-affected and untreated areas or burned and mulched soils); (ii) it is possible to predict runoff and erosion after fire using multi-regression models based on soil properties and covers. The investigation has adopted as a case studies two pine forests of Central-Eastern Spain subjected to both prescribed fire and wildfire, and, in the latter case, to post-fire treatment with mulching.

2. Materials and methods

2.1. Study area and sites

The experimental sites were selected in two pine forests of Castilla - La Mancha (Central Eastern Spain), close to the city of Albacete. In the first forest area (Lezuza), a prescribed fire was applied in March 2016. The second site (Liétor) was completely burned by a wildfire in July 2016 and partly treated with mulching in the following September (Fig. 1).

The study area has a typically Mediterranean semi-arid climate that is classified as BSk (where "B" stands for "dry", "S" for "steppe",

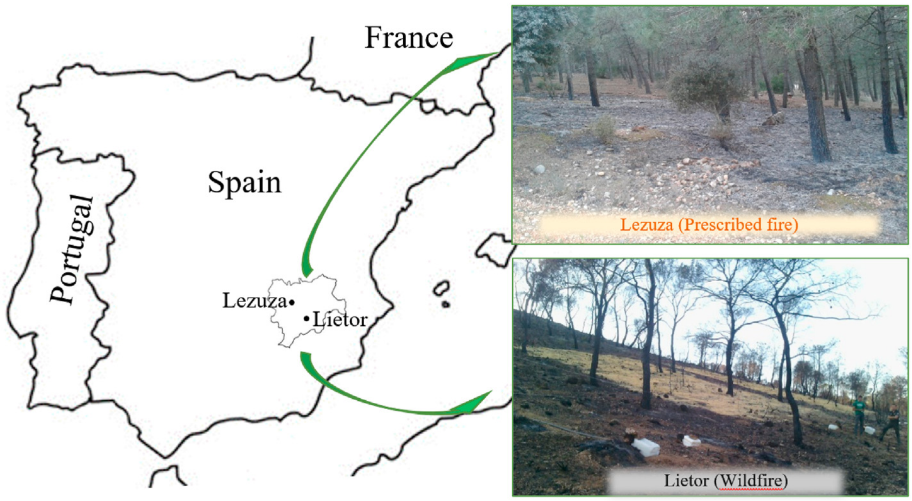

Fig. 1. Location and layout of forest plots subject to prescribed fire and wildfire and monitored for hydrological observations (Lezuza and Liétor, Castilla La Mancha, Spain). Geographic coordinates and map source: Lezuza X: 557588 E, Y: 4306475 N; Liétor: X: 600081 E, Y: 4262798 N (unburned area); X: 598358 E, Y: 4264032 N (burned area).

and "k" for "cold"), according to the Köppen–Geiger (Kottek et al., 2006). The mean annual rainfall and temperature are 282 (Liétor) and 450 (Lezuza) mm, and 13.5 (Liétor) and 16 (Lezuza) °C, respectively (Spanish National Meteorological Agency, 1950–2016). The highest precipitation is in October (44.5 mm) and the lowest in May (39.6 mm). A hot and dry period (air relative humidity below 50% with zero or very scarce rainfall) is from June to September.

2.1.1. Forest burned by prescribed fire (Lezuza)

The forest site of Lezuza covers a hilly area between 1010 and 1040 m a.s.l., with a mean slope of about 15%. The soils, with a clay texture (30.7 ± 3.4% of sand, 27.8 ± 2.5% of silt and 41.5 ± 4.1% of clay), are Alfisols with Xeralf Rhodoxeralf horizon (USDA-SCS, 1975) (Table 1).

The forest is a mixed stand of *Pinus halepensis* and *Pinus pinaster*, planted about 50 years ago. The mean tree density and height are about 500 trees per hectare and 6.40 m, respectively. The shrub and herbaceous layers of the forest floor (depth of 5–7 cm) include *Quercus faginea Lam.* L., *Quercus ilex* subsp. *Ballota*, *Quercus coccifera* L., *Juniperus oxycedrus*, *Brachypodium retusum* P. and *Thymus* sp.

In this forest site, the prescribed fire was applied under reference air conditions (wind speed of 14 km/h, air temperature of 14 °C and relative humidity of 63%) for forest protection.

2.1.2. Forest burned by wildfire (Liétor)

The forest site in Liétor is between 520 and 770 m a.s.l., with a mean slope of 15–20% (Table 1). The soils, with a sandy-loam texture (50.7 ± 2.2% of sand, 36,8 ± 6.5% of silt and 12.5 ± 5.2% of clay, are Inceptisols and Aridisols (USDA-SCS, 1975).

The main forest species is *Pinus halepensis* Mill, with a mean tree density between 500 and 650 trees per hectare and height between 7 and 14 m. The shrub and herbaceous layers are composed by *Rosmarinus officinalis* L., *Brachypodium retusum* (Pers.) Beauv., *Cistus clusii* Dunal, *Lavandula latifolia* Medik., *Thymus vulgaris* L., *Helichrysum stoechas* (L.) Moench, *Macrochloa tenacissima* (L.) Kunth, *Quercus coccifera* L. and Plantago *albicans* L. The forest floor (about 3–5 cm deep) is covered by needles, twigs, cones, and branches fallen by the trees.

The wildfire of July 2016 burned about 830 ha with a tree mortality of 100% (Table 1), and was classified as high-severity fire according to Vega et al. (2013). Two months after the wildfire (September 2016), an area in the burned forest was mulched with barley straw. This biomass was manually distributed over ground (depth of 3 cm) at a dose of 0.2 kg/m^2 (dry weight). This operation protected the burned soils with a vegetal cover of over 80%, in accordance to the guidelines of Vega et al. (2014) for forests of Northern Spain.

2.2. Experimental plots

Experimental plots were installed in the two forests, in order to measure the hydrological variables (Maidment, 1993; Kirkby, 1991; Beven & Kirkby, 1993), and soil properties and covers. The plots were randomly distributed in areas with the same geomorphological and vegetation characteristics for their comparability. In detail, twelve plots (4-m long × 2-m wide) were installed in Lezuza, of which six plots were located in the unburned area and the other six in the burned site. Nine rectangular plots (3-m long × 1-m wide) were installed in Liétor. Three plots were in the forest out of the burned area, and six in the burned area. Of the latter plots, three

Table 1
- Main characteristics of forest sites and plots subject to prescribed fire and wildfire (Lezuza and Liétor, Castilla La Mancha, Spain).

Characteristics	Prescribed fire (Lezuza)		Wildfire (Liétor)		
	Soil condition				
	Unburned	Burned	Unburned	Burned	Burned and mulched
Number of plots	6	6	6	6	6
Plot area (m^2)	8		200		
Elevation (m)	1010–1040		520–770		
Slope (%)	15 ± 4.4	14.5 ± 2.6	15–20		
Aspect	N	N-NE	W-SW and N		

were not treated after fire, and three plots were mulched.

In both sites, the upper and lateral sides of all plots were hydraulically isolated by a geotextile fabric pounded into the ground. At the lower side, a metal fence was installed to collect the runoff by a pipe into a plastic tank.

2.3. Measurement of the studied variables

According to Fernández et al. (2011) and Prats et al. (2014), the runoff and erosion rates suddenly increase immediately after the fire and decrease throughout one year, and the background levels recover after many years. For these reasons, the monitoring activity has focused on a “window of disturbance” (Prosser & Williams, 1998) of one year after the fires.

2.3.1. Hydrological variables

A meteorological station (WatchDog 2000), including a tipping bucket rain gauge and a thermometer, was installed in each forest site to measure the total daily precipitation, storm duration, rain intensity, and air temperature. In the hourly rainfall series, two consecutive events were considered as separate, if no rainfall was recorded for 6 h or more (Wischmeier and Smith, 1978).

Immediately after each rainfall event, the runoff volumes were measured in the plots. The runoff coefficients of the monitored events (hereafter RC) were calculated dividing the runoff volume (in mm) to the rainfall depth. After mixing the runoff water collected in the tank, a water sample was collected in a bottle of about 0.5 L. Then, the sample was oven dried (at 105 °C) for 24 h in laboratory and the sediments were weighted. The sediment concentration (SC) was estimated as the ratio between the total sediment weight and the runoff volume. The soil loss (SL) for each plot was the product of SC by the runoff volume.

The hydrological response of the soil to the rainfall was analysed using the RC (which standardizes the runoff to the rainfall unit) and SC variable.

2.3.2. Soil properties

As selection of hydrological properties, the soil hydraulic conductivity (SHC) and soil water repellency (SWR) were considered and measured in three points per plot, randomly chosen. More specifically, SHC was determined using a Mini-Disk Infiltrometer (Decagon Devices, 2013), while SWR was measured using the Water Drop Penetration Test (WDPT) method (Letey, 1969; Woudt, 1959). The SHC measurements were carried out according to the MDI technical manual, and (Robichaud, Lewis, & Ashmun, 2008; 2008b). The WDPT method estimates SWR by measuring the time that a drop takes to completely infiltrate into the soil. In this study, 15 drops of distilled water were released, using a pipette, on the soil surface of a 1-m transect. The time necessary for drops to infiltrate completely into the soil was measured by a stopwatch. SWR depends on soil water content (e.g., Dekker et al., 2009; Vogelmann et al., 2013), and this property was simultaneously measured with SWR and SHC by a probe placed on the soil surface and connected a data logger (UX120 4-channel Analog Logger, Onset HOBO, Massachusetts, USA).

For both measurements (SHC and SWR), the litter layer on a small area was removed by a small shovel, and the soil surface was cleaned using a brush. This area was leveled to prepare a horizontal surface for placing the infiltrometer or applying the WDPT method. The three values of SHC and SWR for each plot were finally averaged.

The experimental procedure and equations to calculate SHC as well as the SWR classification according to the values of WDPT (Bisdom et al., 1993) are reported in the works by Bisdom et al. (1993), Zema et al. (2021a; 2021b) and Zhang (1997), where more details can be found.

Finally, the organic matter (OM) content of the soils was measured in triplicate, considering the influence of this soil property on the other factors (e.g., SHC, Jarvis et al., 2013; Wahl et al., 2003, SWR, Buczko et al., 2002; Martínez-Zavala & Jordán-López, 2009). OM was determined by oxidation with K_2CrO_7 in an acid medium and titration of the excess dichromate with $(NH_4)_2Fe(SO_4)_2$ (Yeomans & Bremner, 1989).

2.3.3. Soil covers

As soil covers, the vegetation, litter, and ash (indicated by VC, LC, and AC, respectively) in percent over the total surveyed area were measured in each plot at the same dates as the hydraulic properties and OM. Regarding VC, the tree canopy and shrub covers, VC(c) and VC(s), were measured in Liétor, while only the shrub cover (VC) was determined in Lezuza (since the prescribed fire did not affect the canopy). Three longitudinal transects (each one with a length of 3 m) were identified, and the soil covers were measured using touch lengths in each transect. The values for each plot were the mean of the three measurements.

2.4. Statistical analysis

MANOVA (Multivariate ANalysis Of VAriance) was applied to all parameters (response variables), assuming as factors the soil condition (unburned, burned and not treated, and burned and mulched in Liétor, unburned, and burned and not treated in Lezuza). 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 (equality of variance and normal distribution), the data were subjected to normality tests or were square root-transformed whenever necessary.

Then, the Principal Component Analysis (PCA) was applied, in order to identify a low number of independent and derivative variables (Principal Components, PCs) (Rodgers and Nicewander, 1988). This process simplifies the analysis of the large number of original parameters, loosing as little as possible information. The original variables (expressed by different measuring units) were standardised and the correlation matrix was computed using Pearson's method. The first three PCs were chosen, since these explained at least a percentage of 70% of the original variance.

Moreover, the scores of the soil samples on the three PCs were grouped in clusters using the Agglomerative Hierarchical Cluster Analysis (AHCA). This is a distribution-free ordination technique to group samples with similar characteristics by considering an original group of variables. As similarity-dissimilarity measure the Euclidean distance was used (Zema et al., 2015).

Finally, the correlations between the runoff volume and soil loss (dependent variables), and the soil properties and covers (independent variables) were analysed by linear multi-regression models. This was done, in order to evaluate whether it is possible to predict these hydrological variables from soil parameters of ease measurement and independent on rainfall.

The statistical analysis was carried out using the XLSTAT release 2019 software.

2.5. Evaluation of the predictions of the multi-regression models

The prediction capacity of the multi-regression models was evaluated by two approaches: (i) by visually comparing the observed and modelled values of runoff coefficient and sediment concentration in scatterplots; and (ii) by adopting the following criteria (statistics and indexes), commonly used in hydrological modelling:

- the main statistics (i.e., the maximum, minimum, mean and standard deviation of both the observed and simulated values)
- the coefficient of determination (r^2)
- the coefficient of efficiency of Nash and Sutcliffe (1970, NSE)
- the percent bias (PBIAS).

The equations, and the acceptance limits or optimal values for their calculations are reported in the works of Krause et al. (2005); Krysanova et al. (2016); Moriasi et al. (2007); Van Liew et al. (2003); and Zema et al. (2012). To summarise, values of r^2 over 0.5 are deemed acceptable. NSE is optimal, if equal to 1; good, if $\geq$ 0.75; satisfactory, if 0.36 $\leq$ NSE $\leq$0.75; and unsatisfactory, if $\leq$ 0.36. If NSE <0, the mean value is a better predictor compared to the model output. PBIAS indicates whether the model over-predicts (if negative) or under-predicts (if positive) the output variable. Values of this index below 0.25 and 0.55 for runoff and erosion, respectively, are considered fair.

3. Results and discussion

3.1. Forest burned by prescribed fire (Lezuza)

3.1.1. Hydrological response

Throughout the 1.5-year observation period, sixteen storms (totalling 368 mm) produced runoff and erosion. The maximum and the minimum rainfall depths of these storms were 33 and 17 mm, while their intensity was in the range 1.5–6.2 mm/h (Fig. 2). Fire almost thoroughly removed the shrub and herbaceous vegetation cover and the litter, leaving the soil bare. One would expect that, for all the events in the short-period after a prescribed fire, the runoff and erosion increase compared to the unburned areas, since the burned soils are exposed to higher runoff generation capacity and rainfall erosivity. On average, the runoff was between 0.25 and 0.69 mm in the unburned plots and between 0.16 and 0.75 mm in the burned areas. Erosion was up to 0.23 g/m^2 in unburned areas and to 0.30 g/m^2 in burned plots (Fig. 2). However, in the experimental plots only for 50% of the recorded events runoff from burned soils was higher compared to the unburned plots, and this percentage increased to 80% for the erosion. This means that not always the soil subjected to prescribed fire generates noticeably more runoff and soil loss compared to the unburned areas. These findings agree with the majority of relevant studies (Benavides-Solorio and MacDonald, 2005; Coelho et al., 2002; de Dios; Morris et al., 2014). Also other authors (e.g., Keeley, 2009; Pereira et al., 2018) report that the hydrological impacts of low-severity fires are general low. The prescribed fire is not able to change those soil properties that govern runoff and erosion in burned areas and, therefore, erosion is not noticeable following a prescribed fire (Benavides-Solorio and MacDonald, 2001; Coelho et al., 2004; de Dios; Morris et al., 2014).

Overall, if the studied hydrological variables (runoff and erosion) are averaged throughout the entire observation period, the RC was the same in the unburned and unburned soils (1.67 $\pm$ 0.26 and 1.67 $\pm$ 0.47 mm, respectively). The SC was 91.84 $\pm$ 84.05 mg/L in the unburned plots, about 25% less than the burned areas (124 $\pm$ 118 mg/L) (Fig. 2).

3.1.2. Soil covers and properties

After the prescribed fire, the vegetation cover decreased from 64.9% to 15.4% and the litter from 30.7 $\pm$ 4.5% to 45.6 $\pm$ 15.1%. Fire released ash over 21 $\pm$ 12.4% of the plot areas (Table 2).

Regarding the soil properties, the unburned soils did not show repellency (WDPT of 4.8 $\pm$ 8.2 s, class 0 according to Bisdom et al. (1993), and the SHC was 14.2 $\pm$ 12.1 mm/h. Compared to these values, fire did not increase the SWR (WDPT of 3.9 $\pm$ 5.5 s, class 0), except for a very slight repellency noticed in some small areas. This may be surprising, since a high clay content in soils (as in this study) is correlated to SWR (Stoof et al., 2011; Zavala et al., 2014). Presumably, the soil hydrophobicity increased in very localized areas (Neary & Leonard, 2021), without playing significant effects over larger zones. Also the water infiltration was not altered by the prescribed fire (SHC of 14.8 $\pm$ 12.1 mm/h in the unburned areas) (Table 2). This contrasts with the literature findings that generally report that water infiltration often decreases after the prescribed fires (although not significantly), but the original SHC restores after some months (Fernández et al., 2008; Plaza-Álvarez et al., 2019; Robichaud, 2000). Significant reductions of SHC are generally due to the synergistic effects of increased SWR and soil sealing, and removal of vegetation cover (Cawson et al., 2012), but these effects were not notices in this study.

The OM content of soil increased this soil property from 2.4 $\pm$ 0.4% (unburned plots) to 3.0 $\pm$ 0.4% (burned plots) due to the prescribed fire (Table 2). Higher OM contents of soil are common after a fire, presumably due to the incorporation of unburned or partially burned slash fragments into the soil or to the incomplete combustion of the organic matter (Alcañiz et al., 2018; Hueso-González et al., 2018; Soto & Diaz-Fierros, 1993; Úbeda et al., 2005). According to Scharenbroch et al. (2012), the temperature of soil during burning is not so high to determine organic matter oxidation.

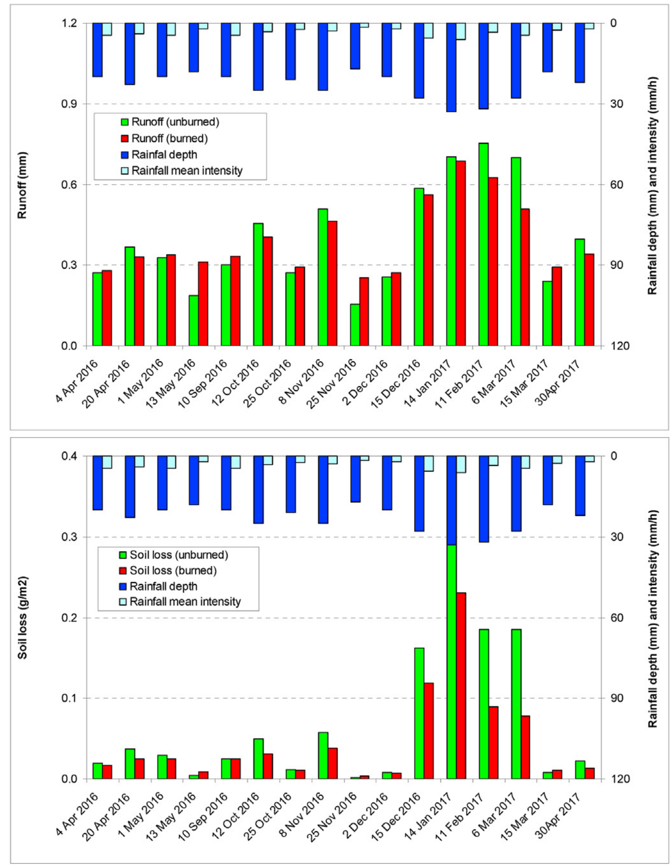

Fig. 2. Rainfall depth and intensity, runoff volume and soil loss measured in pine forest subject to prescribed fire (Lezuza, Castilla La Mancha, Spain).

3.1.3. Identification of the hydrological response drivers

The PCA identifies three derivative and uncorrelated Principal Components (PC1, PC2 and PC3). All PCs explain together 76.5% of

Table 2
Mean and standard deviation of soil covers and properties, and hydrological variables in pine forest subject to prescribed fire (Lezuza) and wildfire (Liétor) (Castilla La Mancha, Spain).

Soil condition	Vegetation cover		Litter cover (%)	Ash (%)	Soil Water Repellency (WDPT, s)	Soil Hydraulic Conductivity (mm/h)	Organic Matter Content (%)	Runoff Coefficient (–)	Sediment Concentration (mg/L)
	(tree canopy, %)	(shrub, %)							
Prescribed fire (Lezuza)									
Mean									
Unburned	–	64.9 (4.5) a	30.7 (3.1) a	0.0 (0.0) a	4.8 (8.2) a	14.2 (12.1) a	2.4 (0.4) a	1.67 (0.26) a	91.8 (84.1) a
Burned	–	15.4 (4.0) b	45.6 (15.1) b	21.0 (12.4) b	3.9 (5.5) a	14.8 (12.1) a	3.0 (0.4) b	1.67 (0.47) a	124.1 (118.2) a
Wildfire (Liétor)									
Mean									
Unburned	6.0 (0.0) a	69.0 (0.0) a	10.0 (0.0) a	0.0 (0.0) a	1.7 (0.7) a	8.6 (3.6) a	2.4 (0.2) a	0.05 (0.03) a	0.26 (0.19) a
Burned	0.0 (0.0) b	12.0 (13.3) b	3.0 (0.0) a	39.3 (34.2) b	5.1 (1.9) a	12.3 (6.4) a	5.0 (0.7) b	1.31 (1.60) a	14.72 (16.28) b
Burned and mulched	0.0 (0.0) b	19.3 (18.4) b	53.6 (15.1) b	7.8 (4.3) a	19.1 (30.3) a	9.2 (4.2) a	9.6 (0.9) c	1.06 (1.21) a	4.79 (1.90) ab

Notes: the standard deviation is reported in bracket; different letters indicate significant differences among the soil conditions after Tukey's test ($p < 0.05$).

the total variance of the original variables, and PC1 and PC2 explain 61.3% of this variance. In more detail, high VC, ash and OM are associated (loadings >0.785) to high values of PC1, while RC and SC have high loadings on PC2 (>0.721). PC3 is significantly influenced (loadings >0.444) by SWR and SHC (Fig. 3a).

Moreover, the correlations among the soil properties and covers (e.g., the vegetation cover, soil water repellency and infiltration) that theoretically influence runoff and erosion are low (data not shown). This result may appear surprising, since high runoff (measured by RC) and erosion (SC) rates are usually associated to low vegetation cover, OM content and ash (e.g., Cawson et al., 2012; Lucas-Borja, González-Romero, et al., 2019; Pereira et al., 2018). In our PCA these factors are decoupled; in other words, these important soil properties and covers influence a derivative variable (PC1) that is not correlated to PC2, on which, conversely, RC and SC heavily weigh. Other important hydrological parameters of soil (SHC and SWR) influence the third and uncorrelated PC. The low influence of soil parameters on the hydrological response may be explained by the low severity of the prescribed fire, which is not able to significantly change the soil properties up to noticeable levels. A confirmation of this explanation is provided by AHCA. As a matter of fact, plotting the scores of soil properties and covers on a PC1-PC2-PC3 chart, two clusters of observations are evident: a first cluster consists of observations made in burned areas, and a second cluster groups the variables related to the unburned plots (Fig. 3b). However, the AHCA also shows that one cluster contains observations collected in both unburned and burned plots (Fig. 3c), and these observations partially overlay (Fig. 3b). This analysis shows that the two soil conditions (burned and unburned soils) are not completely distinct, but, in some cases, the hydrological characteristics, and the properties and covers of burned and unburned soils are similar.

From the results of these multivariate statistical techniques, we conclude that none of the analysed soil covers and properties plays a clear and evident influence on the hydrological response of burned soils after prescribed fire.

3.1.4. *Prediction of runoff and erosion by multi-regression models*

The following prediction models were provided by the multi-regression analysis of RC and SC for the unburned and burned conditions of soil:

- Unburned soils

$$RC\,[-] = 2.533 \times 10^{-2} - 8.5 \times 10^{-5}\,VC\,[\%] - 1.306 \times 10^{-3}\,OM\,[\%] \quad (1)$$

$$SC\,[mg/L] = -271 + 14.008\,VC\,[\%] - 4.664\,SHC\,[mm/h] \quad (2)$$

- Burned soils

$$RC\,[-] = 1.988 \times 10^{-2} - 5.734 \times 10^{-5}\,Ash\,[\%] - 1.360 \times 10^{-4}\,SHC\,[mm/h] \quad (3)$$

$$SC\,[mg/L] = 166 + 1.063\,Ash\,[\%] - 4.353\,SHC\,[mm/h] \quad (4)$$

In the unburned soils, Eq. (1) was developed to predict RC, and uses VC and OM as input parameters; Eq. (2) estimates SC from VC and SHC. In the soils treated with prescribed fire, RC is predicted by Ash and SHC (Eq. (3)), while SC derives from estimations of Ash and SHC (Eq. (4)). From these equations, it is evident that Ash is an influencing factor of both runoff and erosion processes.

The prediction capacity of these models can be considered satisfactory for RC, as shown the high values of NSE (>0.95). Also the predicted statistics are very close to the corresponding observations (Table 3), although the points are quite scattered around the line of perfect agreement ($r^2 < 0.21$) (Fig. 4). In contrast, the predictions of SC are less reliable, since the points are more scattered compared to RC predictions (especially for the highest values) (Fig. 4). Moreover, r^2 and RMSE are over the acceptance limit, and a negative value of the minimum SC is even predicted (Table 3). The only analysis of NSE coefficient (>0.61) is misleading, since this high value derives from a balance of the errors in the extreme values. However, all the proposed equations are able to predict the mean values of both RC and SC with high accuracy (Table 3), which is useful to give a rough estimation of the expected mean rates of runoff and erosion.

The regression analysis shows that the only use of soil properties and covers can predict soil hydrology with reliability only for runoff, but not for erosion. For the latter variable, the input of the climatic variables is essential. This result is in agreement with (Lucas-Borja et al., 2020), who demonstrated that, in the same experimental conditions as this study, the simulation of runoff volumes by the linear regression using precipitation as input give satisfactory predictions. In contrast, Parhizkar et al. (2021), although working in a different environment with soil conditions not affected by fire, showed that models based on simple linear functions of soil covers (straw mulch) can be reliable to predict runoff and erosion.

3.2. Forest burned by wildfire (Liétor)

3.2.1. Hydrological response

The total precipitation recorded throughout the monitoring period was 420 mm, but only nine events (total rainfall of 413 mm) produced surface runoff and erosion. The precipitation depth was between 12 and 94 mm (Fig. 5), while its intensity was in the range 0.98–28 mm/h. In contrast to what observed in Lezuza, the water volumes and sediment weights collected in the burned plots were always higher compared to the observations made in the unburned soils. More specifically, the runoff was in the range 0.04–2.20 mm in the burned areas, and up to 0.08 mm in the unburned plots. The erosion was between 0.14 and 4.73 g/m^2 in the burned plots and up to 0.07 g/m^2 in the unburned areas (Fig. 5). The annual erosion (0.166 tons/ha) is around 10% of the limit value suggested by Bazzoffi (2009), and Wischmeier and Smith (1978) for agricultural areas (about 10–12 tons/ha-year).

However, it should be highlighted that the runoff and erosion heavily increased in the few months after the wildfire, as shown by the first event of October 21, 2016 (Fig. 5). This enhanced hydrological response surveyed in the burned soil may be due to the combination of some effects of the fire, such as the release of ash, changes in the physico-chemical properties of soil, and water repellency; the ash seals the soil, reducing its infiltration capacity, the combustion of the organic matter content reduces the aggregate stability of the soil, and the SWR makes the soil hydrophobic (DeBano et al., 1970; Shakesby et al., 2000). The development of a water-repellent layer (also due to the ash released by fire) over the soil surface and the destruction of soil aggregates reduce the water infiltration, and thus increase its hydrological response. The higher runoff and erosion measured after the fire are also due to the almost total removal of vegetation due to burning. The fire leaves soil bare and thus exposed to rainfall erosivity, and increases its erodibility, due to rainsplash erosion and sediment entrapment by the overland and concentrated flow. However, the shrub and herb vegetation quickly recovery over time after the wildfire, and this quick revegetation decreases the runoff generation on the soil (Dı´az-Delgado and Pons, 2001). After the sudden increase due to the wildfire, a temporal reduction in runoff and erosion was recorded in burned soils, and this indicates that the hydrological response of soil decreases over time. This reduction is also noticed by several authors in the early storms immediately after wildfire (e.g., de Dios Benavides-Solorio & MacDonald, 2005; DeBano et al., 1998; MacDonald et al., 2000). Also Gimeno-García et al. (2007), in Mediterranean shrublands, showed that the runoff and erosion in the first post-fire year are much higher compared to the natural hydrological response of the unburned soils.

The soil treatments with mulching gave runoff volumes between 0.02 and 1.65 mm, and soil loss between 0.21 and 0.99 g/m^2 (Fig. 5). Both these hydrological variables were noticeably higher compared to the corresponding observations recorded in the unburned soils, but lower compared to the burned plots, as expected. Runoff was lower in mulched plots compared to the burned and not treated areas only after one storm, while erosion was higher after some events. It is important to notice that, compared to the burned plots, in the mulched areas the runoff decreased on average only by 9.1% in the short term after the wildfire. In contrast, the soil loss was lower by 65.6%, while the hydrological response of burned soil increased by three orders of magnitude. This reduced hydrological response to fire in mulched soils confirms that this post-fire treatment is effective to reduce erosion in wildfire-affected areas. This effectiveness is quantitatively shown by the decrease in runoff by about 25% after the first rainfall event, and in soil loss by 85% after the first three events (Fig. 5). The reduction in the hydrological response of soil treated with mulching confirm the findings of many other researches, who evaluated the mulch efficacy in controlling runoff and erosion after wildfires (e.g., Bautista et al., 2009, pp. 353–372; Keizer et al., 2018; Lopes et al., 2020; Lucas-Borja, González-Romero, et al., 2019; Prats et al., 2019). The beneficial effects of mulching on soil hydrology is due to the presence of the ground cover due to the straw application, especially in occasion of the first rain events after the wildfire. The mulch cover reduces the kinetic energy of rainfall, resulting in a limited soil particle displacement due to rainsplash (Ran et al., 2012; Te Chow, 2010; Zema, Nunes, & Lucas-Borja, 2020). The effectiveness of mulching at reducing the surface runoff is instead lower (Lucas-Borja, 2021; Lucas-Borja, Plaza-Álvarez, et al., 2019; Zema, 2021). This is demonstrated by the fact that, after the wildfire, the straw mulch controlled the soil erosion rates, but had no real impact on the surface runoff, as found also by (Lucas-Borja, Plaza-Álvarez, et al., 2019).

Other beneficial effects of mulching are: (i) the increase in rain interception due to the higher soil cover; (ii) the reduction in surface sealing and crusting; and (iii) the increase in surface roughness, which reduces the velocity of the overland flow, which results in a decreased soil detachment by the sheet and concentrated flows (Lopes et al., 2020; Prats et al., 2019).

By averaging the studied hydrological variables throughout the monitoring period, RC was 1.06 ± 1.21 mm in the burned and mulched plots, 20% less than in the burned and not treated areas (1.31 ± 1.60 mm) and about 2000% more than in the unburned sites (0.05 ± 0.03 mm). SC in burned and mulched plots (4.79 ± 1.90 mg/L) was by 68% lower compared to the burned sites (14.72 ± 16.28 mg/L), but by about 1800% higher compared to the unburned areas (0.26 ± 0.19 mg/L) (Fig. 5).

3.2.2. Soil properties and covers

The wildfire completely burned the tree canopy cover (which covered 6% of the total unburned area after the fire) and partially removed the shrub vegetation and litter, reducing VC(s) from 69% (unburned plots) to 12 ± 13.3% and LC from 10 ± 3% (unburned) to 3% (Table 2). The partial or complete removal of the vegetation cover determines that a higher proportion of the precipitation turns to runoff (García-Orenes et al., 2017; Shakesby, 2011; Zituni et al., 2019). It is well known that the wildfire influences the effects of the vegetation cover on the hydrological properties of soil as well as the changes in the properties of the burned soils (Albert-Belda et al., 2019; Wittenberg et al., 2020). Therefore, after the fire, the interception and evapo-transpiration decrease, and net precipitation increases, generating more runoff compared to the unburned soils (Vieira, Serpa, et al., 2018; Zituni et al., 2019). Moreover, a soil where vegetation has been totally removed by burning is more susceptible to rainsplash erosion and particle detachment by overland flow (Zema, 2021).

The ash released by the wildfire covered 39.3 ± 34.2% of the plot areas (Table 2). Ash is a key driver of soil hydrology in burned areas, since it might seal the soil surface, reducing water infiltration (Inbar et al., 2014; Plaza-Álvarez et al., 2019; Wittenberg et al., 2020). However, the ash effects on the studied soils were not noticeable. More specifically, in the burned areas, sealing, surface crust formation, and pore clogging, which are common according to Niemeyer et al. (2020), were not visually observed, and the influence on SHC was not noticeable. Pereira et al. (2018) reported that the lack of soil protection and the sparse ash cover increase the impacts of raindrops on soil compaction and facilitate sediment detachment.

In spite of its high severity, wildfire did not induce SWR in the burned plots (WDPT of 5.1 ± 1.9 s against 1.7 ± 0.7 s in the unburned area, class 0 of the classification by Bisdom et al. (1993). The lack of fire effects on SWR should be due to very high soil temperature during the wildfire, which was at high severity (over 300–400 °C). This severity level determined SWR disappearance, as reported by Pereira et al. (2018) and Varela et al. (2010). Forest residue mulch did not affect SWR, in accordance with (Prats, Sergio Alegre, et al., 2016).

The wildfire increased SHC (from 8.6 ± 3.6 mm/h, unburned area, to 12.3 ± 6.4 mm/h, burned and not treated plots). This effect may be due to the increased content of OM (5.0 ± 0.7% in the burned areas vs. 2.4 ± 0.2% in the unburned plots), and to the absence of SWR (the soils were wettable after the wildfire) (Table 2). This contrasts several studies, which, after high-severity fires, report reduced infiltration rates (e.g., Benavides-Solorio & MacDonald, 2001; Inbar et al., 2014; Mayor et al., 2007; Shakesby, 2011). The higher OM content detected in the burned soils may be expected after a wildfire, although being uncommon (Certini, 2005; Keizer et al., 2018). According to González-Pérez et al. (2004) and Inbar et al. (2014), in some cases the organic matter content in the soil affected by a wildfire can be significantly higher than in the unburned soil. This is due to the mixing of partially burned plant materials in the soil exposed to direct fire. In other words, the loss of organic matter due to combustion is balanced by the supply of partially burned residues and charred leaves, falling immediately after fire (Gimeno-García et al., 2007; Zavala et al., 2014).

In the burned and mulched areas, VC(s), LC and Ash were 19.3 ± 18.4%, 53.6 ± 15.1% and 7.8 ± 4.3%, respectively (Table 2). It must be highlighted that the ash cover in the mulched areas is higher. Moreover, this cover is close to the values measured in burned and not treated plots, since a part of the surface soil with ash was shadowed by the mulch material. The value of WDPT (19.1 ± 30.3 s) was higher compared to both the unburned, and burned and not treated plots, and this value shows a slight SWR. The water infiltration (SHC equal to 9.2 ± 4.2 mm/h) was lower compared to the burned and not treated soils, and close to the values measured in the unburned plots. A noticeable increase in the OM content (9.6 ± 0.9%) was also observed in the burned and mulched plots, which is beneficial for plant regeneration (Table 2).

3.2.3. *Identification of the hydrological response drivers*

Three derivative variables (PC1, PC2 and PC3) were provided by PCA. These new variables explain 86.3% of the original variance, 74% for PC1 and PC2, and 58.3% for PC1 alone. PC1 is associated to VC(c), VC(s), AC, SWR, OM, RC and SC with loadings higher than 0.63. Only the original variables LC and SHC influence PC2 and PC3, respectively (loading of 0.827 for LC and of 0.480 for SHC) (Fig. 6a). A clear gradient along the PC1 is evident between the unburned and burned soils (both untreated and mulched), and another gradient was found along the PC2 between the soils that were mulched and the burned and untreated plots (Fig. 6b). More specifically, when the VC of both tree and shrub layer increases, the runoff coefficient and its sediment load decrease. This relation is clearly demonstrated by the positive coefficients of correlation of VC(s) and VC(c), and the negative correlation of RC and SC with the PC1 (data not shown).

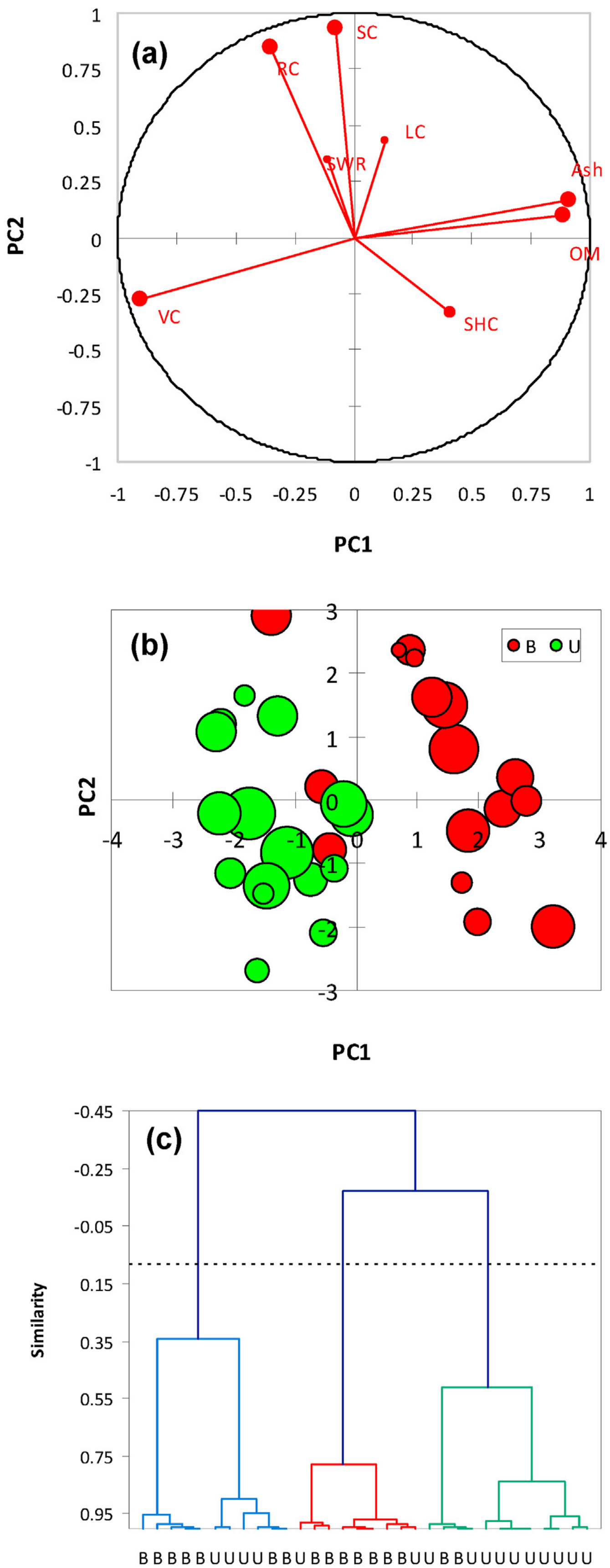

Fig. 3. Loadings of the original variables (a, soil covers and properties, and hydrological variables), scores (b) on the first two Principal Components (PC1 and PC2) provided by PCA, and dendrogram (c) provided by the Agglomerative Hierarchical Cluster Analysis (AHCA) applied to observations in pine forest subject to prescribed fire (Lezuza, Castilla La Mancha, Spain).
Notes: VC = vegetation cover; LC = litter cover; BS = bare soil; Ash = ash cover; SWR = soil water repellency; SHC = soil hydraulic conductivity; OM = organic matter; RC = runoff coefficient; SC = sediment concentration; the bubble area of the score plot of figure b is proportional to the value of the PC3; the y-axis of the dendrogram reports the similarity level, while the dotted line is the clustering level; U = unburned; B = burned.

Table 3
Statistics and indexes to evaluate the prediction capacity of multi-regression models in forest plots subject to prescribed fire (Lezuza) and wildfire (Liétor) (Castilla La Mancha, Spain).

Hydrological variable		Mean	Standard deviation	Minimum	Maximum	r^2	NSE	RMSE	PBIAS
PRESCRIBED FIRE (LEZUZA)									
Runoff coefficient	Unburned								
	Observed	0.017	0.003	0.014	0.022	0.07	0.98	0.0025	0.00
	Simulated	0.017	0.001	0.015	0.018				
	Burned								
	Observed	0.017	0.005	0.009	0.025	0.21	0.95	0.0040	0.00
	Simulated	0.017	0.002	0.011	0.019				
Sediment concentration	*Unburned*								
	Observed	91.8	84.0	15.4	336.8	0.27	0.68	69.34	0.00
	Simulated	91.8	44.0	−9.8	148.8				
	Burned								
	Observed	124.1	118.1	11.9	430.9	0.16	0.61	105.15	0.00
	Simulated	124.1	46.5	−16.5	176.9				
WILDFIRE (LIÉTOR)									
Runoff coefficient	*Unburned*								
	Observed	0.001	0.000	0.000	0.001	0.22	0.86	0.0002	0.00
	Simulated	0.001	0.000	0.000	0.001				
	Burned								
	Observed	0.013	0.016	0.004	0.055	0.75	0.86	0.01	0.00
	Simulated	0.013	0.014	0.000	0.045				
	Burned and mulched								
	Observed	0.011	0.012	0.002	0.041	0.33	0.00	0.01	0.64
	Simulated	0.011	0.007	0.001	0.023				
Sediment concentration	*Unburned*								
	Observed	0.26	0.19	0.00	0.60	0.74	0.92	0.09	0.00
	Simulated	0.26	0.16	0.00	0.42				
	Burned								
	Observed	14.7	16.3	1.2	37.8	0.84	0.91	6.23	0.00
	Simulated	14.7	14.9	−1.9	33.0				
	Burned and mulched								
	Observed	4.79	1.90	1.65	7.91	0.33	0.92	1.46	0.00
	Simulated	4.79	1.10	3.32	6.19				

Notes: r^2 = coefficient of determination; NSE = coefficient of efficiency of Nash and Sutcliffe; RMSE = Root Mean Square Error; PBIAS = percent bias.

Moreover, high RC and SC are associated to high values of SWR and ash. This result is expected, due to the clear influence of repellency (which produces soil hydrophobicity) and ash (which seals the soil) on the increase in runoff and erosion rates of burned soils. This increase negatively impacts on the soil aggregate stability and thus om runoff and soil loss. This impact is indirectly confirmed by the negative coefficients of correlation of OM, RC and SC with PC1 (data not shown). In contrast, water infiltration (measured by SHC) does not play a significant effect on RC and SC, and this is confirmed by low correlation coefficients between these variables and the PC1 (data not shown). This limited effect of SHC on runoff and erosion may be due to two processes: (i) the runoff generation in the studied area is not governed by the infiltration-excess mechanism (Lucas-Borja et al., 2018); and (ii) the erosion is mainly due to rainsplash effect rather than to detachment by overland flow.

The evident gradient along the PC2 (influenced only by litter cover) that was found between the mulched and non-mulched soils may be explained by the shadowing effect of the soil exerted by the mulch cover. The mulch material acts as a litter cover in the unburned areas, and this protection reduces the runoff generation and soil erodibility. This means that the vegetal cover (both of the tree and shrub layers), SWR, OM content and ash cover are the factors that most influence the runoff and erosion generation in the experimental areas, although this influence has different magnitude. In other words, while the vegetation cover reduces the runoff and erosion rates, the other factors enhance the hydrological response of soil to high-severity fire. This happens because: (i) the vegetation shadows the soil from the direct impact of the precipitation (reducing the soil loss), and increases the travel time of flow (with a decreased runoff rate); (ii) the repellency - increases the hydrophobicity of soil, and, as a consequence, the overland flow; the OM content is strictly correlated to SWR, and increases this effect (Assunta et al., 2014; Cesarano et al., 2016; Zema et al., 2021b); finally, (iii) the ash cover left by fire may have clogged the soil pores and induced sealing of the soil surface (Keesstra et al., 2014; Onda et al., 2008). Studies focusing on low-intensity fires have shown that ash contributes to reduce infiltration in burned soils, creating a thin layer of low porosity and permeability (Balfour & Woods, 2007; Carrà et al., 2021).

In the score plot of Fig. 6b, three clusters of observations made in different soil conditions (unburned, burned and not treated, burned and mulched are evident. The AHCA better defines this grouping: the observations made in unburned, and burned and mulched soils are grouped in two separate clusters, while the burned and not treated soils are distributed in these clusters, and in a third group (Fig. 6c).

Therefore, the application of these multivariate statistical techniques to the experimental dataset demonstrates that wildfire and mulching exert important influences on the hydrological response of forest soils, in contrast to what observed for the prescribed fire.

3.2.4. Prediction of runoff and erosion by multi-regression models

The multi-regression analysis proposes the following six prediction models to estimate RC and SC for the three soil conditions:

- Unburned soils

$$RC\,[-] = 1.183 \times 10^{-3} - 3.061 \times 10^{-5}\,SHC\,[mm/h] - 1.652 \times 10^{-4}\,OM\,[\%] \quad (5)$$

$$SC\,[g/L] = -1.855 - 1.396 \times 10^{-2}\,SHC\,[mm/h] + 0.917\,OM\,[\%] \quad (6)$$

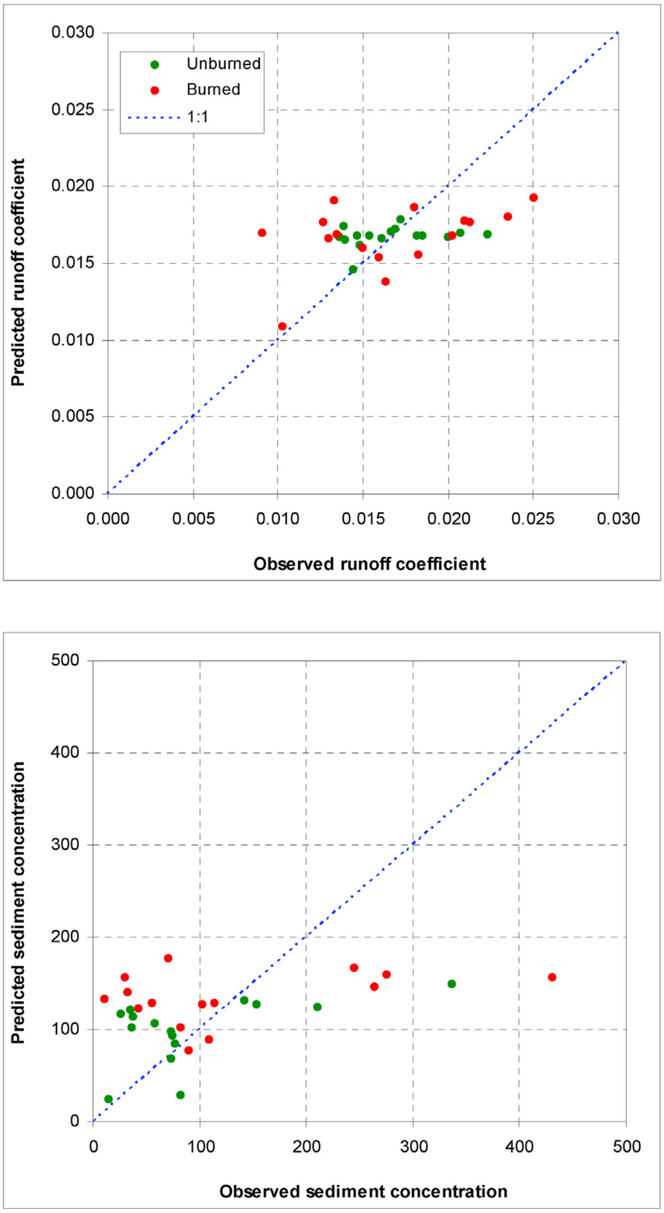

Fig. 4. Scatter plots of observations against predictions by multi-regression models applied to runoff coefficients and sediment concentrations (in mg/L) observed in pine forests subject to prescribed fire (Lezuza, Castilla La Mancha, Spain).

- Burned soils

RC [−] = −0.103 - 1.062 × 10^{-2} SWR [s] - 1.032 × 10^{-3} SHC [mm/h] + 3.695 × 10^{-2} OM [%] (7)

SC [g/L] = −35.500 + 1.342 VC(s) [%] - 0.867 Ash [%] (8)

- Burned and mulched soils

RC [−] = −3.122 × 10^{-2} + 5.281 × 10^{-4} LC [%] + 1.465 × 10^{-3} SHC [mm/h] (9)

SC [g/L] = 7.895−6.799 × 10^{-2} LC [%] + 2.801 × 10^{-2} SWR [s] (10)

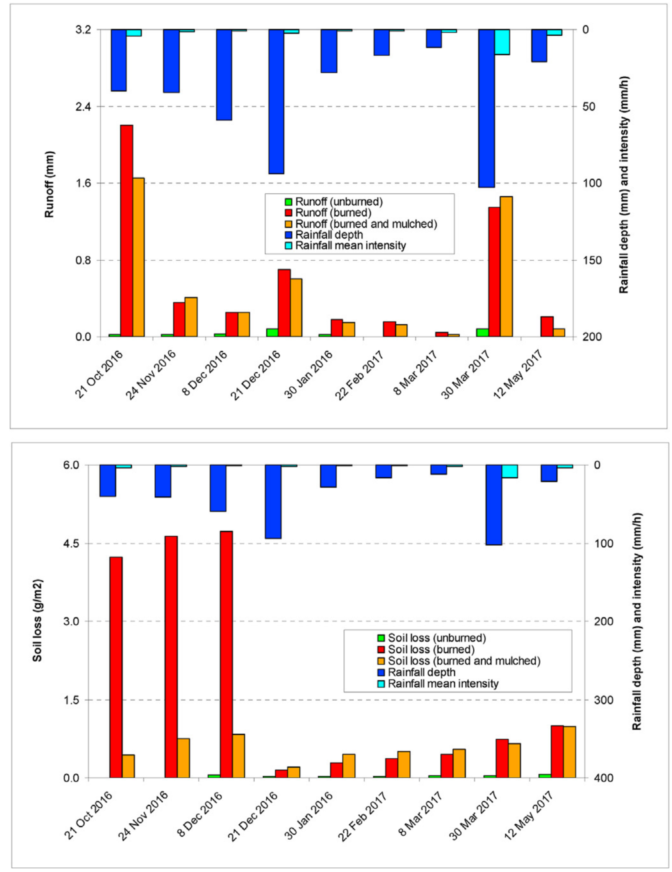

Fig. 5. Rainfall depth and intensity, runoff volume and soil loss measured in pine forest subject to wildfire and soil mulching (Liétor, Castilla La Mancha, Spain).

For the unburned soils, both models (Eq. (5) and (6)) use only two variables as input (SHC and OM). For burned soils, RC is predicted using SWR, SHC and OM (Eq. (7)), and SC using VC(s) and Ash (Eq. (8)). For the burned and mulched soils, LC is used to predict RC and SC, SHC for RC, and SWR for RC (Eq. (9) and (10)).

The prediction capacity of the runoff coefficient is inaccurate for unburned, and burned and mulched soils. This model inaccuracy is shown by the low r^2 and high RMSE (Table 3), and the high scattering of observation around the line of perfect agreement, Fig. 7), although the statistics are well predicted (Table 3).

In contrast, the proposed multi-regression models show a good prediction capacity for the runoff coefficient in burned and non-treated soils, and for the sediment concentration under all soil conditions. This is visually shown by the scatter plots (Fig. 7). The application of the quantitative indexes confirms this model accuracy (NSE >0.86, RMSE <0.5 observed standard deviation, PBIAS = 0, and very low differences in mean observed and predicted values) (Table 3). The negative values of the minimum sediment concentration predicted by Eq. (8) for an erosive event must be highlighted. However, land managers are interested to the mean and maximum rates rather than the lower values, and this model inaccuracy seems to be less important. These results suggest that the proposed multi-regression models can be adopted for easy estimations of runoff coefficients, and accurate predictions of the sediment concentrations under all soil conditions. Moreover, for soil burned by high-severity fires, the changes in soil covers and properties are more influencing drivers of erosion compared to the precipitation characteristics.

Our results are in contrast with Vieira, Malvar, et al. (2018), who

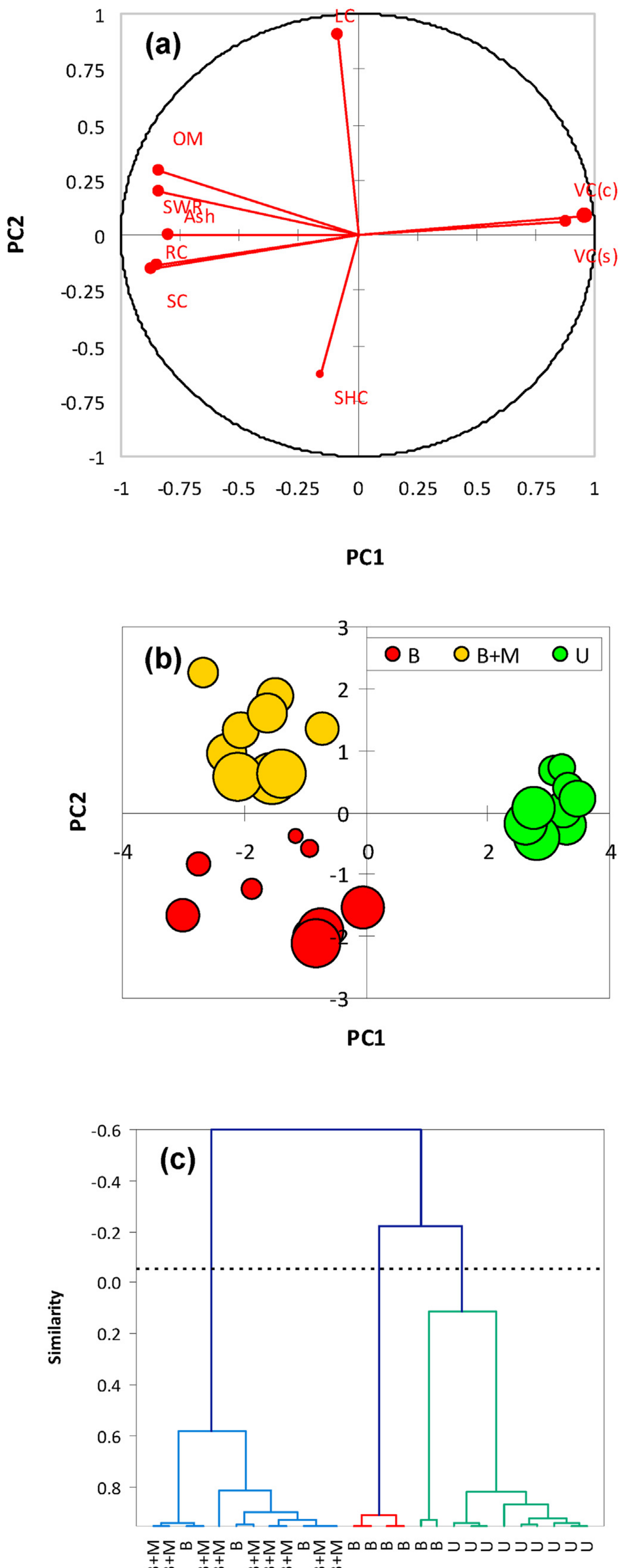

Fig. 6. Loadings of the original variables (a, soil covers and properties, and hydrological variables), scores (b) on the first two Principal Components (PC1 and PC2) provided by PCA, and dendrogram (c) provided by the Agglomerative Hierarchical Cluster Analysis (AHCA) applied to observations in pine forest subject to wildfire and soil mulching (Liétor, Castilla La Mancha, Spain).
Notes: VC(s) = vegetation cover in the shrub layer; VC(c) = tree canopy cover in the tree layer; LC = litter cover; BS = bare soil; Ash = ash cover; SWR = soil water repellency; SHC = soil hydraulic conductivity; OM = organic matter; RC = runoff coefficient; SC = sediment concentration; the bubble area of the score plot of figure b is proportional to the value of the PC3; the y-axis of the dendrogram reports the similarity level, while the dotted line is the clustering level; U = unburned; B = burned; B + M = burned and mulched.

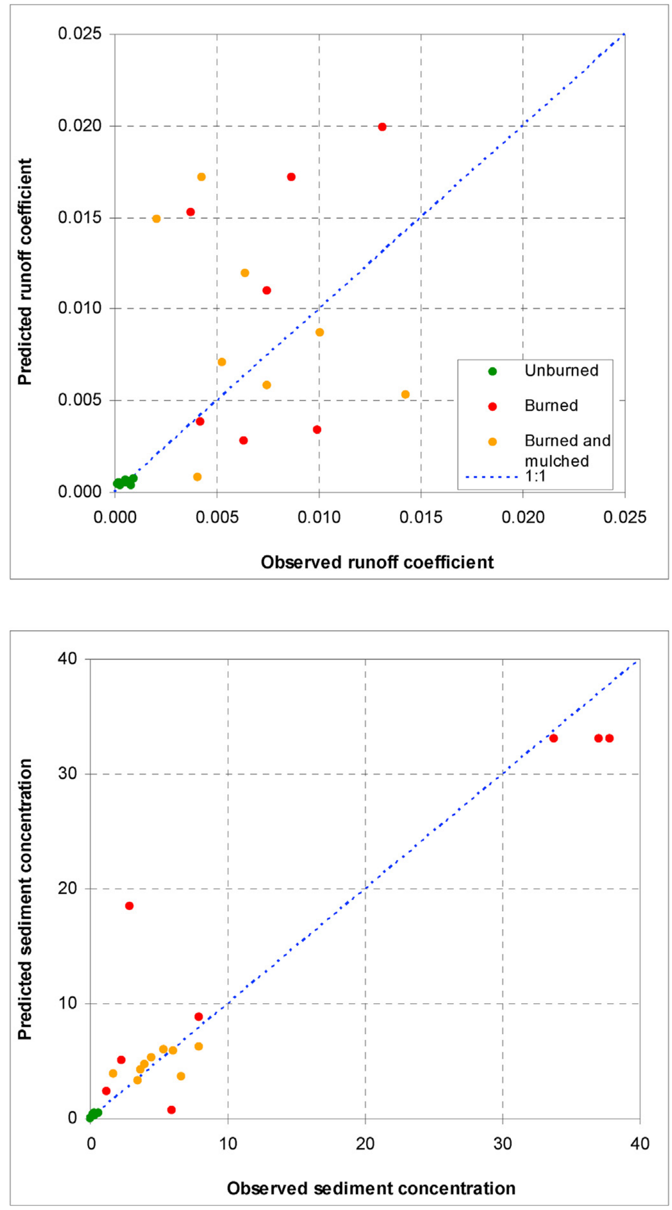

Fig. 7. Scatter plots of observations against predictions by multi-regression models applied to runoff coefficients and sediment concentrations (in g/L) observed in pine forests subject to wildfire and soil mulching (Liétor, Castilla La Mancha, Spain).

found that post-fire runoff is largely explained by rainfall amounts and SWR, while erosion processes are better modelled using the rainfall intensity and ground cover variables, such as the bare soil percentage. The multi-regression analysis of our study may be important for a better understanding of the dynamics of burned forests, since can help adapting hydrological models to post-fire environments.

4. Conclusions

The study has explored the influence of soil covers and properties on surface runoff and soil loss in a Mediterranean pine forest after a prescribed fire and a wildfire (the latter followed by straw mulching).

According to the two working hypotheses setup for this study, in the case of prescribed burning, the study has shown that:

(i) the prescribed fire has a limited impact on runoff and erosion compared to the unburned areas, since the low fire severity is not able to determine noticeable changes in soil properties and covers
(ii) the multi-regression models developed in this study are reliable to predict the runoff coefficients for the modelled events, but only the mean erosion rates.

The analysis carried out on the soils burned by the wildfire and treated with straw mulching has demonstrated that:

(i) compared to the unburned soils, the wildfire increases many-fold the runoff and erosion rates (due to the removal of the vegetation cover, soil repellency, and ash left by fire); the mulching reduces the hydrological response of the burned areas;
(ii) the prediction models proposed by the multi-regression analysis are reliable to estimate only the erosion in the burned and mulched soils, while the predictions of runoff are satisfactory to estimate the only mean rates.

Overall, this study has helped to better understand the physical processes that govern runoff generation and erosion after fires of different severity, linking these hydrological effects to the main soil properties and covers. The availability of simple regressions models to predict erosion after wildfire may support the planning activities of forest managers and hydrologists towards a more effective forest soil conservation. Future work should validate the relationships among the soil hydrology, and the properties and covers, preferably under different post-fire management techniques; moreover, under the modeling approach, evaluations at the catchment scale may overcome the limited spatial analysis carried out in this study.

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List of acronyms

VC =	vegetation cover (%)
VC(s) =	vegetation cover (shrub, %)
VC(c) =	vegetation cover (tree canopy, %)
LC =	litter cover (%)
Ash =	ash cover (%)
SWR =	soil water repellency (WDPT, s)
SHC =	soil hydraulic conductivity (mm/h)
OM =	organic matter content of soil (%)
RC =	runoff coefficient (%)
SC =	sediment concentration (g/L or mg/L)
SL =	soil loss (g/m^2 or mg/m^2)
WDPT =	water drop penetration test (s)
r^2 =	coefficient of determination
NSE =	coefficient of efficiency of Nash and Sutcliffe
RMSE =	Root Mean Square Error
PBIAS =	percent bias

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