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Exploring and Modeling the Short-Term Influence of Soil Properties and Covers on Hydrology of Mediterranean Forests after Prescribed Fire and Mulching

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Abstract: Several studies have analyzed the changes in individual soil properties and covers and quantified the hydrological response of burned forest soils (with or without post-fire treatment). Less research exists on the influence of these changes on runoff and erosion rates immediately after a prescribed fire and post-fire treatment. Moreover, hydrological modeling of burned areas is based on complex models rather than relying on simple regression equations. This study carries out a combined analysis of the hydrological response of soil and its driving factors in three forests (pine, oak, and chestnut) of Southern Italy that were subjected to prescribed fire and post-fire treatment with mulching. Moreover, simple regression models based on a limited set of soil properties/covers are proposed to predict runoff and erosion. The Principal Component Analysis has shown that the runoff coefficients increase when the water infiltration rate and litter cover decrease and repellency, ash cover, organic carbon content, and bare soil area increase. All the analyzed variables play a secondary role in influencing the sediment concentration. Due to these properties, clear differences in soil properties and covers have been found between unburned and burned soils. The distinctions between the burned soils (mulched or not) are much lower. The proposed regression models use a very low number of soil covers and two dummy variables as input parameters. These models are very accurate in simulating the surface runoff and soil erosion in all soil conditions in the short term.

Keywords: surface runoff; sediment concentration; water infiltration; soil water repellency; prediction models; linear regression

1. Introduction

Prescribed fire is the planned use of low-severity fire to reduce wildfire risk [1,2]. This technique has been applied in several environments to mitigate the ecological impacts of wildfires in forests [3]. Prescribed burning also offers important advantages as efficiently reducing fuel load, and even trees, at a much more competitive cost than mechanical or manual clearing [4]. However, some national and regional forest services are still reluctant to adopt prescribed fire programs on a broad scale.

Currently, prescribed fire is an effective tool to achieve fuel reduction, ecological restoration, or maintenance of ecosystem services [5,6]. The prescribed burning removes forest litter and understory vegetation, leaving the soil bare in the so-called "window of disturbance" of forest soils [7] that lasts from some months to one year after fire application. The first two to three events after fire, in particular, are responsible for the main changes in soil properties [8–10] and the highest erosion [11]. These soil changes and vegetation removal increase the runoff and erosion rates in forest areas [12] with possible heavy on-site and offsite effects.



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Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). In order to control and mitigate the hydrological response of burned soils in the window of disturbance, several treatments have been proposed (e.g., soil preparation, mulching, log erosion barriers, contour felled log debris); the effectiveness of these treatments has been verified in many environmental contexts [12,13]. Mulching is one of the most common soil conservation options after fires of different severity [14,15], and this technique has also been experimented as anti-erosive action in wildfire-affected areas [16–18]. The mulch cover protects the soil from rainfall erosivity and improves the soil quality, if used properly and at the correct time [15,19]. However, negative effects of mulching have been also observed, since the mulch material reduces water infiltration under unsaturated conditions compared to the untreated soils, particularly in the driest season [20].

In the Mediterranean forests, the changes in the hydrological response of burned soils can be more intense compared to other environments [21,22], since the soils are generally shallow and have low aggregate stability and low contents of organic matter and nutrients [23]. Ample literature has discussed the impacts of fire at different intensity on soil hydrology. However, the studies on the hydrological effects of prescribed fire are not exhaustive and often contrasting [10,24], especially when the soils are subject to post-fire management. For instance, [25] and [26] observed increases in runoff and erosion by one or two orders of magnitude compared to the unburned areas [27]. In contrast, [28] and [29] reported minimal erosion after a prescribed fire [9]. Another study, [30], even showed lower erosion in areas burned with prescribed fire compared to unburned forests, despite comparable runoff.

These contrasting results mainly derive from the complexity of the hydrological processes of burned areas. As a matter of fact, in fire-affected areas, many environmental factors play important roles in ecosystem changes and hydrological response, such as the type and chemical properties of soils, topography, fire history, fuel quantity, vegetation species, weather patterns, etc. [3,31]. The adoption of post-fire management techniques, such as mulching, can increase the complexity of these processes. Therefore, in post-fire soil hydrology, which is influenced by several factors (e.g., vegetation dynamics, soil changes, water and sediment flows, precipitation patterns), it is important to disentangle the importance of each factor on the hydrological response of burned soils. It is quite clear how and to what extent fire induces changes in soil hydrology, e.g., [32,33], and vegetation cover, e.g., [34,35]. However, the combined effects of the different factors on the hydrological response of soils in the short term after a prescribed fire and following soil conservation techniques is not completely understood. These effects are variable depending on the site characteristics, vegetation species, and soil types [17]. Therefore, there is a need to explore how the changes in soil properties and surface conditions impact runoff and erosion rates immediately after a prescribed fire and post-fire treatments. However, to the best of the authors' knowledge, no studies have analyzed runoff and erosion in areas treated with prescribed fire and post-fire mulching in combination to the changes in a significant ensemble of soil properties and covers. Only [36] applied a multiple regression model 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 than focusing on a short-time window.

A better understanding of the hydrological processes in fire-affected areas and their associations with soil properties and covers has also important implications for hydrological modeling [37]. Another important concern for authorities and land managers is the need to predict the runoff and erosion rates in burned forests, both without any action and under alternative scenarios of post-fire management [36,38]. The use of hydrological models is a viable tool for this purpose, but the choice and implementation of these models may be difficult and time-consuming. Conversely, simple regression models could be more efficient and of easier use, at least for rough and quick evaluations in the absence of more sophisticated tools [38]. However, these models must be prepared and calibrated in the same geomorphological and hydrological context of the burned area. Hydrological modeling of burned and burned and treated areas has been carried out for several years

and in many environmental contexts, e.g., [36,39]. Less modeling experiences have instead evaluated the prediction capacity of runoff and erosion using regression equations based on soil properties and covers as input parameters.

A clear identification of the key drivers of soil hydrology through processing of experimental data is a key task to predict the runoff and erosion rates under variable soil conditions. This information is essential for hydrologists in their professional activities and indirectly important for landscape managers charged with soil conservation and environmental protection tasks.

This study aims to fill the absence of a combined analysis of the hydrological response of soil and its driving factors as well as the lack of simple models for runoff and erosion predictions. The specific objectives are the following: (i) the identification of the soil properties and covers that most influence surface runoff and erosion; and (ii) the evaluation of the runoff/erosion prediction capacity of linear regression models based on a limited number of soil properties and covers. For these objectives, a case study of three forest sites (pine, chestnut, and oak) in Calabria (Southern Italy under Mediterranean semiarid conditions) treated with prescribed fire and post-fire soil mulching with fern has been adopted.

2. Materials and Methods

2.1. Study Area

The study area was close to Samo (Calabria, Southern Italy), between 600 and 900 m above sea level (Figure 1 and Table 1). In this area, three forest sites were identified. The first site ("Calamacia") was a pine (*Pinus pinaster* Aiton) stand reforested in the early 1980s. The second site ("Rungia") was a natural oak stand (*Quercus frainetto* Ten.). The third site ("Orgaro") was a chestnut stand (*Castanea sativa* Mill., about 30 years old). None of the three forest stands was subjected to management (Table 1).



Figure 1. Location of the experimental forest sites (Samo, Calabria, Southern Italy); datum: EPSG: 4326 WGS 84.

Characteristics		Site					
	Characteristics	Calamacia	Rungia	Orgaro			
Geographic coordinates *		38°04′53″ N; 16°01′46″ E	38°05′20″ N; 16°00′37″ E	38°04′59″ N; 16°01′50″ E			
	Aspect	South-West	North-East	West			
	Altitude (m a.s.l.)	650-700	900–950	700–750			
	Slope (%)	20.0 ± 0.82	19.1 ± 1.65	20.3 ± 0.96 chestnut (Castanea sativa Mill.)			
	species	pine (Pinus ningster Aiton)	oak (Ouercus frainetto Ten)				
Trac	density (n/ha)	950 ± 86.4	$\frac{(246)}{225 \pm 44.7}$	725 ± 89.1			
nee	diameter at breast height (cm)	28.3 ± 9.4	40.7 ± 8.9	20.2 ± 5.6			
	height (m)	20.5 ± 1.4	18.2 ± 1.9	9.6 ± 1.2			
	basal area (m ² /ha)	67.9 ± 6.5	31.1 ± 3.6	24.3 ± 4.4			
	Understory vegetation	Quercus ilex L., Rubus ulmifolius S.	Cyclamen hederifolium	Rubus ulmifolius S., Pteridium aquilinum L.			
	Litterfall layer depth (cm)	± 4.6	12.2 ± 3.9	6.1 ± 4.0			

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

Note: * datum: EPSG: 4326 WGS 84. The area has a typical semi-arid climate ("Csa" class, "Hot-summer Mediterranean" climate), according to Koppen classification [40]. Winters are mild and rainy, while summers are warm and dry. The mean precipitation is 1102 mm/yr and the mean temperature is 17.4 °C (weather station of Sant'Agata del Bianco, 38°05'47"N; 16°04'51"E, 2000–2020).

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

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

City	Main Forest	Soil		Tuno			
Site	Species	Condition	Silt (%)	Clay (%)	Sand (%)	Type	
Calamacia	pine	unburned	10.0 ± 1.01	9.0 ± 0.00	81.0 ± 0.99	sandy loam	
	-	burned	6.3 ± 3.06	8.7 ± 0.58	85.0 ± 3.61		
Rungia	oak	unburned	12.7 ± 1.53	9.7 ± 0.58	77.7 ± 1.15	loamy	
0		burned unburned	10.3 ± 2.25 12.3 ± 2.31	8.7 ± 0.58 8.0 ± 1.73	81.0 ± 2.02 79.7 ± 0.58	sand	
Orgaro	chestnut	burned	11.3 ± 1.53	8.7 ± 0.58	80.2 ± 1.04		

2.2. Prescribed Fire Operations and Mulching Application

In early June 2019, the prescribed fire was applied in the three forest sites by the Environmental Regional Agency ("Calabria Verde"), under the surveillance of the National Corp of Firefighters. During the fire application, wind was absent and air humidity was close to 50–60%. The mean soil temperature, measured by thermocouples, was under 25 °C with a peak of 29 °C.

Immediately after the prescribed fire, a part of the burned areas was covered with fern as mulch material. The plants were cut in the same forests and manually shredded in small pieces (maximum length of 5 cm). The fresh residues were spread on the ground to form a mulch layer of 2–3 cm. The applied dose was 500 g/m² of fresh weight (200 g/m² of dry matter). This dose is commonly used during straw mulching after fire [18,20].

2.3. Experimental Design

In each experimental site, three series of plots were delimited on hillslopes of each forest species at distance between 1.5 and 20 m from each other (Table 1). Three plots were installed in the unburned soils (considered as "control"). In the burned area, six other plots were located, of which three plots were not treated and three plots were mulched with fern. Overall, the experimental design consisted of three forest species (pine, oak,

and chestnut) \times three soil conditions (unburned, burned and not treated, and burned and mulched) \times three replications, for a total of 27 plots.

Each plot was 3-m long and 1-m wide and covered an area of 3 m^2 . In order to prevent the inflow of surface water, the plots were hydraulically isolated using metallic sheets that were inserted below the ground surface. A transverse channel and a longitudinal pipe were installed downstream of each plot, to intercept the flows of water and sediments, which were collected into 100-litre tanks.

2.4. Monitoring of the Hydrological Variables

The hydrological measurements started immediately after site installation (mid-June 2019) and were carried out throughout four months (until early November 2020).

Precipitation depth, duration, and intensity were measured by a tipping bucket rain gauge (measuring 5-min data) at a weather station with that was located 1 km from the experimental sites.

The surface runoff and sediment concentration after precipitation were measured following the procedures suggested by [16,41]. Only the runoff volumes produced by rainfalls over 13 mm, which can be considered as "erosive events" according to [42], were monitored. To summarize, the runoff water in the tank was stirred to achieve a good suspension, and three separate samples of the suspension were collected, totalling about 0.5 litres. The samples were brought to the laboratory and oven-dried at 105 °C for 24 h. After drying, the sediments were weighted and referred to the sample volume, in order to calculate the sediment concentration.

To characterize the hydrological response of the experimental soils to rainstorms under the different soil conditions, the runoff coefficients (hereafter "RunoffCoeff") and sediment concentrations ("SedConc") were considered for the first two events monitored until early November 2020. The Runoff Coeff was calculated by dividing the runoff volume (in mm) to the rainfall depth, while the SedConc was measured to characterize erosion.

2.5. Measurement of the Soil Properties and Covers

2.5.1. Hydrological Properties

The hydrological properties of soil selected for this study were the water infiltration rate (IR) and soil water repellency (SWR). Each property was measured in three points per plot, which were randomly selected.

More specifically, IR was determined using a portable Eijelkamp[®] rain simulator [43,44]. The methods of measurement are described in detail in the works by [45,46]. To summarize, this simulator reproduced a rainfall with a height and intensity of 18 mm and 360 mm h⁻¹, respectively. The simulator was previously calibrated by generating a rainfall of 3 mm and intensity of 37.8 mm h⁻¹ over a surface area of 0.3 m \times 0.3 m.

The SWR was estimated using the Water Drop Penetration Test (WDPT) method [47,48] close (at about 0.25 m) to the measurement point of IR. The experimental procedures to measure SWR as well as the SWR classification according to the values of WDPT [49] are reported in the works by [49–51]. To summarize, 15 drops of distilled water were released on the soil surface, using a pipette. The time needed by the drops to penetrate the soil was measured, in order to estimate the WDPT. The SWR was measured on a soil with natural water content, which was measured by a soil moisture probe connected to a UX120 4-channel Analog Logger (Onset HOBO, Bourne, MA, USA).

Before measuring IR and SWR, the litter was removed by a small shovel from the soil surface, which was leveled to prepare a horizontal surface. The values of IR and SWR measured in the three points of each plot were finally averaged.

2.5.2. Chemical Properties

One day after the simulation of the prescribed fire, samples of soil were randomly collected between 0 and 5 cm below the soil surface of each plot (Table A1 in Appendix A).

The main chemical properties of the soil samples (pH, electrical conductivity, contents of organic carbon, total nitrogen, potassium, magnesium, calcium, and phosphates) were analyzed in laboratory (Table A1). The analytical methods are described in [52].

2.5.3. Soil Covers

The following properties of the soil surface (hereafter "soil covers") were also measured in field one day after the prescribed fire: shrub (SC) and litter (LC) cover, bare soil (BS), stoniness (St), as well as ash cover (AC). These soil covers were expressed in percent over the total surveyed area.

These soil covers were measured in nine areas (5 m \times 5 m) close to the points of soil sampling. The grid method [53]—using a 0.50 \times 0.50 m grid square on the sampling areas—for SC, and the photographic method [54] for LC, BS, St, and AC were used (Table A1).

2.6. Statistical Analysis

ANOVA (Analysis of Variance) was applied to all measured parameters (hydrological variables, soil properties, and covers, considered as response variables), assuming the soil condition (unburned, burned and not treated, and burned and mulched) as factors (independent variables). The statistical significance of the differences in the response variables was evaluated by the pairwise comparison using Tukey's test (at p < 0.05). A normality test or a square root-transformation was applied to the variables, whenever necessary, in order to satisfy the equality of variance and normal distribution assumed by the statistical tests.

Then, a Principal Component Analysis (PCA) was applied, in order to identify the derivate variables (Principal Components, PCs) [55] and simplify the analysis of the measured parameters, losing as little information as possible. Before PCA, the original variables (expressed by different measuring units) were standardized, and Pearson's method was used to compute the correlation matrix. The first four PCs, explaining together a percentage of 85% of the original variance, were chosen.

The PCA was integrated by the Agglomerative Hierarchical Cluster Analysis (AHCA) a distribution-free ordination technique—in order to group parameters with similar characteristics. The Euclidean distance was used as similarity-dissimilarity measure [56].

Finally, the correlations between the RunoffCoeff and SedConc (dependent variables) on one side and the soil properties and covers (independent variables) on the other side were analyzed by linear regression models. These models made possible the prediction of these hydrological variables from easily measured soil parameters and independently on rainfall. The statistical analysis was carried out using the XLSTAT release 2019 software.

All variables will be indicated with the acronyms explained in the .

2.7. Evaluation of the Accuracy of the Regression Models

The accuracy of the regression models was evaluated by two approaches: (i) by visually comparing the observed and modelled RunoffCoeff and SedConc in scatterplots; and (ii) by adopting the following criteria:

- the main statistics (i.e., the maximum, minimum, mean, and standard deviation of the observed and simulated values).
- the coefficient of determination (r^2) .
- the coefficient of efficiency of [57] (NSE).
- the Root Mean Square Error (RMSE).
- the percent bias (PBIAS).

The equations for their calculations with the acceptance limits or optimal values are reported in the works by [58–60] and summarized in Table 3.

Index	Equation	Range of Variability	Acceptance Limits or Optimal Values
r ²	$r^{2} = \left[\frac{\sum\limits_{i=1}^{n} (O_{i} - \overline{O})(P_{i} - \overline{P})}{\sqrt{\sum\limits_{i=1}^{n} (O_{i} - \overline{O})^{2}} \sqrt{\sum\limits_{i=1}^{n} (P_{i} - \overline{P})^{2}}}\right]^{2}$	0 to 1	$r^2 > 0.50 \ [60-62]$
	2, , ,		Model accuracy [60]:
NSE	NSE = $1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - \overline{O})^2}$	$-\infty$ to 1	 good if NSE ≥ 0.75 satisfactory if 0.36 ≤ NSE < 0.75 unsatisfactory if NSE < 0.36
RMSE	$\text{RMSE} = \sqrt{\frac{\sum\limits_{i=1}^{n} (P_i - O_i)^2}{n}}$	0 to ∞	RMSE < 0.5 of observed SD [63]
			<0.25 [59]
PBIAS	PBIAS = $\frac{\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} O_i}$	$-\infty$ to ∞	 PBIAS < 0 indicates model underestimation PBIAS > 0 indicates model overestimation [64]

Table 3. Indexes, related equations, and range of variability to evaluate the prediction capacity of the regression models.

Notes: r^2 = coefficient of determination; NSE = coefficient of efficiency of Nash and Sutcliffe; RMSE = Root Mean Square Error; PBIAS = percent bias; n = number of observations; O_i , P_i = observed and predicted values at the time step i; \overline{O} = mean of observed values; SD = standard deviation.

3. Results and Discussion

3.1. Hydrological Characterization

Throughout the monitoring period, two erosive rainstorms were recorded, 65 mm on 15 July 2019 (with duration of 36 h and mean intensity of 2 mm/h) and 50 mm on 9 October 2019 (duration of 14.6 h and mean intensity of 1.9 mm/h). The first rainfall events after burning, when fire has almost thoroughly removed the shrub, herbaceous vegetation cover, and the litter, noticeably increase runoff and erosion [11]. This is in close accordance with the majority of studies, which showed that prescribed fire generates noticeably more runoff and soil loss compared to the unburned areas [9,29,65].

Compared to the unburned soils, both RunoffCoeff and SedConc increased in the burned sites of all forests. For RunoffCoeff, the highest increase was measured in pine forest (+682%) and the lowest in the chestnut site (+183%). The increases in SedConc were also the highest in pine forest (+216%) and the lowest (+25%) in the chestnut site (Figure 2a). The mulch application reduced these increases especially for RunoffCoeff. More specifically, in comparison to the burned and not treated sites, the reduction in RunoffCoeff was between -39% (oak) and -76% (chestnut), while these reductions for SedConc were in the range -2% (oak) to -50% (pine) (Figure 2).

The application of the prescribed fire resulted in a reduction in IR of 45–50% compared to the unburned sites. The mulching treatment limited these reductions by 7% (oak sites) to 18% (chestnut), while IR increased by 9% in mulched soils of pine (Figure 2b). Finally, fire induced a strong repellency in pine and oak forests, while the SWR was slight in the chestnut site. The repellency conditions of mulched soils were not different compared to the burned and not treated sites (Figure 2). The significant reductions in IR are generally due to the synergistic effects of increased SWR and soil sealing and removal of vegetation cover [24].

The investigation has been carried out immediately after the prescribed fire—that is, when burning has removed all understory vegetation. Therefore, the effect of the different species on the soil hydrological response may be negligible in this short term.



Figure 2. Hydrological observations (**left**, RunoffCoeff = runoff coefficient and SedConc = Sediment Concentration; **right**, IR = infiltration rate and SWR = soil water repellency) in the experimental sites measured immediately after the prescribed fire and mulching treatment (Samo, Calabria, Southern Italy). Legend: P = pine; C = chestnut; O = oak; U = unburned; B = burned and not treated; M = burned and mulched; different letters indicate significant differences among the soil conditions and forest species after Tukey's test (p < 0.05); lowercase letters refer to RunoffCoeff and IR, capital letters to SedConc and SWR).

3.2. Identification of the Hydrological Response Drivers

PCA identified four derivate and uncorrelated Principal Components (PC1 to PC4), which together explain 87.9% of the total variance of the original variables. More specifically, PC1 and PC2 explain 66.4% of this variance, while PC3 explains another 14.7%, and PC4 explains the remaining 6.74%. The analysis of the factor loadings on the four PCs shows that all the original variables are associated (loadings > 0.63, all significant at *p* < 0.05) to PC1, except: (i) SC and St, which weigh on the second PC (loading > 0.85); (ii) pH and EC that are associated to PC3 (loading over 0.54); and (iii) SedConc, which influences PC4 (loading of 0.62) (Table 4 and Figure 3).

Moreover, a clear gradient along the PC1 is evident between unburned and burned soils (both untreated and mulched), and another gradient is found along the PC2 between the soils of the oak forest and those of the other species (Figure 3).

The associations between the RunoffCoeff and other hydrological variables (in particular the IR, LC, SWR, A, BS, and OC) in driving the first PC are somehow expected. In other words, the plot of Figure 3 reveals that the RunoffCoeff increases when the IR and litter cover decrease, and SWR, ash cover, OC content and bare soil area decrease. This is shown by the positive—for RunoffCoeff, SWR, A, BS, and OC—and negative—for IR and LC—coefficients of correlation among the original variables and PC1.

The association between the RunoffCoeff and SWR and ash cover is also expected, due to the clear influence of repellency (which produces soil hydrophobicity) and ash (which seals the soil) on high runoff generation capacity of burned soils [30,66–68]. Moreover, the litter cover retains water and thus reduces the rainfall input on soil and decreases the velocity of the overland flow. This means that the SWR, ash, and litter cover are the factors that most influence the runoff generation, although with different magnitude. This happens because: (i) litter shadows soil from the direct impact of the precipitation, and increases the travel time of flow; (ii) repellency—and OC content, which is strictly correlated to SWR, [51,69,70]—increases the hydrophobicity of soil and, as a consequence, the overland flow; (iii) the ash cover left by fire clogs the soil pores and seals the soil surface [30,67]. Other studies focusing on the impacts of prescribed fires have shown that ash contributed to reduced infiltration, creating a thin layer (few mm) of low porosity and permeability [46,71].

Additionally, IR has a significant effect on the RunoffCoeff, and this may be due to the fact that runoff generation in the studied area is governed by the infiltration-excess mechanism [20], on which water infiltration plays a key role. It is also interesting to notice that, immediately after the fire, the OC and nutrient (TN and phosphates) contents as well as the ion concentrations increased in the soil surface, and this may be an effect of the decrease in IR that immobilize these elements or compounds in the upper soil layer. However, the increase in OC is not able to induce an improvement of soil aggregate stability (and thus a reduction in runoff), which is indirectly confirmed by the positive coefficients of correlation between the OC and RunoffCoeff.

Unexpectedly, the erosion variability is not associated to the RunoffCoeff, since the SedConc weighs on the fourth PC rather than on the PC1. This could be explained by the prevailing erosion mechanism in the experimental soils, which is due to rainsplash rather than to detachment by overland flow. Presumably, the limited area and length of the experimental plots (3 m² and 3 m, respectively) prevented the formation of an erosive overland flow and rill erosion.

The evident gradient along PC2 among the oak soils and the soils of the other two species is influenced by stoniness and shrub cover (Figure 3), which are respectively lower and higher in oak forest under all the soil conditions.

In the score plot of Figure 3 and the dendrogram provided by AHCA (Figure 4), three clusters of observations are evident: a first cluster consists of records related to the burned areas; a second cluster groups the variables of the unburned plots (mulched or not treated) of pine and chestnut; a third cluster relates to the observations at the burned soils (treated and not treated) in the oak forest. This analysis shows a clear distinction between burned and unburned soils, while the treatment with fern mulching is not able to change the main hydrological and chemical properties and soil covers.

Original	Principal Components						
Variables	PC1	PC2	PC3	PC4			
RunoffCoeff	0.732	-0.066	0.197	0.426			
SedConc	0.335	-0.468	0.447	0.619			
IR	-0.838	-0.342	-0.051	0.085			
SWR	0.703	0.010	-0.484	-0.015			
А	0.827	-0.098	-0.517	-0.096			
BS	0.919	-0.299	-0.175	-0.070			
LC	-0.797	0.465	-0.109	-0.104			
SC	0.135	0.936	-0.240	0.054			
St	-0.337	-0.853	-0.189	-0.247			
pН	0.280	-0.193	0.819	-0.389			
ĒC	-0.460	0.523	0.535	-0.092			
OC	0.717	-0.360	-0.188	-0.475			
TN	0.803	-0.378	0.155	0.132			
PO4 ³⁻	0.757	0.401	-0.222	0.077			
K ⁺	0.634	0.241	0.628	-0.268			
Mg ²⁺	0.829	0.190	0.393	-0.068			
Ca ²⁺	0.730	0.639	-0.074	0.004			

Table 4. Factor loadings of the soil properties on the first four Principal Components provided by the PCA applied to soil covers and properties, and hydrological variables observed in the experimental sites immediately after the prescribed fire and mulching treatment (Samo, Calabria, Southern Italy).

Notes: Values in bold correspond for each variable to the factor for which the correlation is significant. RunoffCoeff = runoff coefficient; SedConc = sediment concentration; SWR = soil water repellency; IR = infiltration rate; BS = bare soil; LC = litter cover; SC = shrub cover; A = ash; St = stoniness; EC = electrical conductivity; OC = organic carbon; TN = total nitrogen; PO₄³⁻ = phosphates; K⁺ = potassium; Mg²⁺ = magnesium; Ca²⁺ = calcium.



Figure 3. Loadings of the original variables (**left**, soil covers and properties, and hydrological variables), and scores (**right**) on the first two Principal Components (PC1 and PC2) provided by PCA in the experimental sites immediately after the prescribed fire and mulching treatment (Samo, Calabria, Southern Italy). Legend: P = pine; C = chestnut; O = oak; U = unburned; B = burned and not treated; M = burned and mulched; RunoffCoeff = runoff coefficient; SedConc = sediment concentration; SWR = soil water repellency; IR = infiltration rate; BS = bare soil; LC = litter cover; SC = shrub cover; A = ash; St = stoniness; EC = electrical conductivity; OC = organic carbon; TN = total nitrogen; PO₄³⁻ = phosphates; K⁺ = potassium; Mg²⁺ = magnesium; Ca²⁺ = calcium.



Figure 4. Dendrogram provided by the Agglomerative Hierarchical Cluster Analysis (AHCA) applied to observations in the experimental sites immediately after the prescribed fire and mulching treatment (Samo, Calabria, Southern Italy). Legend: P = pine; C = chestnut; O = oak; U = unburned; B = burned and not treated; M = burned and mulched; the *y*-axis of the dendrogram reports the similarity level, while the dotted line the clustering level.

From the results of these multivariate statistical techniques, we conclude that the prescribed fire, although being of low intensity, is able to significantly alter the hydrological response of forest soil in the short term, while mulching does not isolate the characteristics of burned soils.

3.3. Hydrological Predictions

In the experimental sites, Equation (1), developed to predict RunoffCoeff, uses LC and SC as input parameters as well as two "dummy" variables, Scond(B) and Scond(M), that relate to the soil conditions "burned and not treated" (B) and "burned and mulched" (M). Scond(B) and Scond(M) are equal to one and zero, respectively, in burned and not treated areas, while they are zero (for Scond(B)) and one (Scond(M)) in burned and mulched zones; both variables are equal to zero in unburned sites. Therefore, the RunoffCoeff is given by the following equation:

 $RunoffCoeff = 0.152 - 1.704 \times 10^{-3} LC + 2.373 \times 10^{-3} SC + 0.156 \times Scond(B) - 3.738 \times 10^{-2} \times Scond(B + M)$ (1)

Equation (2) estimates SedConc from A, BS, and LC as well as the dummy variables as Equation (1), using the following formula:

 $SedConc = 4.441 + 1.394 \times 10^{-2} \times A - 5.514 \times 10^{-2} \times BS - 3.856 \times 10^{-2} \times LC + 1.126 \times Scond(B) + 0.544 \times Scond(B + M)$ (2)

From these equations, it is evident that LC is an influencing factor of both runoff and erosion processes.

The prediction capacity of the model (1) can be considered very good for RunoffCoeff (Figure 5). This excellent agreement between observed and predicted data is confirmed by the high values of NSE (>0.86), r^2 (>0.75), and RMSE (<50% of the observed standard deviation). The PBIAS close to zero does not show significant over- or under-estimation of the observed RunoffCoeff by the linear model. Moreover, the predicted statistics (mean and maximum values) are very close to the corresponding observations (Table 5), with errors lower than 22%. The scatter plots show points related to couples of observations and corresponding predictions that are close to the line of perfect agreement (Figure 4a).

The predictions of SedConc given by the linear model (2) are less accurate compared to the RunoffCoeff, but generally satisfactory (Figure 5). The prediction scattering is higher compared to Equation (1), especially for the burned and mulched soils ($r^2 = 0.24$) (Figure 4b. The poor value of the latter coefficient may be due to the natural variability of soils. The NSE values are very high (>0.94) and PBIAS is close to zero, which indicate good model performance in predicting SedConc. The mean and maximum values of the predicted SedConc show an error lower than 19% compared to the corresponding observations (Table 5).

We conclude that the proposed equations can predict with satisfactory accuracy the mean and maximum values of both RunoffCoeff and SedConc, and this accuracy is useful to give a rough estimation of the expected runoff and erosion rates under all soil conditions. Moreover, these models show how, for soil burned by low-intensity fires, the changes in soil covers are the most influencing drivers of runoff and erosion compared to the soil properties and precipitation characteristics (which have not been used in the linear models proposed in this study). This means that regression models that only use a selection of soil covers are able to predict soil hydrology with reliability without the need of precipitation data. However, the longitudinal slope of the experimental plots was the same, and therefore the influence of this factor on the soil hydrological response was not evaluated. The coefficients of the proposed regression models must be experimentally calibrated in soils of noticeably different slopes, but the prediction accuracy of these models (and thus their applicability) should not be significantly different.



Figure 5. Scatter plots of observations against predictions by regression models applied to runoff coefficients (RunoffCoeff, **left**) and sediment concentrations (SedConc, **right**) in the experimental sites immediately after the prescribed fire and mulching treatment (Samo, Calabria, Southern Italy). The gray lines are the 95%-confidence interval. Legend: B = burned and not treated; M = burned and mulched.

Table 5. Statistics and indexes to evaluate the prediction capacity of regression models in the experimental sites immediately after the prescribed fire and mulching treatment (Samo, Calabria, Southern Italy).

Hydrological Variable	Mean	Standard Deviation	Minimum	Maximum	r^2	Ε	RMSE	PBIAS	
Unburned									
Observed	0.08	0.04	0.02	0.13	0.0 -	0.99	0.01	0.00	
Predicted	0.08	0.04	0.02	0.13	0.95				
			Burned						
Observed	0.01	0.02	0.00	0.06	0.75	0.97	0.01	0.00	
Predicted	0.01	0.01	0.00	0.04	0.75	0.86			
		Burne	d and mulched						
Observed	Observed 0.13 0.06 Predicted 0.13 0.04		0.06	0.24	0.91 0.9	0.07	6 0.03	0.00	
Predicted			0.10	0.18		0.96			
Sediment concentration									
Unburned									
Observed	1.05	0.61	0.41	2.32	0.96	0.07	0.22	0.00	
Predicted	1.05	0.51	0.55	1.89	0.86	0.97	0.22	0.00	
	Burned								
Observed	Observed 1.76 0.53		1.05	2.77	0.50 0	0.06	0.26	0.00	
Predicted	1.76	0.31	1.37	2.26	0.50	0.96	0.36	0.00	
Burned and mulched									
Observed	1.18	0.31	0.75	1.68	0.24	0.04	0.20	0.00	
Predicted	1.18	0.31	0.79	1.68	0.24	0.94	0.29	0.00	

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

Our findings are in accordance with the study by [72], who showed that models based on simple linear functions of soil covers (straw mulch) can reliably predict runoff and erosion (although these authors worked in a different environment and in soil conditions not affected by fire). In contrast, [38] have demonstrated in similar experimental conditions as this study (pine forests of SE Spain treated with prescribed fire) that accurate simulations of runoff volumes by linear regression models require precipitation data as input. Similarly, [36] found that post-fire runoff is largely explained by rainfall amounts and SWR, while erosion processes are better explained by rainfall intensity and ground cover variables, such as the bare soil percentage. Overall, the results of our regression analysis may be important for a better understanding of the dynamics of burned forests, since they can help in adapting hydrological models to post-fire environments.

4. Conclusions

The study has explored the short-term influence of soil covers and properties on surface runoff and erosion in three Mediterranean forests (pine, oak, and chestnut) after prescribed fire and post-fire mulching with fern. To this aim, a field campaign of hydrological monitoring has been carried out immediately after the fire and treatment, measuring precipitations, runoff volumes, and soil losses in instrumented plots as well as a representative dataset of soil cover and properties in the same areas.

The PCA has shown that the runoff coefficients increase when the water infiltration rate and litter cover decrease, and repellency, ash cover, organic carbon content, and bare soil area increase. These soil properties and covers are the most influencing drivers of surface runoff. All the analyzed variables play instead a secondary role on the sediment concentration, presumably because the dominant mechanism of erosion in the experimental site is rainsplash rather than sediment detachment due to overland flow. Due to these properties, clear differences in soil hydrological and chemical properties as well as soil covers have been found between unburned and burned (mulched or not) soils, while the distinctions between burned and treated, and burned and not treated soils are much lower.

Two simple linear regression models have been proposed for the forest areas, in order to predict the runoff coefficients and sediment concentrations under the three soil conditions. The equations use a very low number of soil covers and two dummy variables as input parameters. These models are very accurate in simulating the surface runoff and soil erosion in unburned and burned (mulched or not) soils in the short term, as shown by the quantitative comparisons with the corresponding observations.

Obviously, the results of this investigation are relevant to the specific conditions of the study area (soil texture and slope, climate, etc.), and thus these results should be validated in soils of different geomorphologic characteristics and forest ecosystems. The regression models proposed in this study also are specific of the experimental conditions and therefore should be applied in the same or at least similar environment. Their transferability to the hillslope scale should not be questionable (when its profile and surface characteristics are uniform), while the model's applicability at the watershed scale must be verified through targeted investigations.

Overall, this study has helped to better understand the physical processes that govern runoff generation and erosion after fires of low intensity, linking these hydrological effects to the main soil properties and covers. The landscape managers are stimulated by these results to increase the natural (e.g., by hydromulching) or artificial (by traditional mulching) cover of recently burned soils, in order to protect the soil from non-tolerable erosion rates. The availability of the simple regressions models proposed in this study may support the planning activities of forest managers and hydrologists in order to roughly predict the runoff and erosion rates in soils subjected to prescribed fire and post-fire treatment.

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Abbreviations

0	oak
Р	pine
С	chestnut
U	unburned
В	burned
B + M	burned + mulched
LC	litter cover (%)
SC	shrub cover (%)
BS	bare soil (%)
AC	ash cover (%)
St	stoniness (%)
SWR	soil water repellency (WDPT, s)
IR	infiltration rate (mm/h)
EC	electrical conductivity (dS/cm)
OC	organic carbon (%)
TN	total nitrogen (%)
PO4 ³⁻	phosphates (%)
K^+	potassium (%)
Mg ²⁺	magnesium (%)
Ca ²⁺	calcium (%)
RunoffCoeff	runoff coefficient (%)
SedConc	sediment concentration (g/L)
WDPT	water drop penetration test (s).

Appendix A

Soil Cover or	Forest Species-Soil Condition								
Property	P-U	P-B	P-M	C-U	C-B	C-M	O-U	O-B	O-M
A (9/)	0.0 ± 0.0	85.3 ± 5.5	85.7 ± 4.2	0.0 ± 0.0	19.0 ± 3.0	18.7 ± 3.5	0.0 ± 0.0	97.3 ± 1.2	98.0 ± 1.0
A (70)	а	с	с	а	cb	b	а	d	d
BS (%)	9.3 ± 1.5	$84.3\pm2.5~\mathrm{d}$	84.0 ± 2.6	33.7 ± 4.0	64.0 ± 7.0	64.3 ± 6.5	3.3 ± 0.6	94.3 ± 1.5	93.3 ± 1.5
D3 (70)	а		d	b	С	с	а	d	d
LC (%)	82.0 ± 6.0	11.0 ± 4.6 a	12.0 ± 6.0	23.0 ± 4.6	7.0 ± 2.6	6.3 ± 2.5	92.7 ± 2.3	5.0 ± 1.7	5.0 ± 2.6
LC (70)	С	$11.0 \pm 4.0 a$	а	b	а	а	с	а	а
SC (%)	9.0 ± 1.0	4.3 ± 0.6	3.3 ± 1.5	3.7 ± 2.1	0.7 ± 1.2	1.3 ± 0.6	43.7 ± 5.7	30.0 ± 5.3	30.0 ± 4.6
500 (70)	а	а	а	а	а	а	с	b	b
St (%)	6.9 ± 0.4	7.0 ± 0.5	7.0 ± 0.4	3.3 ± 0.3	4.1 ± 0.3	4.1 ± 0.2	0.5 ± 0.3	0.5 ± 0.1	0.6 ± 0.1
51 (70)	С	с	с	b	b	b	а	а	а
рН (_)	6.5 ± 0.1	6.4 ± 0.2	6.6 ± 0.2	6.3 ± 0.1	7.2 ± 0.2	7.0 ± 0.0	6.5 ± 0.1	6.6 ± 0.2	6.5 ± 0.1
p11(-)	а	а	ab	а	С	bc	а	а	а
FC (dS/m)	253 ± 5.8 cd	189 ± 2.2	214 ± 4.6 abc	231 ± 17.0 bcd	249 + 34.3 hcd	235 ± 5.4 bcd	269 ± 11.9	238 ± 9.2	209 ± 1.9
	200 ± 0.0 cu	а	211 ± 1.0 ubc	201 ± 17.0 bed	21) ± 01.0 bed	200 ± 0.1 bed	d	bcd	ab
OC(%)	5.2 ± 0.2	6.5 ± 0.2	7.0 ± 0.1	4.3 ± 0.1	6.0 ± 0.1	6.0 ± 0.2	5.0 ± 0.1	6.2 ± 0.2	6.2 ± 0.2
00 (70)	b	d	e	а	С	С	b	cd	cd
TN (%)	0.5 ± 0.0 ab	0.6 ± 0.0	0.5 ± 0.0 abc	0.5 ± 0.0	0.6 ± 0.0	0.5 ± 0.1	0.5 ± 0.0	0.6 ± 0.0	0.6 ± 0.0
11 (70)	0.0 ± 0.0 db	с	0.0 ± 0.0 abc	abc	С	bc	а	С	С
PO_{13}^{3-} (%)	$51.5 \pm 1.2 \text{ a}$ $75.8 \pm 1.7 \text{ cd}$	75.8 ± 1.7 cd	61.6 ± 0.7	53.3 ± 1.9	65.9 ± 0.6	64.8 ± 1.8	71.3 ± 0.6	79.6 ± 1.6	105 ± 2.7
10_4 (70)		75.0 ± 1.7 cu	b	а	b	b	с	d	е
$K^{+}(0/2)$	38.3 ± 1.2 a	$122 282 \pm 102$	49.9 ± 1.1	32.4 ± 1.3	99. 0 ± 2.0	91.7 ± 3.8	57.9 ± 2.7	78.2 ± 2.1	88.2 ± 2.9
K (70)	50.5 ± 1.2 a	$50.2 \pm 1.7 a$	b	а	f	e	с	d	е
$M\alpha^{2+}(0/2)$	7.4 ± 2.2	20.4 ± 1.0 h	272 ± 19 hc	21.9 ± 2.7	38.1 ± 6.3	35.2 1.3	23.5 ± 1.6	41.0 ± 4.6	36.6 ± 4.2
1vig (70)	а	$20.4 \pm 1.0 0$	27.2 ± 1.7 DC	b	d	cd	b	d	cd
$C_{2}^{2+}(0/2)$	232 + 262	537 ± 29 ha	61.2 ± 3.5 cd	47.8 ± 3.6	57.1 ± 6.2	70.3 ± 1.8	86.6 ± 3.2	130 ± 2.7	111 ± 3.6
Ca-' (%)	25.2 ± 2.0 d	33.7 ± 2.9 BC	01.2 ± 0.0 cu	b	bc	d	e	g	f

Table A1. Mean and standard deviation of the soil covers and properties in the experimental sites immediately after the prescribed fire and mulching treatment (Samo, Calabria, Southern Italy).

Notes: P = pine; C = chestnut; O = oak; U = unburned; B = burned and not treated; M = burned and mulched; RunoffCoeff = runoff coefficient; SedConc = sediment concentration; SWR = soil water repellency; IR = infiltration rate; BS = bare soil; LC = litter cover; SC = shrub cover; A = ash; St = stoniness; EC = electrical conductivity; OC = organic carbon; TN = total nitrogen; PO₄³⁻ = phosphates; K⁺ = potassium; Mg²⁺ = magnesium; Ca²⁺ = calcium; different letters indicate significant differences among the soil conditions and forest species after Tukey's test (p < 0.05).

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