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Short-term hydrological response of soil after wildfire in a semi-arid landscape covered by Macrochloa tenacissima (L.) Kunth

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Thank you very much for the opportunity to revise our manuscript. We have addressed all your comments and we hope the manuscript is now ready for acceptance. Thank you very much for your suggestions, which have improved a lot the initially submitted version.

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Short-term hydrological response of soil after wildfire in a semi-arid landscape covered by *Macrochloa tenacissima* (L.) Kunth

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Abstract

A proper monitoring and management of semi-arid landscapes affected by wildfire is needed to reduce its effects on the soil hydrological response in the wet season. Despite ample literature on the post-fire hydrology in forest soils, it is not well documented how the hydrologic processes respond to changes in vegetation cover and soil properties of semi-arid lands (such as the rangeland and areas with sparse forests) after wildfire. To fill this gap, this study evaluates soil hydrology in a semi-arid soil of Central Eastern Spain dominated by *Macrochloa tenacissima* (a widely-spread species in Northern Africa and Iberian Peninsula) after a wildfire. Rainfall simulations were carried out under three soil conditions (bare soil, ~~and~~ burned ~~or~~ and soils with unburned vegetation) and low-to-high slopes, and infiltration, surface runoff and erosion were measured. Infiltration rates did not noticeably vary among the three soil conditions (maximum variability equal to 20%). Compared to the bare soil, the burned area (previously vegetated with *M. tenacissima*) produced a runoff volume lowered by 27%. In contrast, in the area covered by the same species but ~~not~~ unburned, ~~the~~ runoff was lowered by 58%. The burned areas with *M. tenacissima* produced soil losses that were similar as those measured in bare soils, and, in steeper slopes, even higher. Erosion was instead much lower (-83%) in the sites with unburned vegetation. Overall, the control of erosion in these semi-arid lands is beneficial~~,~~ to reduce the possible hydrological effects downstream of these fire-prone areas~~, a~~. In~~nd,~~

~~in~~ this direction, the establishment of vegetation strips of *M. tenacissima* in large and steep drylands of bare soil left by fire may be suggested to land managers.

Keywords: water infiltration; bare soil; runoff; soil loss; rainfall simulator.

Highlights:

- Soil hydrology in a semi-arid soils dominated by *Macrochloa tenacissima* is evaluated
- Infiltration rates did not noticeably vary among soils
- Compared to bare soils, runoff decreased in both burned and unburned sites
- Erosion was similar in bare and burned soils, and lower in unburned sites
- ~~Vegetation strips of~~ *M. tenacissima* strips in drylands are suggested as post-fire management

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1. Introduction

Fire risk is particularly high in semi-arid and arid climates, where hot and dry summers increase the frequency and occurrence of wildfire many months per year (Stavi, 2019). In many areas, post-fire regeneration of forest vegetation is slow, due to the water scarcity and the intrinsic properties of soils (generally shallow, with low aggregate stability, and poor in organic matter and nutrients) (Cantón et al., 2011). Moreover, the increase in mean temperature and reduction in precipitation that are forecasted by the future scenarios of climate change (Collins et al., 2013) will aggravate the fire risk and damage.

Wildfire is a major ecological process in forests and ~~rangelands~~forest (Pierson et al., 2001), and its impacts affect several ecosystem compontents (air, water, soil, plants, fauna) (DeBano et al., 1998; Lucas-Borja et al., 2019). The impacts of natural or fraudulent wildfires on soils and water cause many hydrological and geomorphological changes in the landscape, both in the short and long period (Shakesby and Doerr, 2006). After a wildfire, vegetation and litter are totally removed, leaving the ground surface exposed to rainsplash. Moreover, several soil properties change with effects lasting also several years, especially due to hydrophobicity and reduction in aggregate stability (Glenn and Finley, 2010; Zema, 2021). All these changes heavily modify the hydrological response of burned soil compared to the unburned areas, with implications for infiltration, overland flow and erosion (Shakesby and Doerr, 2006). It has been demonstrated that runoff and erosion rates may increase by some orders of magnitude even after fires of low severity, such as the prescribed fire (Cawson et al., 2012). These increases may lead to hazardous floods and unsustainable erosion both inside the fire-affected zones and in the valley areas high runoff and erosion rates lead to heavy environmental onsite (e.g.~~,~~ soil loss, landslides) and off-site impacts (e.g.~~,~~ flooding, transport of polluting compounds, damage of urban infrastructures)~~ impacts~~ (Lucas-Borja et al., 2020; Prats et al., 2015; Zema et al., 2021a).

A proper control of soil hydrology is needed to reduce the wildfire effects on the forest ecosystems of arid and semi-arid areas. Water infiltration is a key parameter to govern the hydrological response of burned soils in Mediterranean semi-arid ecosystems, since the hydrological processes generating runoff and erosion are dominated by the infiltration-excess mechanism (Lucas-Borja et al., 2018). Therefore, a deep understanding of water infiltration is essential, since the hydraulic conductivity of Mediterranean soils can be extremely low (Doerr et al., 2003; Zema et al., 2021b). Low infiltration produces ~~2~~non-tolerable rates of surface runoff and soil erosion (Robichaud and Waldrop, 1994; Zema et al., 2020b; 2020a), if rainfall exceeds the surface retention of soil infiltration-excess (Doerr et al., 2000). Fire can further decrease water infiltration, due to soil water repellency, which very often affects the semi-arid soils (Alcañiz et al., 2018; Cawson et al., 2016; Zema et al., 2021b). Therefore, the analyis of soil's hydrological parameters (infiltration, runoff, peak flow, soil loss) is basic to provide a detailed knowledge on how to control and mitigate the hydrological risks and other environmental hazards in semi-arid environments (Moody et al., 2013; Shakesby, 2011).

Ample literature is available on the hydrological effects of fires atdifferent severity on forest soils (e.g.~~, (~~Alcañiz et al., 2018; Certini, 2005; Zavala et al., 2014). However, few studies have examined the wildfire impacts on rangeland hydrology, and it is not well documented how hydrological processes (infiltration, runoff and erosion) respond to changes in vegetation cover and soil properties after wildfire (Pierson et al., 2001). Moreover, there is an emphasis on case studies in Northern America, while much less attention has been paid to other environments, such as the landscapes of the Mediterranean Basin under semi-arid Mediterranean conditions (Shakesby and Doerr, 2006). Here, many ~~rangelands~~forest are covered by shrubs and grass, such as *Macrochloa tenacissima* (L.) Kunth (hereinafter *M. tenacissima*), especially in Northern Africa and Iberian Peninsula. To the authors' best knowledge, ~~in these areas~~the hydrological response of soil affected by wildfire has not been evaluated in these areas, and comparisons with vegetated and unburned areas and bare soils still lack.

To fill these literature gaps, this study evaluates the hydrological response of ~~a ~~semi-arid soils dominated by *M. tenacissima*to wildfire in a landscape of Central Eastern Spain using a rainfall simulator. Three soil conditions are considered (i, bare soil, assumed as reference; ii, burned soils with *M. tenacissima*, and iii, unburned soil with the same species), in order to evaluate how infiltration, runoff, peak flow and erosion rates are modified by fire and vegetation. We hypothesize that in these semi-arid areas covered by *M. tenacissima*: (i) fire reduces infiltration compared to unburned areas; (ii) runoff and erosion are higher in bare soils, and decrease in areas covered with *M. tenacissima*; (iii) the hydrological response in areas dominated by *M. tenacissima* and affected by fire is more similar ~~as~~ to that of the ~~areas with~~ bare soil~~s~~ areas than the response of unburned areas. The results of this investigation may give landscape planners insight on suitable practices towards mitigation of flood and erosion risks in fire-affected areas of the semi-arid environment.

2. Materials and methods

2.1. *Study area*

The field experiments were carried out in a rural landscape with sparse forests close to Agramón (geographical coordinates 38.42188N, -1.63747E, province of Albacete, Castilla-La Mancha, Spain) (Figure 1).

The area elevation ranges between 520 and 770 m, and the study sites have west or southwest aspects. The climate is semi-arid and its type can be classified as “BSk” according to the Köppen classification (Kottek et al., 2006). The mean annual temperature and precipitation are 16.6°C and 321 mm, respectively. Soils are classified as *Calcid Aridisols* and have a silt loam texture (USDA, 1999) (Table 1).

In July 2020, a wildfire burned a forest area. The mean value of the soil burn severity was estimated using the methodology proposed by (Vega et al., 2013). Two weeks after the wildfire, a burned forest area of about 1 km^2 was selected. In this area, crown fire resulted in 100% tree mortality. Wildfire severity was evaluated as higher according to the regional forest service. Before the wildfire, the stand density ranged from 500-650 trees/ha with tree heights between 7 and 14 m. The dominant overstory vegetation consisted of Aleppo pine *(Pinus halepensis* Mill.). Additional understory vegetation was mainly *Macrochloa tenacissima* (L.) Kunth. To a lesser extent, other vegetal species were *Rosmarinus officinalis* L., *Brachypodium retusum* (Pers.) Beauv., and *Thymus vulgaris* L.

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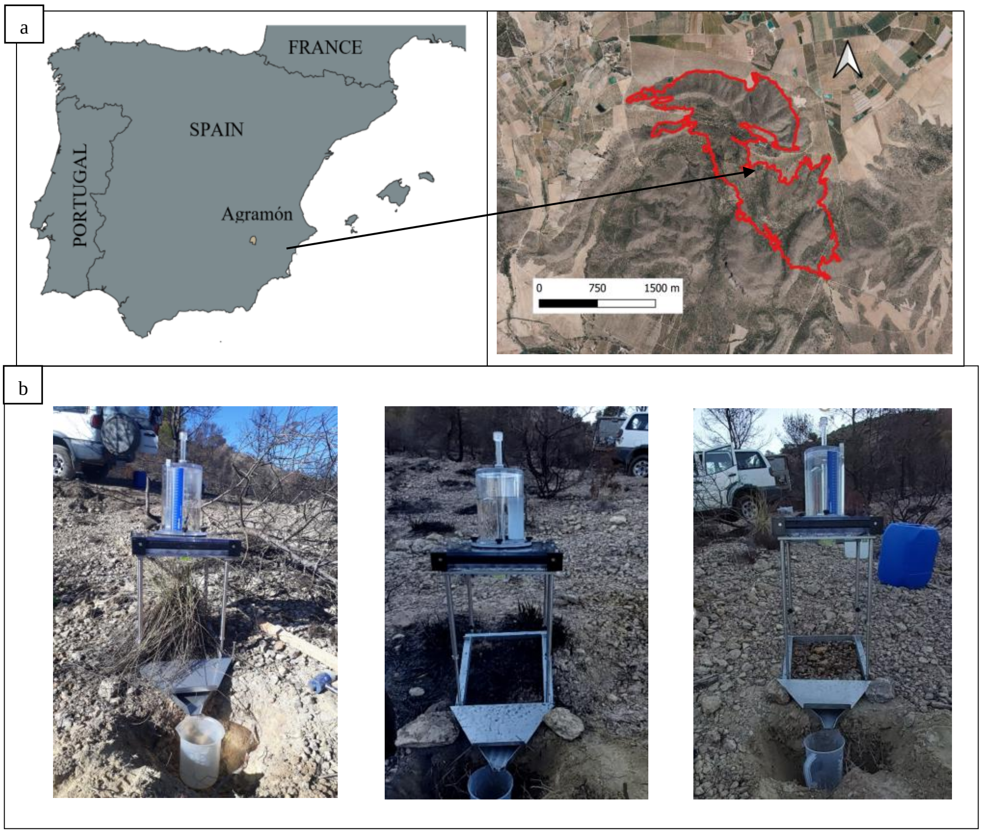

Figure 1 – Geographical location of the study area (Agramòn, Castilla La Mancha, Spain) (a), and rainfall simulations carried out underthree experimental soil conditions (unburned*M. tenacissima* - left, burned *M. tenacissima* – center, and bare soil - right) (b).

Table 1 – Mean values (± standard errors) of texture, organic matter content and surface covers of the experimental soils (Agramòn, Castilla La Mancha, Spain).

Soil condition	**Soil texture (% content)**			**Organic matter content (%)**	**~~Soil~~ Soil surface cover (%)**				
	S~~s~~and	**~~s~~Silt**	**~~c~~Clay**		**P~~p~~lants**	**D~~d~~ead matter**	**A~~a~~sh**	**R~~r~~ock**	**B~~b~~are soil**
Bare soil	26.3 ± 1.56 a	59.4 ± 1.23 a	14.3 ± 0.57 a	2.88 ± 0.04 a	0 a	2.0 ± 0.59 a	0 a	70.5 ± 6.06 a	17.5 ± 3.67 a
Burned *M. tenacissima*	31.7 ± 1.55 a	55.5 ± 0.78 a	12.8 ± 1.90 a	5.13 ± 0.21 b	0 a	0 b	85.0 ± 7.97 b	13.5 ± 2.21 b	1.50 ± 0.91 b
Unburned *M. tenacissima*	30.2 ± 2.82 a	51.2 ± 1.08 a	18.5 ± 2.27 a	2.35 ± 0.27 a	91.2 ± 5.55 b	0 b	0 a	5.50 ± 0.72 c	3.48 ± 0.27 c

Note: different letters indicate significant differences ($p < 0.05$).

2.2. *Experimental design for rainfall simulations and hydrological monitoring*

In the burned forest, a site of about 5 ha was selected. The experimental design consisted of three soil conditions (bare soil, unburned and burned *M. tenacissima*) × three slopes (L, low slope,< 20%, M, medium slope, between 20% and 30%, and H, high slope, > 30%). The distance between the areas with different soil conditions was lower than 250 m.

For each slope and soil condition, rainfall was simulated in small areas randomly chosen. Eight, ~~ten~~ 10 and 22 simulations were carried out in bare soils, four, 18 and 18 again in burned *M. tenacissima*, and 12, 24 and 4 in unburned *M. tenacissima*, for slopes ~~with slopes~~ < 20%, between 20% and 30%, and > 30%, respectively. An Eijelkamp® rainfall simulator was used (Hlavčová et al., 2019; Iserloh et al., 2013), following the methods by Bombino et al. (2019) and Carrà et al. (2021). The device was gently placed over the ground, caring that the vegetation was not disturbed by this operation. A rainfall with a height and intensity of 50 mm and 200 mm/h was simulated over a surface area of 0.3~~0~~ m x 0.3~~0~~ m. These characteristics relate to precipitation with 10-year return interval in the area. The drop diameter was 5.9 mm and the falling height was 40 cm from the ground. The simulator was calibrated prior to the simulation campaign by generating the same rainfall as the field experiments. The water volume in the sprinkler tank (about 2.2 litres) was dosed by varying the pressure head, as suggested in the operating manual. During each rainfall simulation (15 min), the runoff water and sediments were collected in a small graduated bucket and then measured. The mean infiltration rate was calculated as the difference between the rainfall height and runoff divided by the duration.

Moreover, the infiltration curves of one point for each soil condition and slope were determined by subtracting the runoff generated by the rainfall at each time interval. The runoff height in the bucket was read each 30 s and subtracted from the rainfall height at the same time. The peak flow and time to peak - the time measured from the rainfall start to the peak flow occurrence - were identified in the hydrograph.

2.3. *Sampling and analyses of properties and covers of soils*

Nine soil samples (~~each of~~ 600 g each) were collected from the sites under each soil condition. The samples were ~~made up~~ composed of six sub-samples collected from randomly selected locations in each soil condition, to capture the soil spatial variability. Each sub-sample was gently excavated from the topsoil (-5 cm) after removing the litter layer. Then, the sample was passed through a 2 mm sieve and stored at 4° C until the subsequent analyses conducted in the following day. On the composite sample, the soil texture was estimated after sieving and the application of the hydrometer method. Moreover, the organic matter content (OM, %) was determined using the potassium dichromate oxidation method (Nelson and Sommers, 1996).

Finally, in the sites under the three soil conditions, where the rainfall simulations were carried out, the following soil covers were measured: plants, rock fragments, dead matter, ash and bare soil (in areal percentage). The grid method (Vogel and Masters, 2001) for plant cover and bare soil, and the photographic method for the remaining variables were used. The grid method was applied, using a 0.50 x 0.50-m grid square on the sampling areas.

2.4. Statistical analysis

The statistical significance of the differences among soil conditions and slopes, and their interactions, was calculated using a 2-way ANOVA for surface runoff and soil loss. The latter were considered as dependent variables, while the soil condition and slope were the independent factors. The pairwise comparison by Tukey's test (at $p < 0.05$) was also used to evaluate the statistical significance of the differences in the two hydrological variables among factors. In order to satisfy the assumptions of the statistical tests (equality of variance and normal distribution), the data were subjected to a normality test or were square root-transformed whenever necessary. The statistical analysis was carried out using the XLSTAT software (release 2019, Addinsoft, Paris, France).

3. Results

The hydrographs generated by the rainfall simulation experiments are illustrated in Figures 2 to 4. These hydrographs depict the time variability of the infiltration and runoff rates under a constant rainfall intensity on soils with different soil conditions (unburned and burned *M. tenacissima*, and bare soil) and slopes (low, medium, high). The infiltration rate started from a value equal to the rainfall intensity, which means that initially all precipitation infiltrated. When soil progressively saturated, the infiltration rate decreased and runoff began (Figure 2a, 2b and 2c). After the minimum value of the infiltration rate, corresponding to the peak flow, runoff decreased and, for some soil conditions and slopes (unburned *M. tenacissima* with low and high slopes, bare soil with medium slope, and burned M. tenacissima with high slope), depleted at the end of the rainfall simulation (Figures 2, 3 and 4).

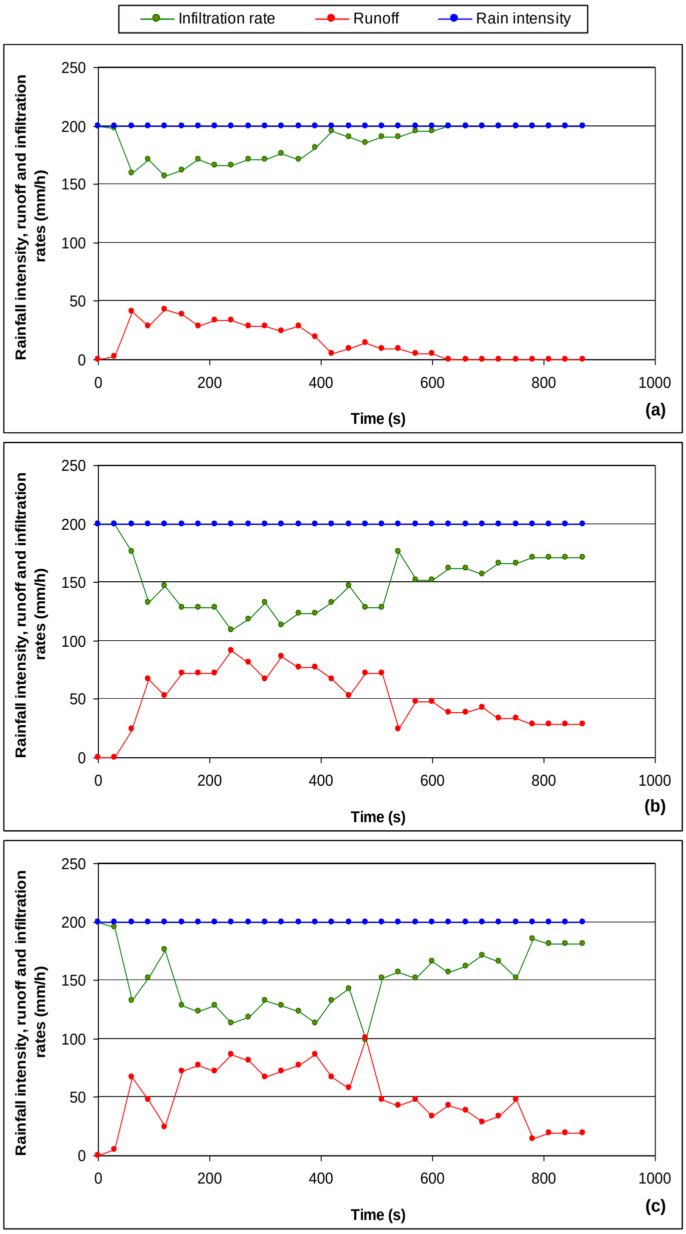

Figure 2 - Hydrological variables (rainfall intensity, and runoff and infiltration rates) measured by rainfall simulator under three soil conditions (a, unburned *M. tenacissima*; b, burned *M. tenacissima*; c, bare soil) and low slope (< 20%) in Agramòn (Castilla La Mancha, Spain).

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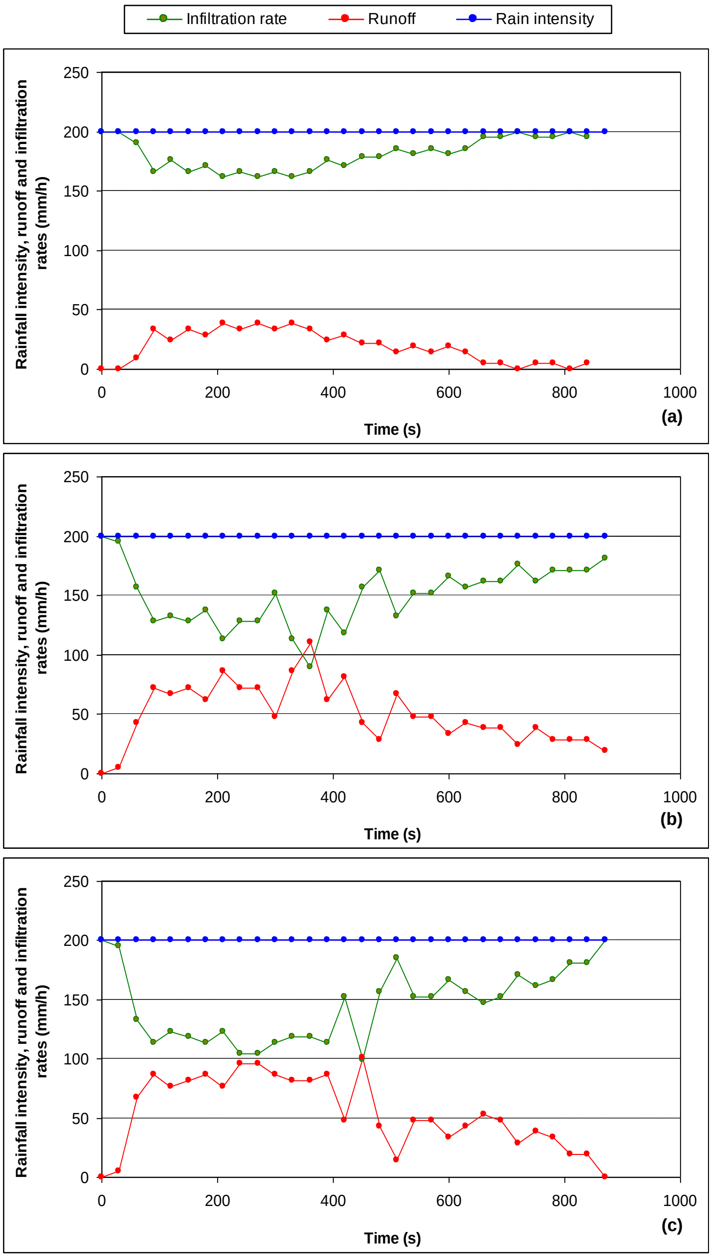

Figure 3 - Hydrological variables (rainfall intensity, and runoff and infiltration rates) measured by rainfall simulator under three soil conditions (a, unburned *M. tenacissima*; b, burned *M. tenacissima*; c, bare soil) and medium slope (20 to 30%) in Agramòn (Castilla La Mancha, Spain).

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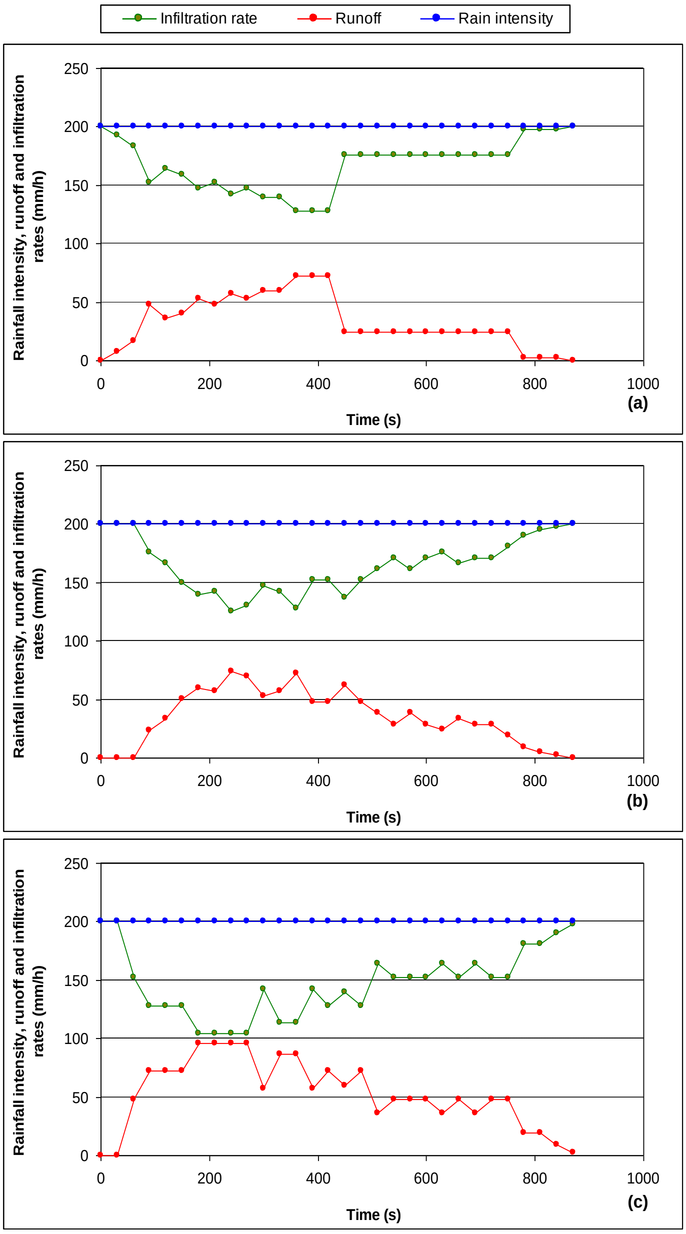

Figure 4 - Hydrological variables (rainfall intensity, and runoff and infiltration rates) measured by rainfall simulator under three soil conditions (a, unburned *M. tenacissima*; b, burned *M. tenacissima*; c, bare soil) and high slope (> 30%) in Agramòn (Castilla La Mancha, Spain).

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ANOVA showed that the surface runoff measured by the rainfall simulator was significantly different among the three soil conditions (F = 364; $p < 0.001$), slopes (F = 55.2; $p < 0.001$), and their interactions (F = 18.5; $p < 0.0001$). In more detail, the highest runoff was observed in bare soil (13.0 ± 0.59 mm, value averaged among the three soil slopes), and the minimum in the unburned soils (5.51 ± 1.38 mm), while the soils with burned *M. tenacissima* produced intermediate runoff (9.55 ± 1.01 mm). The runoff increased with soil slope, and the highest and lowest volumes were observed in steeper soils (10.4 ± 1.34 mm, values averaged by soil condition) and lower slopes (7.71 ± 0.79 mm) (Figure 5b).

Regarding infiltration, the bare soil showed the lowest value (148 ± 2.37 mm/h, averaged by slope), while the highest rate was observed in unburned soils (178 ± 5.53 mm/h). According to the soil slope, averaging the measured values by soil condition, the maximum infiltration rate was observed ~~measured~~ in the soils with lower slope (169 ± 3.14 mm/h), and the minimum in the steeper soils (158 ± 5.34 mm/h), although the areas with medium slope showed infiltration rates (160 ± 2.44 mm/h) similar as the latter (Figure 5a).

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The highest erosion was ~~measured~~observed in the soils with burned *M. tenacissima* (404 ± 160 kg/ha, value averaged by slope), and the lowest in unburned soils (56.1 ± 27.6 kg/ha). As for runoff, the highest and lowest soil losses, ~~measured~~observed in steeper soil (336 ± 181 kg/ha) and soils with lower slope (213 ± 26.9 kg/ha) were expected, while erosion in soil profiles with medium slope (213 ± 26.9 kg/ha) was close to lower profiles (Figure 5c). The differences in soil loss were significant for soils with different condition (F = 53.3; $p < 0.001$), slope (F = 6.99; $p = 0.001$) and interaction soil condition × slope (F = 2.86; $p = 0.027$).

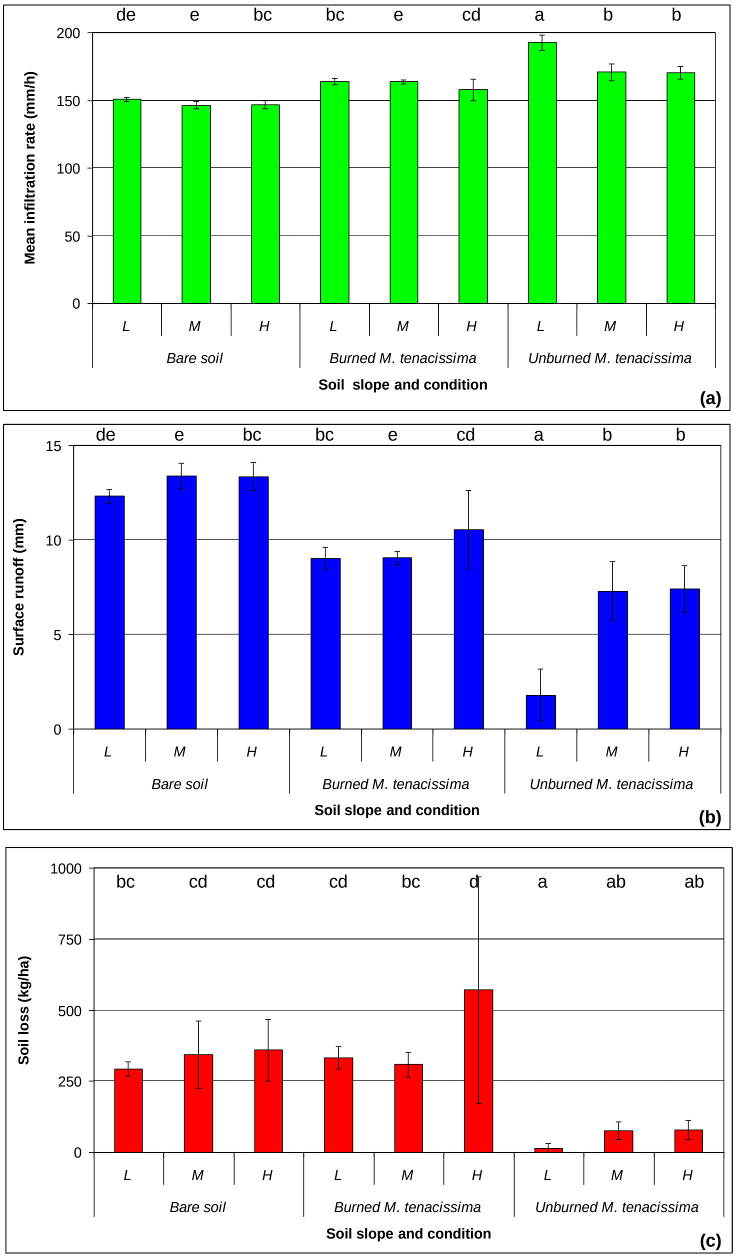

Figure 5 - Mean infiltration rate (a), surface runoff (b) and soil loss (c) (mean ± std. dev.) ~~measured~~observed by rainfall simulator under three soil conditions and slopes (L, < 20%; M, 20 to

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30%; H, > 30%) in Agramòn (Castilla La Mancha, Spain). Different letters indicate significant differences ($p < 0.001$).

~~It is interesting to notice that s~~Sediment concentration increased with runoff in soils with *M. tenacissima* (burned or not), as shown by the significant coefficients of correlation ($r^2 = 0.31$ and 0.68, $p < 0.05$ respectively). Also soil loss was significantly correlated with runoff for the same soil conditions ($r^2 = 0.61$, soils covered by *M. tenacissima*, and 0.84, soil with burned *M. tenacissima*, $p < 0.05$). The highest coefficients of correlation ($r^2 > 0.59$, soil with unburned *M. tenacissima*, with a peak of 0.93, bare soil) were found between sediment concentration and soil loss (Figure 6).

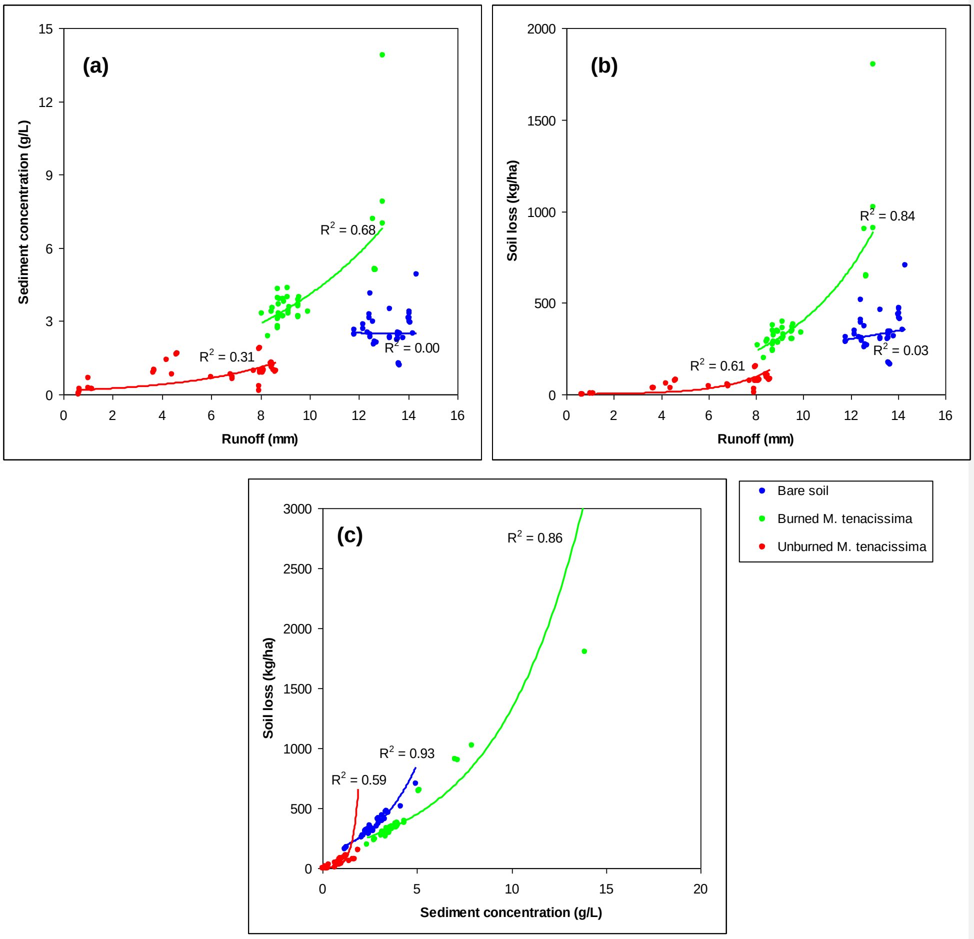

Figure 6 - Correlations among the hydrological variables ~~measured~~observed by rainfall simulator under three soil conditions and slopes (L, < 20%; M, 20 to 30%; H, > 30%) in Agramòn (Castilla La Mancha, Spain).

For milder and steeper slopes, peak flow was lower in soils with unburned *M. tenacissima* (43.2 and 72 mm/h in lower and higher slopes, respectively) and higher in bare soils (101, L slope, and 96, H, mm/h), while the highest peak flow was ~~measured~~observed in burned soils for medium slopes (110 mm/h) (Figure 7). In soils with lower and medium slopes, the times to peak were lower in areas with unburned *M. tenacissima* (120 s, L, and 210 s, M slope), and higher in bare areas (450 s, M, and 480 s, L), while, in steeper soils, the bare soils showed the lowest peak flow (180 s) and the soils with unburned values the highest (360 s) (Figure 7).

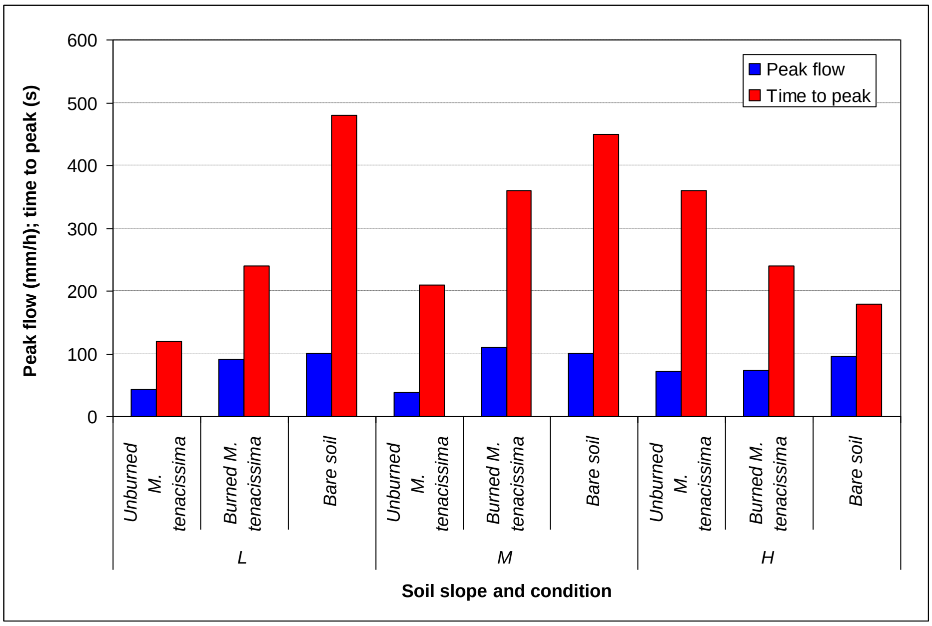

Figure 7 - Values of peak flow and time to peak measured by rainfall simulator under three soil conditions and slopes (L, slope < 20%; M, slope between 20 and 30%; H, slope > 30%) in Agramòn (Castilla La Mancha, Spain).

4. Discussion

Investigations about the hydrological response of soils covered by *Macrochloa* and affected by wildfire are important, considering the large extent of ~~rangelands~~forest dominated by this species and the large occurrence of fire in these areas. Infiltration did not follow a temporal decrease from the start of the rainfll simulation, but increased after the runoff peak. This is in accordance with Pierson et al. (2008), who explained that infiltration curves show minimum values levels near the rainfall onset; then, infiltration rates increases through the simulation, and these effects indicate incomplete water repellency, gradual wetting of the water repellent areas, and subsequent quick infiltration though preferential flow paths into wettable layers (DeBano, 1981).

This study has shown that infiltration rates are not highly variable among bare soils and areas covered by burned or unburned *M. tenacissima* (maximum variability equal to 20%). Moreover, infiltration did not appreciably vary among the different slopes under the same soil condition. Only an increase of 5-6% was observed in areas vegetated (burned or not) compared to bare soils, while ~~differences in infiltration~~ up to 40% differences in infiltration were found between burned and unburned soils of sagebrush ecosystems ~~were found~~ by (Pierson et al., 2008). The lower infiltration rates of burned areas in comparison to unburned soils are in accordance with many studies, which have demonstrated the decrease in soil hydraulic conductivity due to fire effects (Certini, 2005; Plaza-Álvarez et al., 2019; Zavala et al., 2014).

Since the ~~OM~~ organic matter content in unburned soil is even lower compared to the burned areas, the soil texture is the same, and the root system was not affected by fire, other soil properties may have influenced the infiltration capacity of soils, such as the aggregate stability, porosity, ash, soil water repellency (Lucas-Borja et al., 2019; Pereira et al., 2018). Some of these soil properties were not measured in this study, since we focused on~~the attention was paid to~~ the soil's hydrological effects of burning and vegetation rather than to the causes. Ash released by wildfire and post-fire repellency may alter the hydrological response of burned soils compared to unburned site. In short, ash may clogs soil pores and induce surface sealing (Keesstra et al., 2014) or, in contrast, can increase water adsorption before infiltration (Cerdà and Doerr, 2008). Soil water repellency generally reduces water infiltration through inducing hydrophobicity (Doerr et al., 2000; Pierson et al., 2008). Since the infiltration rates did not noticeably change between the three soil conditions (although being lower in burned and bare soils), it was revealed that ash did not affect or at least had a limited effect on infiltration (pore clogging or surface sealing) and adsorbed rainfall. For this reason, it was assumed that no repellency noticeably affected soil surface of burned areas, but this statement would require further investigation.

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In spite of the low variability of infitration, the hydrological response was significantly different among the studied soil conditions and,~~. I~~in general, the experiment ~~has demonstrated~~demonstrates that ~~higher~~ runoff volumes are higher ~~are observed~~ when water infiltration decreases. In runoff generation mechanism, the effects of ~~the other water losses, such as~~ interception and ~~, secondarily at the event scale,~~ evapo-transpiration, must be considered. Moreover, the presence of shrub species, such as *M. tenacissima*, also affects the runoff rate, since its epigeal part slowdowns the velocity of the water stream compared to the bare soil. In the latter soil condition, the absence of vegetation makes the soil susceptible to raindrop impact and sediment entrainment by overland flow (Shakesby and Doerr, 2006).

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In our experiments, ~~in comparison to the bare soil~~, the burned area (previously vegetated with *M. tenacissima*) ~~produced a~~ reduced runoff volume ~~lower~~ by 27% compared to the bare soil, while, in the area covered by the same species but ~~not b~~unburned, ~~the~~ runoff was lower by 58%. This significant reduction is clearly due to the presence of vegetation on soil with the implication of two important hydrological losses. First and mainly, vegetation intercepts by its epigeal system part of the precipitation. Wildfire removes vegetation and litter cover, thus altering key variables in the hydrological cycle; this effect temporarily reduces or blocks evapotranspiration, interception and soil storage capacity for rainfall (Shakesby and Doerr, 2006). The amount of interception can be estimated as the difference of runoff measured between the bare soil (without vegetal cover) and the unburned area (where the epigeal system of *M. tenacissima* is intact). This amount is in the range 11.9% (steeper soil) to 21% (lower slope) of the total precipitation. ~~Itis interesting to notice that Interestingly~~Remarkably, ~~also the burned plants,~~ despite having the canopy partly removed by fire, the burned plants were ~~are~~ able to reduce runoff with interception values from 5.6% (steeper soil) to 8.7% (medium slope) of the total rainfall. Interception of rainfall by burned surfaces of plants tends to increase the size of water drops, which often fall on bare soil and enhance the rainsplash detachment of soil particles (McNabb and Swanson, 1990; Shakesby and Doerr, 2006). Secondly, the vegetated areas showed a higher hydraulic conductivity compared to bare soils, and this increased the water loss by infiltration, reducing the runoff rates. This means that, in fire-affected areas, the presence of burned plants is beneficial to reduce the overland flow after precipitation. The increase in runoff with slope is expected (+35% and +29% in soils with high and medium slope compared to gentler profiles, respectively). Pierson et al. (2001) reported decreases in runoff in burned ~~rangelands~~forest dominated by sagebrush compared to unburned areas, presumably due to the relatively higher infiltration determined by fire. In our study, no significant correlation was observed between runoff volume and soil profile ($r^2 < 0.15$), except in soils with unburned *M. tenacissima* ($r^2 = 0.66$, $p < 0.05$) (data not shown).

Regarding erosion, we ~~have~~ found that the burned areas showed lower runoff than bare soil, but similar soil losses~~. This~~ which indicates that the sediment concentration in the runoff from the burned areas is higher than in bare soil. This increase in sediment concentration in the burned soils may be due to several effects of wildfire, such as the decrease in aggregate stability (in turn linked to the depletion in soil organic matter) that is typical of wildfire-affected areas, which favours sediment detachment and therefore erosion. The vegetation cover was able to reduce erosion only in unburned zones. In contrast, in burned areas covered by *M. tenacissima*, the erosion rates were ~~even~~ similar ~~as~~ to those ~~measured~~ found in bare soils, and, in steeper slopes, even higher. In more detail, compared to the bare soils, the amount of sediments detached from soils covered by *M. tenacissima* and ~~not~~ unburned was ~~on average~~ lower by 83% on average, while, in areas with burned plants, an increase ~~by~~ of 22% was observed~~, and this increase was significant~~. The precipitation simulated in this study can be considered as an extremely erosive event with return interval of many years. Therefore, the erosion rates measured in the experimental areas are below the tolerance limit for agricultural areas (about 10-12 tons/ha-year) (Bazzoffi, 2009; Wischmeier, 1978). The use of a small portable rainfall simulator underestimates rainsplash erosion, due to the lower kinetic energy of the simulated precipitation compared to a natural rainfall with an equal intensity, and does not allow the evaluation of runoff detachment and sediment connectivity at a larger scale. However, the difference between the tolerance limits and the experimental values (up to 570 kg/ha) is too high to make unrealistic this rough comparison. Moreover, the erosive processes in grasslands and shrublands, such as the areas covered by *M. tenacissima*, are generally due to relatively low-to-moderate burn severity of wildfires (Stavi, 2019). Therefore, the erodibility of fire-affected grasslands and shrublands is lower compared to woodlands or forests (Morris et al., 2014).

However, the control of these soil losses is suggested, since, as ~~well known,~~ erosion without mitigation actions may cause severe on-site and off-site effects. This is particularly important in steeper soil profiles, where erosion may be higher by more than 50% compared to lower slopes, as found in this investigation, although no correlations ($r^2 < 0.39$) were found between sediment concentration or soil loss on one side, and runoff on the other side (data not shown). In contrast, we found that soil loss significantly increased with sediment concentration following exponential trends. Rainsplash is the only erosive process measured in rainfall simulation experiments, which ~~instead~~ does not consider soil detachment by overland flow and thus rill and inter-rill erosion. Since the difference in the erosion rates among the different soil conditions and slopes were higher compared to the corresponding differences detected for runoff, we think that the soil loss occurring at larger spatial scales (plot or hillslope) may be even higher than the values measured in this investigation, and this requires deeper investigation in field.

Peak flow and time to peak are other important parameters in soil hydrology, since they govern the flood formation (maximum discharge and concentration times at the watershed scale) in valley areas downstream of the zones, where runoff originates (Neary et al., 1999; Certini, 2005; Shakesby and Doerr, 2006; Cawson et al., 2012; Zema, 2021). The analysis of the soil's hydrological response performed by the rainfall simulation has shown that both these parameters followed the gradient soil with unburned *M. tenacissima* < burned soil with *M. tenacissima* < bare soil, except at the higher slopes, where the times to peak were higher in unburned soils with *M. tenacissima*, and decreased in vegetated and burned areas, and bare soils. Fire tends to destroy obstacles, which reduces water storage and increase the erosive power of overland flow, occurring more readily on the soil surface (Shakesby and Doerr, 2006), although the small scale of our experiment did not allow to observe this effect. The decrease in peak flow in soils with increasing vegetation cover is expected, due to the beneficial effects on soil hydrology under dead or living vegetation (e.g., Cerdà and Doerr, 2008; Prats et al., 2012) and to the increasing infiltration rates. In contrast, Pierson et al. (2002) did not found significant differences in peak flows generating in burned and unburned soils covered by sagebrush. Also the decrease in time to peak along the mentioned gradient, detected in this experiment in steeper soils, may be attributable to the combined effects of vegetation, which increases the travel times of water stream on soil surface, and water infiltration, which leads to delayed runoff formation (Zhao et al., 2016). In contrast, the increases in time to peak in bare and burned soils measured in this study may be surprising. We have ascribed this unexpected result to the significantly higher presence of pebbles and small cobbles over ground under these soil conditions (which were instead absent in steeper slopes), which have reduced the water flow velocity and thus increased the time to peak. Reductions in times to peak in burned and steep ~~rangelands~~forest compared to unburned areas were reported also by Pierson et al. (2001).

In terms of land management, to reduce the wildfire risk and, at the same time, ~~to~~ limit the hydrological impacts of fires, this investigation suggests the establishment of vegetation strips of *M. tenacissima* in large and steep drylands with bare soil left by fire. These strips are able to reduce the spatial connectivity for sediment flows, while the bare areas limit the fire spreading fromone land unit to another, and facilitate fire-fighting actions (Stavi, 2019).

5. Conclusions

This study has evaluated infiltration, runoff and erosion in semi-arid lands covered by *M. tenacissima* (affected by wildfire and unburned) with different soil slopes in comparison to bare soils after simulated rainfalls.

Infiltration rates did not noticeably vary among the three soil conditions, which contrasts the first of our working hypothesis.

In contrast, the second hypothesis of this study is confirmed, since the runoff and erosive response under the different soil conditions and slopes was significantly variable. Compared to the bare soil and burned sites, the unburned areas with *M. tenacissima* generated noticeably lower runoff volumes. Peak flows increased along the gradient soil with unburned *M. tenacissima* < burned soil with *M. tenacissima* < bare soil, except at the higher slopes. Moreover, the vegetation cover was able to reduce erosion only in unburned zones.

The burned areas with *M. tenacissima* produced soil losses that are similar as those measured in bare soils, and, in steeper slopes, also higher, as thought by our third working hypothesis. However, the measured soil losses are not able to produce untolerable erosion rates. Nevertheless, the control of erosion in these semi-arid lands is beneficial, to reduce the possible hydrological effects downstream of these fire-prone areas, and, in this direction, the establishment of vegetation strips of *M. tenacissima* in large and steep drylands with bare soil left by fire may be suggested to land managers.

It should be highlighted that the approach followed in this study in which we use a rainfall simulator, focuses on a local spatial scale,~~use of a rainfall simulator has forced to adopt a local spatial scale in this study, suggesting an~~ with the evaluation of the hydrological variables point by point. This may be one of the limitations of ~~the~~ studies based on portable rainfall simulators, and therefore further research is needed ~~with~~ at field scale ~~extension~~ extending to plots or hillslopes. This extension would also allow the evaluation of the effects on the hydraulic connectivity of the area. Moreover, the rainfall simulations have been carried out at a constant intensity and using a low fall height which~~and these factors~~ do not allow considering the time variability and the effects of high kinetic energy of natural rainfalls. A monitoring study at the plot scale and under natural precipitation may give more insight about the role of the investigated species in controlling erosion on large ~~rangelands~~forest subjected to the wildfire risk.

~~Overall~~Nevertheless, the results of this study go beyond the local case study, since it has been demonstrated that an increased vegetation cover of native species (such as *M. tenacissima* in the Mediterranean Coasts of the Iberian Peninsula and Northern Africa) may reduce the hydrological response of large landscapes affected by the wildfire risk in ~~the~~ semi-arid areas. ~~Once verified the hydrological effectiveness of the other native species in the specific environmental context, the relevant studies may support the actions of land managers in controlling the hydrology of burned areas.~~

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Short-term hydrological response of soil after wildfire in a semi-arid landscape covered by *Macrochloa tenacissima* (L.) Kunth

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Abstract

A proper monitoring and management of semi-arid landscapes affected by wildfire is needed to reduce its effects on the soil hydrological response in the wet season. Despite ample literature on the post-fire hydrology in forest soils, it is not well documented how the hydrologic processes respond to changes in vegetation cover and soil properties of semi-arid lands (such as the forest and areas with sparse forests) after wildfire. To fill this gap, this study evaluates soil hydrology in a semi-arid soil of Central Eastern Spain dominated by *Macrochloa tenacissima* (a widely-spread species in Northern Africa and Iberian Peninsula) after a wildfire. Rainfall simulations were carried out under three soil conditions (bare soil, burned and soils with unburned vegetation) and low-to-high slopes, and infiltration, surface runoff and erosion were measured. Infiltration rates did not noticeably vary among the three soil conditions (maximum variability equal to 20%). Compared to the bare soil, the burned area (previously vegetated with *M. tenacissima*) produced a runoff volume lowered by 27%. In contrast, in the area covered by the same species but unburned, runoff was lowered by 58%. The burned areas with *M. tenacissima* produced soil losses that were similar as those measured in bare soils, and, in steeper slopes, even higher. Erosion was instead much lower (-83%) in the sites with unburned vegetation. Overall, the control of erosion in these semi-arid lands is beneficial to reduce the possible hydrological effects downstream of these fire-prone areas. In this direction, the establishment of vegetation strips of *M. tenacissima* in large and steep drylands of bare soil left by fire may be suggested to land managers.

Keywords: water infiltration; bare soil; runoff; soil loss; rainfall simulator.

Highlights:

- Soil hydrology in a semi-arid soils dominated by *Macrochloa tenacissima* is evaluated
- Infiltration rates did not noticeably vary among soils
- Compared to bare soils, runoff decreased in both burned and unburned sites
- Erosion was similar in bare and burned soils, and lower in unburned sites
- *M. tenacissima* strips in drylands are suggested as post-fire management

1. Introduction

Fire risk is particularly high in semi-arid and arid climates, where hot and dry summers increase the frequency and occurrence of wildfire many months per year (Stavi, 2019). In many areas, post-fire regeneration of forest vegetation is slow, due to the water scarcity and the intrinsic properties of soils (generally shallow, with low aggregate stability, and poor in organic matter and nutrients) (Cantón et al., 2011). Moreover, the increase in mean temperature and reduction in precipitation that are forecasted by the future scenarios of climate change (Collins et al., 2013) will aggravate the fire risk and damage.

Wildfire is a major ecological process in forests and forest (Pierson et al., 2001), and its impacts affect several ecosystem compontents (air, water, soil, plants, fauna) (DeBano et al., 1998; Lucas-Borja et al., 2019). The impacts of natural or fraudulent wildfires on soils and water cause many hydrological and geomorphological changes in the landscape, both in the short and long period (Shakesby and Doerr, 2006). After a wildfire, vegetation and litter are totally removed, leaving the ground surface exposed to rainsplash. Moreover, several soil properties change with effects lasting also several years, especially due to hydrophobicity and reduction in aggregate stability (Glenn and Finley, 2010; Zema, 2021). All these changes heavily modify the hydrological response of burned soil compared to the unburned areas, with implications for infiltration, overland flow and erosion (Shakesby and Doerr, 2006). It has been demonstrated that runoff and erosion rates may increase by some orders of magnitude even after fires of low severity, such as the prescribed fire (Cawson et al., 2012). These increases may lead to hazardous floods and unsustainable erosion both inside the fire-affected zones and in the valley areas high runoff and erosion rates lead to heavy environmental onsite (e.g. soil loss, landslides) and off-site impacts (e.g. flooding, transport of polluting compounds, damage of urban infrastructures) (Lucas-Borja et al., 2020; Prats et al., 2015; Zema et al., 2021a).

A proper control of soil hydrology is needed to reduce the wildfire effects on the forest ecosystems of arid and semi-arid areas. Water infiltration is a key parameter to govern the hydrological response of burned soils in Mediterranean semi-arid ecosystems, since the hydrological processes generating runoff and erosion are dominated by the infiltration-excess mechanism (Lucas-Borja et al., 2018). Therefore, a deep understanding of water infiltration is essential, since the hydraulic conductivity of Mediterranean soils can be extremely low (Doerr et al., 2003; Zema et al., 2021b). Low infiltration produces non-tolerable rates of surface runoff and soil erosion (Robichaud and Waldrop, 1994; Zema et al., 2020b; 2020a), if rainfall exceeds the surface retention of soil infiltration-excess (Doerr et al., 2000). Fire can further decrease water infiltration, due to soil water repellency, which very often affects the semi-arid soils (Alcañiz et al., 2018; Cawson et al., 2016; Zema et al., 2021b). Therefore, the analyis of soil's hydrological parameters (infiltration, runoff, peak flow, soil loss) is basic to provide a detailed knowledge on how to control and mitigate the hydrological risks and other environmental hazards in semi-arid environments (Moody et al., 2013; Shakesby, 2011).

Ample literature is available on the hydrological effects of fires atdifferent severity on forest soils (e.g. Alcañiz et al., 2018; Certini, 2005; Zavala et al., 2014). However, few studies have examined the wildfire impacts on forest hydrology, and it is not well documented how hydrological processes (infiltration, runoff and erosion) respond to changes in vegetation cover and soil properties after wildfire (Pierson et al., 2001). Moreover, there is an emphasis on case studies in Northern America, while much less attention has been paid to other environments, such as the landscapes of the Mediterranean Basin under semi-arid Mediterranean conditions (Shakesby and Doerr, 2006). Here, many forest are covered by shrubs and grass, such as *Macrochloa tenacissima* (L.) Kunth (hereinafter *M. tenacissima*), especially in Northern Africa and Iberian Peninsula. To the authors' best knowledge, the hydrological response of soil affected by wildfire has not been evaluated in these areas, and comparisons with vegetated and unburned areas and bare soils still lack.

To fill these literature gaps, this study evaluates the hydrological response of semi-arid soils dominated by *M. tenacissima*to wildfire in a landscape of Central Eastern Spain using a rainfall simulator. Three soil conditions are considered (i, bare soil, assumed as reference; ii, burned soils with *M. tenacissima*, and iii, unburned soil with the same species), in order to evaluate how infiltration, runoff, peak flow and erosion rates are modified by fire and vegetation. We hypothesize that in these semi-arid areas covered by *M. tenacissima*: (i) fire reduces infiltration compared to unburned areas; (ii) runoff and erosion are higher in bare soils, and decrease in areas covered with *M.*

tenacissima; (iii) the hydrological response in areas dominated by *M. tenacissima* and affected by fire is more similar to that of the bare soil areas than the response of unburned areas. The results of this investigation may give landscape planners insight on suitable practices towards mitigation of flood and erosion risks in fire-affected areas of the semi-arid environment.

2. Materials and methods

2.1. Study area

The field experiments were carried out in a rural landscape with sparse forests close to Agramón (geographical coordinates 38.42188N, -1.63747E, province of Albacete, Castilla-La Mancha, Spain) (Figure 1). The area elevation ranges between 520 and 770 m, and the study sites have west or southwest aspects. The climate is semi-arid and its type can be classified as “BSk” according to the Köppen classification (Kottek et al., 2006). The mean annual temperature and precipitation are 16.6°C and 321 mm, respectively. Soils are classified as *Calcid Aridisols* and have a silt loam texture (USDA, 1999) (Table 1).

In July 2020, a wildfire burned a forest area. The mean value of the soil burn severity was estimated using the methodology proposed by (Vega et al., 2013). Two weeks after the wildfire, a burned forest area of about 1 km^2 was selected. In this area, crown fire resulted in 100% tree mortality. Wildfire severity was evaluated as higher according to the regional forest service. Before the wildfire, the stand density ranged from 500-650 trees/ha with tree heights between 7 and 14 m. The dominant overstory vegetation consisted of Aleppo pine *(Pinus halepensis* Mill.). Additional understory vegetation was mainly *Macrochloa tenacissima* (L.) Kunth. To a lesser extent, other vegetal species were *Rosmarinus officinalis* L., *Brachypodium retusum* (Pers.) Beauv., and *Thymus vulgaris* L.

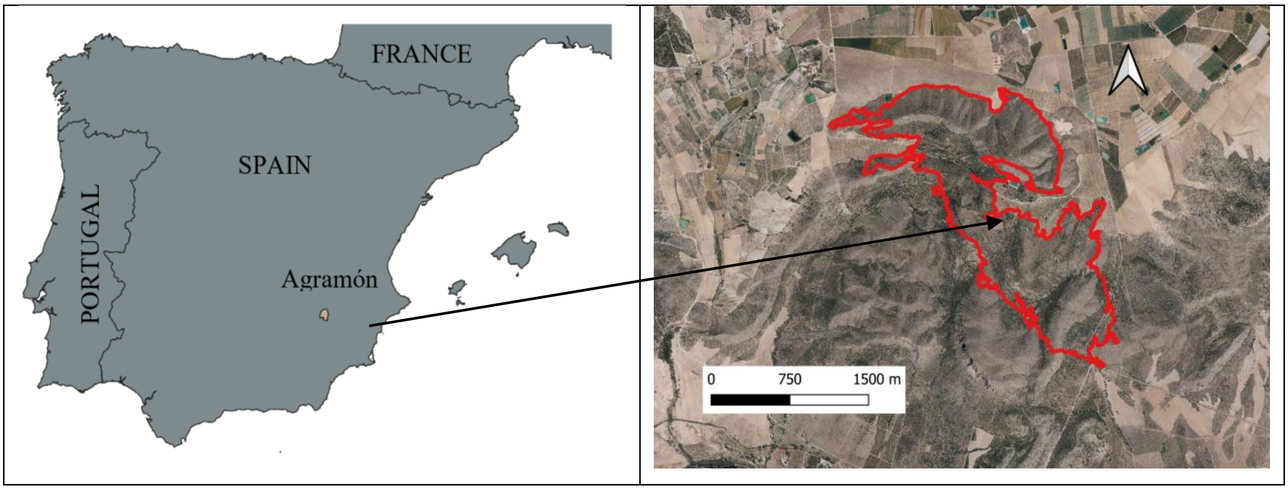

Figure 1 – Geographical location of the study area (Agramòn, Castilla La Mancha, Spain) (a), and rainfall simulations carried out underthree experimental soil conditions (unburned*M. tenacissima* - left, burned *M. tenacissima* – center, and bare soil - right) (b).

Table 1 – Mean values (± standard errors) of texture, organic matter content and surface covers of the experimental soils (Agramòn, Castilla La Mancha, Spain).

Soil condition	**Soil texture (% content)**			**Organic matter content (%)**	**Soil surface cover (%)**				
	Sand	**Silt**	**Clay**		**Plants**	**Dead matter**	**Ash**	**Rock**	**Bare soil**
Bare soil	26.3 ± 1.56 a	59.4 ± 1.23 a	14.3 ± 0.57 a	2.88 ± 0.04 a	0 a	2.0 ± 0.59 a	0 a	70.5 ± 6.06 a	17.5 ± 3.67 a
Burned *M. tenacissima*	31.7 ± 1.55 a	55.5 ± 0.78 a	12.8 ± 1.90 a	5.13 ± 0.21 b	0 a	0 b	85.0 ± 7.97 b	13.5 ± 2.21 b	1.50 ± 0.91 b
Unburned *M. tenacissima*	30.2 ± 2.82 a	51.2 ± 1.08 a	18.5 ± 2.27 a	2.35 ± 0.27 a	91.2 ± 5.55 b	0 b	0 a	5.50 ± 0.72 c	3.48 ± 0.27 c

Note: different letters indicate significant differences ($p < 0.05$).

2.2. *Experimental design for rainfall simulations and hydrological monitoring*

In the burned forest, a site of about 5 ha was selected. The experimental design consisted of three soil conditions (bare soil, unburned and burned *M. tenacissima*) × three slopes (L, low slope,< 20%, M, medium slope, between 20% and 30%, and H, high slope, > 30%). The distance between the areas with different soil conditions was lower than 250 m.

For each slope and soil condition, rainfall was simulated in small areas randomly chosen. Eight, 10 and 22 simulations were carried out in bare soils, four, 18 and 18 again in burned *M. tenacissima*, and 12, 24 and 4 in unburned *M. tenacissima*, for slopes < 20%, between 20% and 30%, and > 30%, respectively. An Eijelkamp® rainfall simulator was used (Hlavčová et al., 2019; Iserloh et al., 2013), following the methods by Bombino et al. (2019) and Carrà et al. (2021). The device was gently placed over the ground, caring that the vegetation was not disturbed by this operation. A rainfall with a height and intensity of 50 mm and 200 mm/h was simulated over a surface area of 0.3 m x 0.3 m. These characteristics relate to precipitation with 10-year return interval in the area. The drop diameter was 5.9 mm and the falling height was 40 cm from the ground. The simulator was calibrated prior to the simulation campaign by generating the same rainfall as the field experiments. The water volume in the sprinkler tank (about 2.2 litres) was dosed by varying the pressure head, as suggested in the operating manual. During each rainfall simulation (15 min), the runoff water and sediments were collected in a small graduated bucket and then measured. The mean infiltration rate was calculated as the difference between the rainfall height and runoff divided by the duration.

Moreover, the infiltration curves of one point for each soil condition and slope were determined by subtracting the runoff generated by the rainfall at each time interval. The runoff height in the bucket was read each 30 s and subtracted from the rainfall height at the same time. The peak flow and time to peak - the time measured from the rainfall start to the peak flow occurrence - were identified in the hydrograph.

2.3. *Sampling and analyses of properties and covers of soils*

Nine soil samples (600 g each) were collected from the sites under each soil condition. The samples were composed of six sub-samples collected from randomly selected locations in each soil condition, to capture the soil spatial variability. Each sub-sample was gently excavated from the topsoil (-5 cm) after removing the litter layer. Then, the sample was passed through a 2 mm sieve and stored at 4º C until the subsequent analyses conducted in the following day. On the composite sample, the soil texture was estimated after sieving and the application of the hydrometer method. Moreover, the organic matter content (OM, %) was determined using the potassium dichromate oxidation method (Nelson and Sommers, 1996).

Finally, in the sites under the three soil conditions, where the rainfall simulations were carried out, the following soil covers were measured: plants, rock fragments, dead matter, ash and bare soil (in areal percentage). The grid method (Vogel and Masters, 2001) for plant cover and bare soil, and the photographic method for the remaining variables were used. The grid method was applied, using a 0.50 x 0.50-m grid square on the sampling areas.

2.4. *Statistical analysis*

The statistical significance of the differences among soil conditions and slopes, and their interactions, was calculated using a 2-way ANOVA for surface runoff and soil loss. The latter were considered as dependent variables, while the soil condition and slope were the independent factors. The pairwise comparison by Tukey's test (at $p < 0.05$) was also used to evaluate the statistical significance of the differences in the two hydrological variables among factors. In order to satisfy the assumptions of the statistical tests (equality of variance and normal distribution), the data were subjected to a normality test or were square root-transformed whenever necessary. The statistical analysis was carried out using the XLSTAT software (release 2019, Addinsoft, Paris, France).

3. Results

The hydrographs generated by the rainfall simulation experiments are illustrated in Figures 2 to 4. These hydrographs depict the time variability of the infiltration and runoff rates under a constant rainfall intensity on soils with different soil conditions (unburned and burned *M. tenacissima*, and bare soil) and slopes (low, medium, high). The infiltration rate started from a value equal to the rainfall intensity, which means that initially all precipitation infiltrated. When soil progressively saturated, the infiltration rate decreased and runoff began (Figure 2a, 2b and 2c). After the minimum value of the infiltration rate, corresponding to the peak flow, runoff decreased and, for some soil conditions and slopes (unburned *M. tenacissima* with low and high slopes, bare soil with medium slope, and burned M. tenacissima with high slope), depleted at the end of the rainfall simulation (Figures 2, 3 and 4).

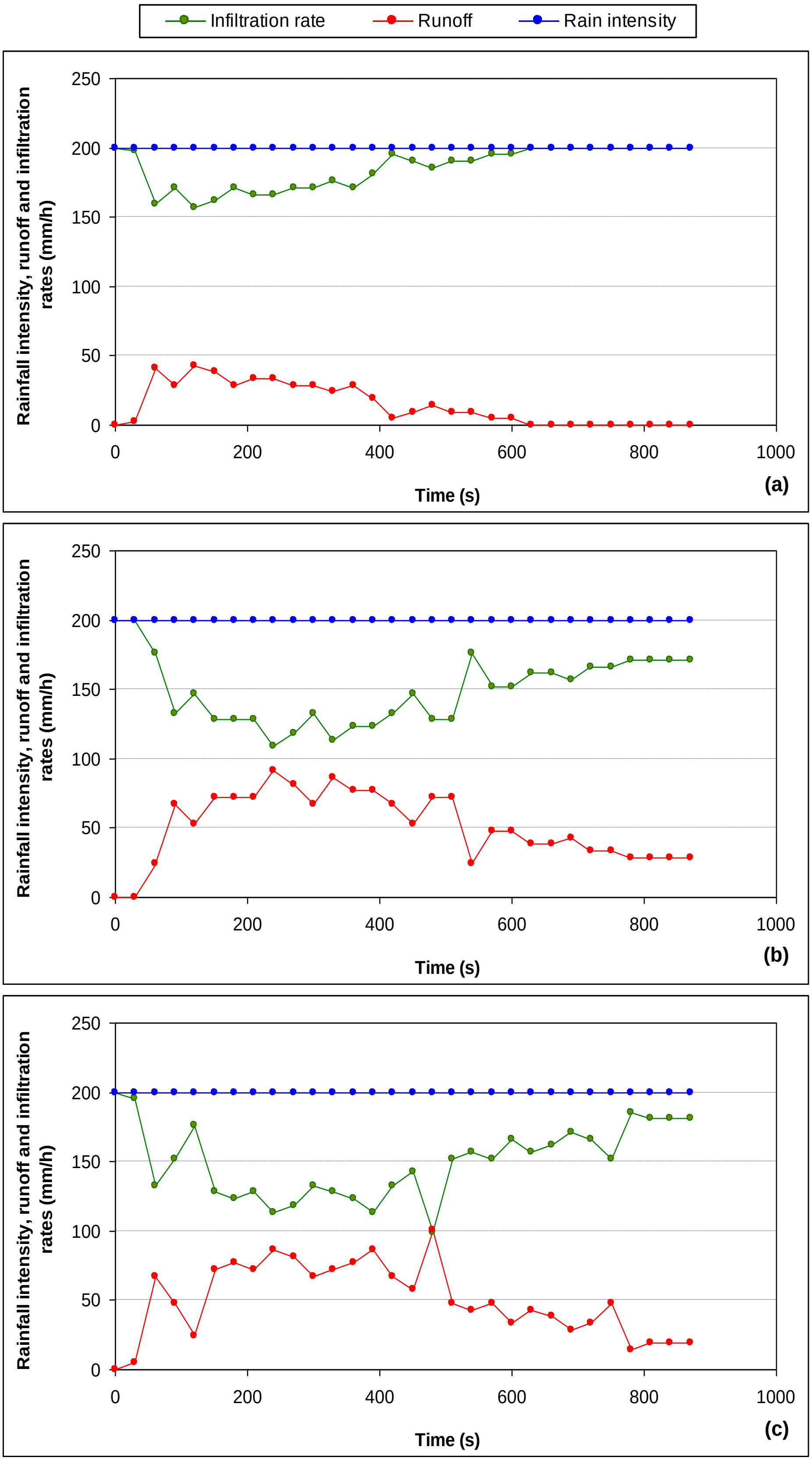

Figure 2 - Hydrological variables (rainfall intensity, and runoff and infiltration rates) measured by rainfall simulator under three soil conditions (a, unburned *M. tenacissima*; b, burned *M. tenacissima*; c, bare soil) and low slope (< 20%) in Agramòn (Castilla La Mancha, Spain).

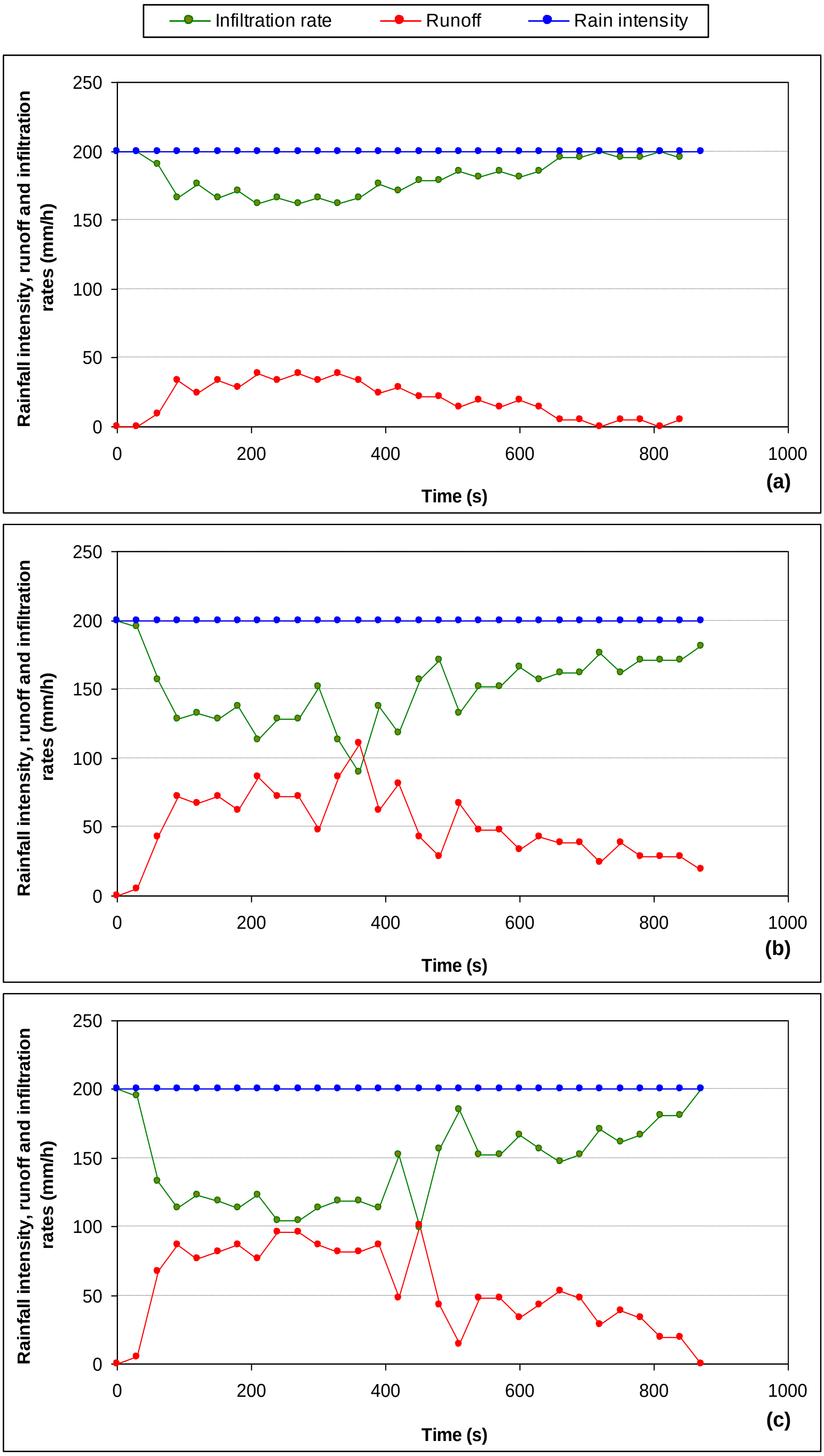

Figure 3 - Hydrological variables (rainfall intensity, and runoff and infiltration rates) measured by rainfall simulator under three soil conditions (a, unburned *M. tenacissima*; b, burned *M. tenacissima*; c, bare soil) and medium slope (20 to 30%) in Agramòn (Castilla La Mancha, Spain).

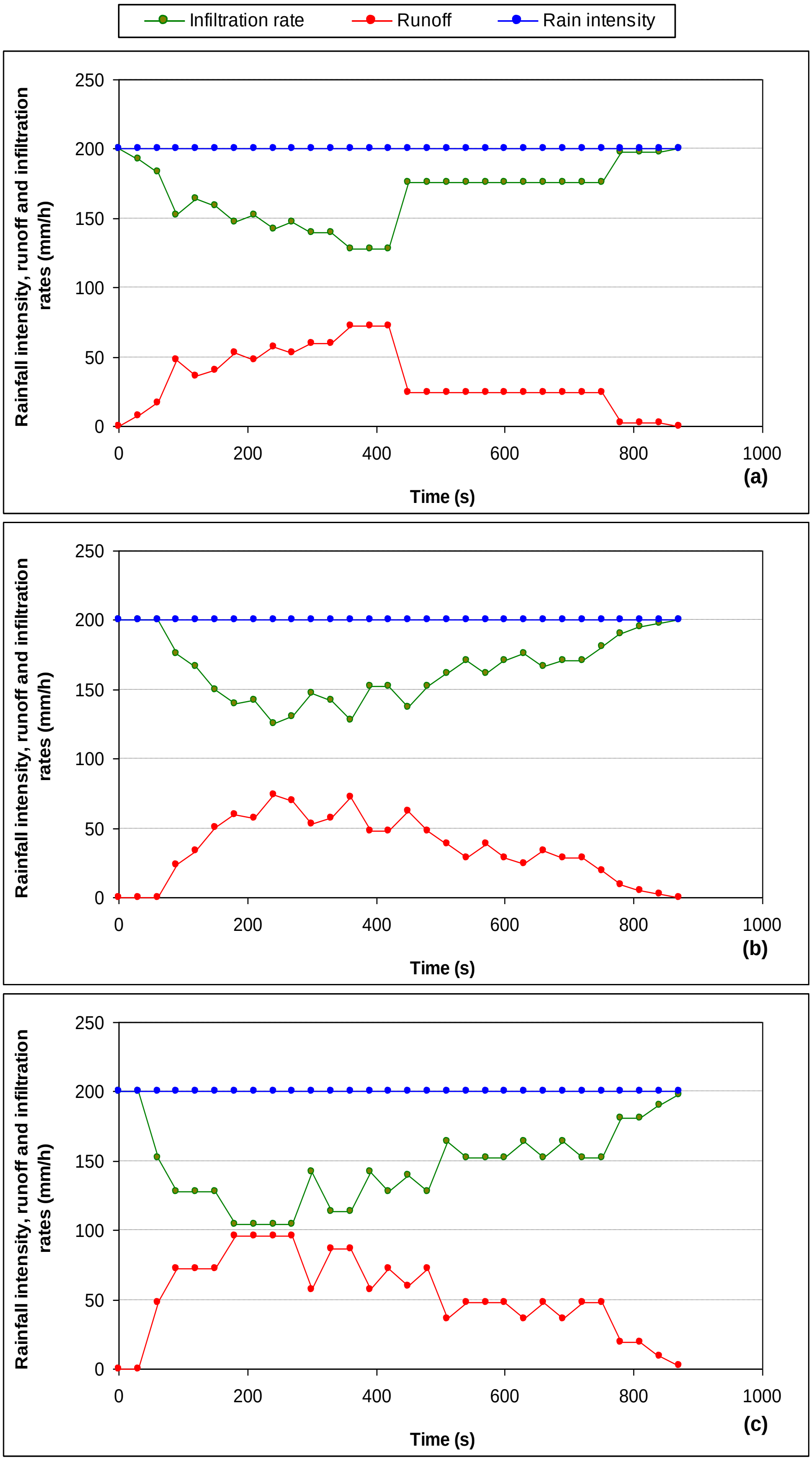

Figure 4 - Hydrological variables (rainfall intensity, and runoff and infiltration rates) measured by rainfall simulator under three soil conditions (a, unburned *M. tenacissima*; b, burned *M. tenacissima*; c, bare soil) and high slope (> 30%) in Agramòn (Castilla La Mancha, Spain).

ANOVA showed that the surface runoff measured by the rainfall simulator was significantly different among the three soil conditions (F = 364; p < 0.001), slopes (F = 55.2; p < 0.001), and their interactions (F = 18.5; p < 0.0001). In more detail, the highest runoff was observed in bare soil (13.0 ± 0.59 mm, value averaged among the three soil slopes), and the minimum in the unburned soils (5.51 ± 1.38 mm), while the soils with burned *M. tenacissima* produced intermediate runoff (9.55 ± 1.01 mm). The runoff increased with soil slope, and the highest and lowest volumes were observed in steeper soils (10.4 ± 1.34 mm, values averaged by soil condition) and lower slopes (7.71 ± 0.79 mm) (Figure 5b).

Regarding infiltration, the bare soil showed the lowest value (148 ± 2.37 mm/h, averaged by slope), while the highest rate was observed in unburned soils (178 ± 5.53 mm/h). According to the soil slope, averaging the measured values by soil condition, the maximum infiltration rate was observed in the soils with lower slope (169 ± 3.14 mm/h), and the minimum in the steeper soils (158 ± 5.34 mm/h), although the areas with medium slope showed infiltration rates (160 ± 2.44 mm/h) similar as the latter (Figure 5a).

The highest erosion was observed in the soils with burned *M. tenacissima* (404 ± 160 kg/ha, value averaged by slope), and the lowest in unburned soils (56.1 ± 27.6 kg/ha). As for runoff, the highest and lowest soil losses, observed in steeper soil (336 ± 181 kg/ha) and soils with lower slope (213 ± 26.9 kg/ha) were expected, while erosion in soil profiles with medium slope (213 ± 26.9 kg/ha) was close to lower profiles (Figure 5c). The differences in soil loss were significant for soils with different condition (F = 53.3; p < 0.001), slope (F = 6.99; p = 0.001) and interaction soil condition × slope (F = 2.86; p = 0.027).

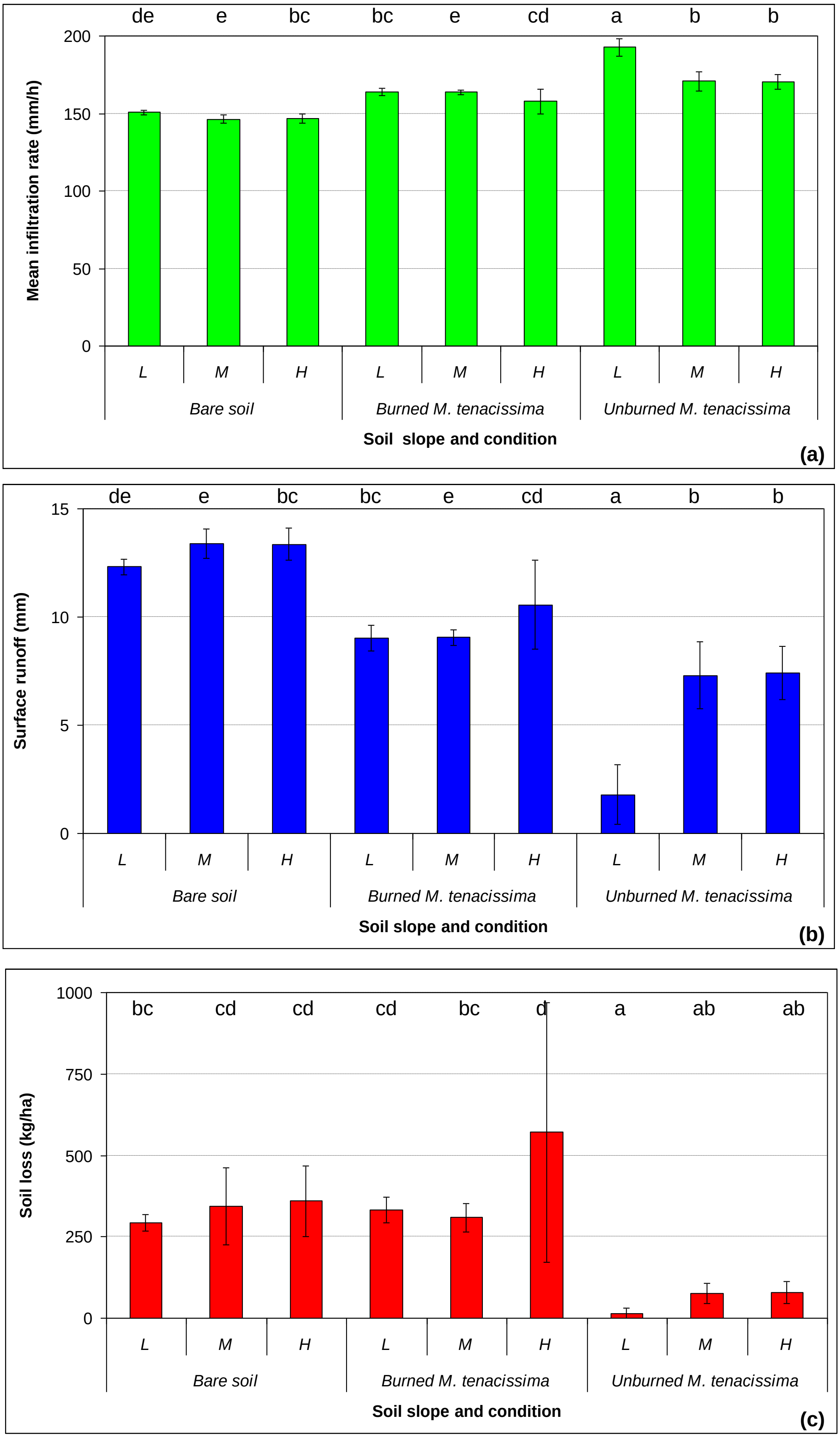

Figure 5 - Mean infiltration rate (a), surface runoff (b) and soil loss (c) (mean ± std. dev.) observed by rainfall simulator under three soil conditions and slopes (L, < 20%; M, 20 to 30%; H, > 30%) in Agramòn (Castilla La Mancha, Spain). Different letters indicate significant differences ($p < 0.001$).

Sediment concentration increased with runoff in soils with *M. tenacissima* (burned or not), as shown by the significant coefficients of correlation ($r^2 = 0.31$ and 0.68, $p < 0.05$ respectively). Also soil loss was significantly correlated with runoff for the same soil conditions ($r^2 = 0.61$, soils covered by *M. tenacissima*, and 0.84, soil with burned *M. tenacissima*, $p < 0.05$). The highest coefficients of correlation ($r^2 > 0.59$, soil with unburned *M. tenacissima*, with a peak of 0.93, bare soil) were found between sediment concentration and soil loss (Figure 6).

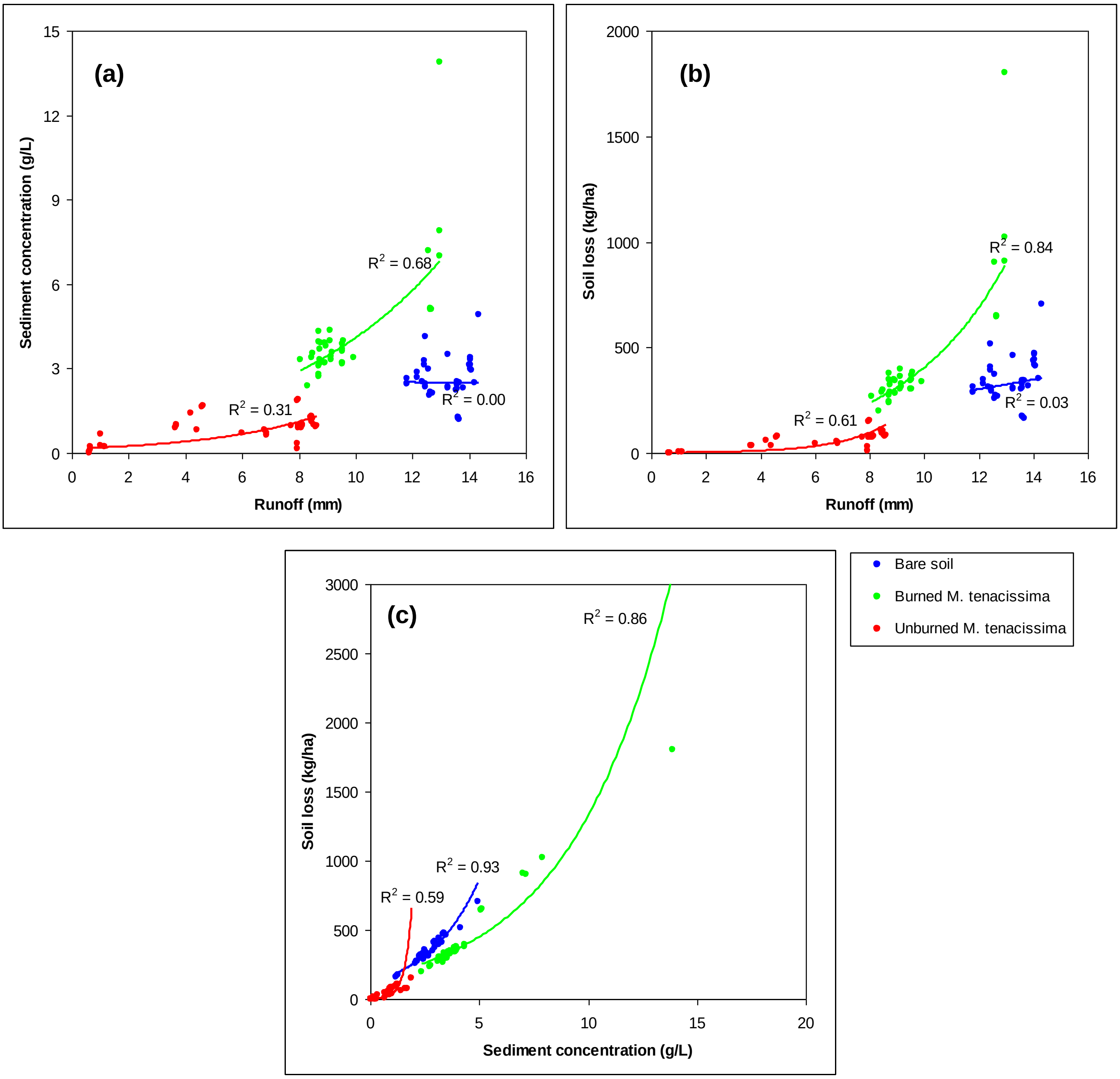

Figure 6 - Correlations among the hydrological variables observed by rainfall simulator under three soil conditions and slopes (L, < 20%; M, 20 to 30%; H, > 30%) in Agramòn (Castilla La Mancha, Spain).

For milder and steeper slopes, peak flow was lower in soils with unburned *M. tenacissima* (43.2 and 72 mm/h in lower and higher slopes, respectively) and higher in bare soils (101, L slope, and 96, H, mm/h), while the highest peak flow was observed in burned soils for medium slopes (110 mm/h) (Figure 7). In soils with lower and medium slopes, the times to peak were lower in areas with unburned *M. tenacissima* (120 s, L, and 210 s, M slope), and higher in bare areas (450 s, M, and 480 s, L), while, in steeper soils, the bare soils showed the lowest peak flow (180 s) and the soils with unburned values the highest (360 s) (Figure 7).

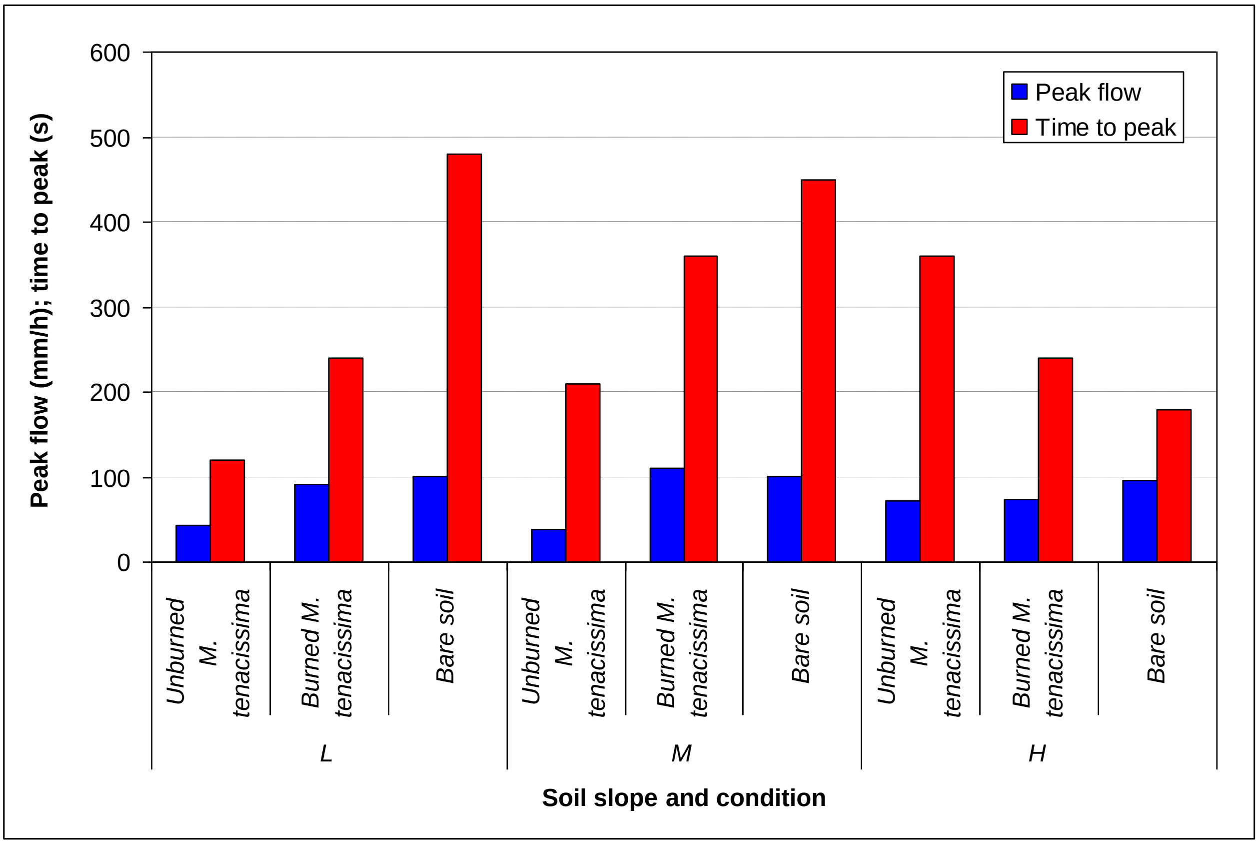

Figure 7 - Values of peak flow and time to peak measured by rainfall simulator under three soil conditions and slopes (L, slope < 20%; M, slope between 20 and 30%; H, slope > 30%) in Agramòn (Castilla La Mancha, Spain).

4. Discussion

Investigations about the hydrological response of soils covered by *Macrochloa* and affected by wildfire are important, considering the large extent of forest dominated by this species and the large occurrence of fire in these areas. Infiltration did not follow a temporal decrease from the start of the rainfll simulation, but increased after the runoff peak. This is in accordance with Pierson et al. (2008), who explained that infiltration curves show minimum values levels near the rainfall onset; then, infiltration rates increases through the simulation, and these effects indicate incomplete water repellency, gradual wetting of the water repellent areas, and subsequent quick infiltration though preferential flow paths into wettable layers (DeBano, 1981).

This study has shown that infiltration rates are not highly variable among bare soils and areas covered by burned or unburned *M. tenacissima* (maximum variability equal to 20%). Moreover, infiltration did not appreciably vary among the different slopes under the same soil condition. Only an increase of 5-6% was observed in areas vegetated (burned or not) compared to bare soils, while up to 40% differences in infiltration were found between burned and unburned soils of sagebrush ecosystems by (Pierson et al., 2008). The lower infiltration rates of burned areas in comparison to unburned soils are in accordance with many studies, which have demonstrated the decrease in soil hydraulic conductivity due to fire effects (Certini, 2005; Plaza-Álvarez et al., 2019; Zavala et al., 2014).

Since the organic matter content in unburned soil is even lower compared to the burned areas, the soil texture is the same, and the root system was not affected by fire, other soil properties may have influenced the infiltration capacity of soils, such as the aggregate stability, porosity, ash, soil water repellency (Lucas-Borja et al., 2019; Pereira et al., 2018). Some of these soil properties were not measured in this study, since we focused on the soil's hydrological effects of burning and vegetation rather than to the causes. Ash released by wildfire and post-fire repellency may alter the hydrological response of burned soils compared to unburned site. In short, ash may clogs soil pores and induce surface sealing (Keesstra et al., 2014) or, in contrast, can increase water adsorption before infiltration (Cerdà and Doerr, 2008). Soil water repellency generally reduces water infiltration through inducing hydrophobicity (Doerr et al., 2000; Pierson et al., 2008). Since the infiltration rates did not noticeably change between the three soil conditions (although being lower in burned and bare soils), it was revealed that ash did not affect or at least had a limited effect on infiltration (pore clogging or surface sealing) and adsorbed rainfall. For this reason, it was assumed that no repellency noticeably affected soil surface of burned areas, but this statement would require further investigation.

In spite of the low variability of infitration, the hydrological response was significantly different among the studied soil conditions and,in general, the experiment demonstrates that runoff volumes are higher when water infiltration decreases. In runoff generation mechanism, the effects of interception and evapo-transpiration, must be considered. Moreover, the presence of shrub species, such as *M. tenacissima*, also affects the runoff rate, since its epigeal part slowdowns the velocity of the water stream compared to the bare soil. In the latter soil condition, the absence of vegetation makes the soil susceptible to raindrop impact and sediment entrainment by overland flow (Shakesby and Doerr, 2006).

In our experiments, , the burned area (previously vegetated with *M. tenacissima*) reduced runoff volume by 27% compared to the bare soil, while, in the area covered by the same species but unurned, runoff was lower by 58%. This significant reduction is clearly due to the presence of vegetation on soil with the implication of two important hydrological losses. First and mainly, vegetation intercepts by its epigeal system part of the precipitation. Wildfire removes vegetation and litter cover, thus altering key variables in the hydrological cycle; this effect temporarily reduces or blocks evapotranspiration, interception and soil storage capacity for rainfall (Shakesby and Doerr, 2006). The amount of interception can be estimated as the difference of runoff measured between the bare soil (without vegetal cover) and the unburned area (where the epigeal system of *M. tenacissima* is intact). This amount is in the range 11.9% (steeper soil) to 21% (lower slope) of the total precipitation. Remarkably, despite having the canopy partly removed by fire, the burned plants were able to reduce runoff with interception values from 5.6% (steeper soil) to 8.7% (medium slope) of the total rainfall. Interception of rainfall by burned surfaces of plants tends to increase the size of water drops, which often fall on bare soil and enhance the rainsplash detachment of soil particles (McNabb and Swanson, 1990; Shakesby and Doerr, 2006). Secondly, the vegetated areas showed a higher hydraulic conductivity compared to bare soils, and this increased the water loss by infiltration, reducing the runoff rates. This means that, in fire-affected areas, the presence of burned plants is beneficial to reduce the overland flow after precipitation. The increase in runoff with slope is expected (+35% and +29% in soils with high and medium slope compared to gentler profiles, respectively). Pierson et al. (2001) reported decreases in runoff in burned forest dominated by sagebrush compared to unburned areas, presumably due to the relatively higher infiltration determined by fire. In our study, no significant correlation was observed between runoff volume and soil profile ($r^2 < 0.15$), except in soils with unburned *M. tenacissima* ($r^2 = 0.66$, $p < 0.05$) (data not shown).

Regarding erosion, we found that the burned areas showed lower runoff than bare soil, but similar soil losses which indicates that the sediment concentration in the runoff from the burned areas is higher than in bare soil. This increase in sediment concentration in the burned soils may be due to several effects of wildfire, such as the decrease in aggregate stability (in turn linked to the depletion in soil organic matter) that is typical of wildfire-affected areas, which favours sediment detachment and therefore erosion. The vegetation cover was able to reduce erosion only in unburned zones. In contrast, in burned areas covered by *M. tenacissima*, the erosion rates were similar to those found in bare soils, and, in steeper slopes, even higher. In more detail, compared to the bare soils, the amount of sediments detached from soils covered by *M. tenacissima* and unburned was lower by 83% on average, while, in areas with burned plants, an increase of 22% was observed.. The precipitation simulated in this study can be considered as an extremely erosive event with return interval of many years. Therefore, the erosion rates measured in the experimental areas are below the tolerance limit for agricultural areas (about 10-12 tons/ha-year) (Bazzoffi, 2009; Wischmeier, 1978). The use of a small portable rainfall simulator underestimates rainsplash erosion, due to the lower kinetic energy of the simulated precipitation compared to a natural rainfall with an equal intensity, and does not allow the evaluation of runoff detachment and sediment connectivity at a larger scale. However, the difference between the tolerance limits and the experimental values (up to 570 kg/ha) is too high to make unrealistic this rough comparison. Moreover, the erosive processes in grasslands and shrublands, such as the areas covered by *M. tenacissima,* are generally due to relatively low-to-moderate burn severity of wildfires (Stavi, 2019). Therefore, the erodibility of fire-affected grasslands and shrublands is lower compared to woodlands or forests (Morris et al., 2014).

However, the control of these soil losses is suggested, since, as erosion without mitigation actions may cause severe on-site and off-site effects. This is particularly important in steeper soil profiles, where erosion may be higher by more than 50% compared to lower slopes, as found in this investigation, although no correlations ($r^2 < 0.39$) were found between sediment concentration or soil loss on one side, and runoff on the other side (data not shown). In contrast, we found that soil loss significantly increased with sediment concentration following exponential trends. Rainsplash is the only erosive process measured in rainfall simulation experiments, which does not consider soil detachment by overland flow and thus rill and inter-rill erosion. Since the difference in the erosion rates among the different soil conditions and slopes were higher compared to the corresponding differences detected for runoff, we think that the soil loss occurring at larger spatial scales (plot or hillslope) may be even higher than the values measured in this investigation, and this requires deeper investigation in field.

Peak flow and time to peak are other important parameters in soil hydrology, since they govern the flood formation (maximum discharge and concentration times at the watershed scale) in valley areas downstream of the zones, where runoff originates (Neary et al., 1999; Certini, 2005; Shakesby and Doerr, 2006; Cawson et al., 2012; Zema, 2021). The analysis of the soil's hydrological response performed by the rainfall simulation has shown that both these parameters followed the gradient soil with unburned *M. tenacissima* < burned soil with *M. tenacissima* < bare soil, except at the higher slopes, where the times to peak were higher in unburned soils with *M. tenacissima*, and decreased in vegetated and burned areas, and bare soils. Fire tends to destroy obstacles, which reduces water storage and increase the erosive power of overland flow, occurring more readily on the soil surface (Shakesby and Doerr, 2006), although the small scale of our experiment did not allow to observe this effect. The decrease in peak flow in soils with increasing vegetation cover is expected, due to the beneficial effects on soil hydrology under dead or living vegetation (e.g., Cerdà and Doerr, 2008; Prats et al., 2012) and to the increasing infiltration rates. In contrast, Pierson et al. (2002) did not found significant differences in peak flows generating in burned and unburned soils covered by sagebrush. Also the decrease in time to peak along the mentioned gradient, detected in this experiment in steeper soils, may be attributable to the combined effects of vegetation, which increases the travel times of water stream on soil surface, and water infiltration, which leads to delayed runoff formation (Zhao et al., 2016). In contrast, the increases in time to peak in bare and burned soils measured in this study may be surprising. We have ascribed this unexpected result to the significantly higher presence of pebbles and small cobbles over ground under these soil conditions (which were instead absent in steeper slopes), which have reduced the water flow velocity and thus increased the time to peak. Reductions in times to peak in burned and steep forest compared to unburned areas were reported also by Pierson et al. (2001).

In terms of land management, to reduce the wildfire risk and, at the same time, limit the hydrological impacts of fires, this investigation suggests the establishment of vegetation strips of *M. tenacissima* in large and steep drylands with bare soil left by fire. These strips are able to reduce the spatial connectivity for sediment flows, while the bare areas limit the fire spreading fromone land unit to another, and facilitate fire-fighting actions (Stavi, 2019).

5. Conclusions

This study has evaluated infiltration, runoff and erosion in semi-arid lands covered by *M. tenacissima* (affected by wildfire and unburned) with different soil slopes in comparison to bare soils after simulated rainfalls.

Infiltration rates did not noticeably vary among the three soil conditions, which contrasts the first of our working hypothesis.

In contrast, the second hypothesis of this study is confirmed, since the runoff and erosive response under the different soil conditions and slopes was significantly variable. Compared to the bare soil and burned sites, the unburned areas with *M. tenacissima* generated noticeably lower runoff volumes. Peak flows increased along the gradient soil with unburned *M. tenacissima* < burned soil with *M.*

tenacissima < bare soil, except at the higher slopes. Moreover, the vegetation cover was able to reduce erosion only in unburned zones.

The burned areas with *M. tenacissima* produced soil losses that are similar as those measured in bare soils, and, in steeper slopes, also higher, as thought by our third working hypothesis. However, the measured soil losses are not able to produce untolerable erosion rates. Nevertheless, the control of erosion in these semi-arid lands is beneficial, to reduce the possible hydrological effects downstream of these fire-prone areas, and, in this direction, the establishment of vegetation strips of *M. tenacissima* in large and steep drylands with bare soil left by fire may be suggested to land managers.

It should be highlighted that the approach followed in this study in which we use a rainfall simulator, focuses on a local spatial scale,with the evaluation of the hydrological variables point by point. This may be one of the limitations of studies based on portable rainfall simulators, and therefore further research is needed at field scale extending to plots or hillslopes. This extension would also allow the evaluation of the effects on the hydraulic connectivity of the area. Moreover, the rainfall simulations have been carried out at a constant intensity and using a low fall height which do not allow considering the time variability and the effects of high kinetic energy of natural rainfalls. A monitoring study at the plot scale and under natural precipitation may give more insight about the role of the investigated species in controlling erosion on large forest subjected to the wildfire risk.

Nevertheless, the results of this study go beyond the local case study, since it has been demonstrated that an increased vegetation cover of native species (such as *M. tenacissima* in the Mediterranean Coasts of the Iberian Peninsula and Northern Africa) may reduce the hydrological response of large landscapes affected by the wildfire risk in semi-arid areas.

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Highlights:

- Soil hydrology in semi-arid soils dominated by *Macrochloa tenacissima* is evaluated
- Infiltration rates did not noticeably vary among soils
- Compared to bare soils, runoff decreased in both burned and unburned sites
- Erosion was similar in bare and burned soils, and lower in unburned sites
- *M. tenacissima* strips in drylands are suggested as post-fire management

Declaration of interests

X The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Demetrio Antonio Zema
(on behalf of the co-authors)

Short-term hydrological response of soil after wildfire in a semi-arid landscape covered by *Macrochloa tenacissima* (L.) Kunth

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