

SHORT-TERM EXPERIMENTAL FIRE EFFECTS IN SOIL AND WATER LOSSES IN SOUTHERN OF SPAIN

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ABSTRACT

This study deals with the experimental fire effects in overland flow and soil erosion at plot scale and considering rainfall erosivity. The study was conducted in from May 2011 to Dec 2013. Six plots of 12-m length and 2-m width are considered: four of them were burned, whilst two of them remained in natural conditions. Overland flow was collected in deposits of 250L after each rainfall event, measured at a meteorological station. Larger rainfall intensities and erosivity were registered after summer and, thus, overland flow and sediment yield, but one order of magnitude higher in the burned plots than in the unburned ones. Especially, the difference in overland flow and soil loss between both set of plots were nearly three folds larger whether the rainfall intensity exceeded 30 mm h^{-1} during 15-min intensity. It is remarkable that the most erosive event generating the maximum values of overland flow and soil loss was registered 16 months after the experimental fire when a rainfall event of 99.2 mm h^{-1} occurred. This delay is considered as consequence of soil surface conditions and ash cover.

KEY WORDS: experimental fire; rainfall erosivity; overland flow; soil loss; plot

INTRODUCTION

Soil erosion is one of the most significant environmental problems worldwide (Bakker *et al.*, 2007). This is particularly true in areas having seasonally contrasted climate and a long history of human pressure, such as the Mediterranean areas that are characterized by decreasing forested areas due to the expansion of livestock rearing in the past, recurrent fires, the cultivation of steep slopes and expansion of urbanization process (López-Bermúdez, 2008; García-Ruiz *et al.*, 2013; Zdruli, 2014; Ferreira *et al.*, 2015).

Soil loss was commonly predicted using empirical models such as the Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1965) and its revisions (RUSLE). Among the empirical coefficients used to calculate potential erosion, rainfall erosivity represents a natural environmental constraint on soil erosion that limits and conditions land use and management (Angulo-Martínez & Beguería, 2009). The concept of rainfall erosivity presented by Hudson (1971) and Wischmeier and Smith (1978) describes the erosivity as an interaction between kinetic energy of raindrops and the soil surface. Its calculation is dependent on maximum rainfall intensity values. This can result in a greater or lower degree of detachment and downslope transport of soil particles according to the amount of energy and intensity of rain by considering the same soil type, the same topographic conditions, soil cover and management (da Silva, 2004). Indeed,

the rainfall erosivity not only controls the soil erosion but also the plant establishment (Wang *et al.*, 2014).

In a Mediterranean environment, wildfire is commonly regarded as one of the major agents of soil erosion and land degradation (DeBano *et al.*, 2005; Cerdà & Mataix-Solera, 2009). Wildfires have a long history in the Mediterranean since late Quaternary (Carrión *et al.*, 2003) and even longer as fire adaptations of many endemic plant species indicate (Pausas *et al.*, 2008). Major concern about wildfires and their effects in the region began in the 1960s, 1970s and 1980s (Shakesby, 2011) as a consequence of an exponential increase in fire activity (Moreno *et al.*, 1998; Pausas, 2004). This increment is commonly due to a decreasing of total rainfall and an increasing of temperature over recent decades (Stott *et al.*, 2004; Harding *et al.*, 2009). However, human influences, including land use change brought about by widespread socio-economic change and urban expansion, have been viewed as the main drivers of the dramatic increase in wildfire activity (Pausas *et al.*, 2008; Shakesby, 2011; Bodí *et al.*, 2012; Carreiras *et al.*, 2014; Pereira *et al.*, 2015). One of the ways in reducing wildfire hazard is prescribed fires to reduce fuel in forests and rangelands, but the little-known effects of such prescribed burnings on entire ecosystems induced debate and research activities in various disciplines.

In Mediterranean areas, overland flow and thus sediment yield are controlled by factors such as rainfall regime, topography, land use and vegetation cover as well as soil properties. The vegetation cover protected the soil from being eroded due to decreasing the probability of overland flow generation. However, the impact of wildfires on vegetation cover and chemical, physical, biological and mineralogical

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properties of soils, which depends on the burn severity (Robichaud, 2000; González-Pérez *et al.*, 2004; Certini, 2005; Shakesby & Doerr, 2006; Shakesby, 2011; Robichaud *et al.*, 2013; Guénon *et al.*, 2013; Prats *et al.*, 2015; Malvar *et al.*, 2015), affects soil hydrology and, consequently, overland flow and soil erosion processes. In general, fire can change soil colour, increase hydrophobicity, reduce organic matter content, diminishes aggregate stability and porosity, enhancing soil surface sealing by mineral particles from broken aggregates or from the surface redistribution of ash (MacDonald *et al.*, 2008; Bodí *et al.*, 2014; Pereira *et al.*, 2014; Tsibart *et al.*, 2014; Hedo *et al.*, 2015).

After the fire, ash plays a major role as a controller of overland flow generation and soil erosion processes (Pereira *et al.*, 2014, 2015). Indeed, some authors have observed that not always, immediately after fire, runoff and erosion rates could be negligible due to the ash that covers totally soil surface after a wildfire (Cerdà, 1998; Cerdà & Doerr, 2008). However, once the ash is removed or crusted into the soil surface due to its mobilization by rainwater drops, there is a remarkable increase in runoff, especially when the soil is water repellent. In turn, soil erosion tends to be reduced due to the recovery of vegetation cover in time (Bodí *et al.*, 2012). In Mediterranean conditions, runoff rate and soil erosion magnitudes are highly variable and erosion rates were generally less than 1 t ha^{-1} per year (Cerdà & Bodí, 2007). Extreme and single rain-wash events trigger extraordinary post-fire erosion processes, especially in Mediterranean areas, in autumn, when burnt soils are unprotected after summer (Shakesby & Doerr, 2006; Mayor, 2007). Nevertheless, this response is not always observed given that soil loss rates are measured either during the first or subsequent years after the wildfire because other factors have to be taken into account. For instance, high rock fragment content on soil surface and within the soil profile, enhancing infiltration and percolation, but also diminishing overland flow velocity (Poesen & Lavee, 1994; Ruiz-Sinoga *et al.*, 2010; Gordillo-Rivero *et al.*, 2014).

The aim of this study is to evaluate the effect of an experimental fire in the short-term hydro-geomorphic response of plots in one Mediterranean environment and considering different rainfall erosivity conditions. Namely, the objectives are to (i) characterize the rainfall erosivity in the study period at the experimental site; (ii) assess the experimental fire effect in overland flow and soil loss at plot scale during rain events differing in rainfall erosivity; and (iii) discuss about other factors explaining the response of plots.

MATERIAL AND METHODS

The experimental site, named El Pinarillo, is located in the Natural Park of Sierra Tejeda, Almirajara and Alhama, in South of Spain (X: 424-240 m; Y: 4-073-098 m; UTM30N/ED50; Figure 1). It is at 470 m asl in the upper part of an alluvial fan (calcareous conglomerates) surrounded by a mountainous area with marble as bedrock. Climate is dry-Mediterranean (mean

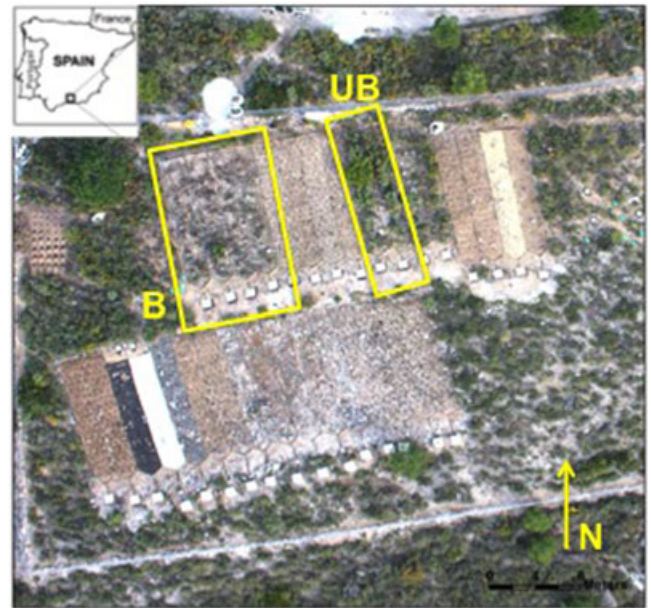


Figure 1. Location map and aerial view of the El Pinarillo experimental site. B: burned plots; UB: unburned plots. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

annual temperature: 18°C ; mean annual rainfall = 589 mm y^{-1}). The summer is a very dry period, and rain events are mainly concentrated from October to April. Currently, vegetation consists of an open pine forest with typical degraded Mediterranean scrubs and tussocks, affected by a fire that occurred in 1991. The area was previously cultivated and abandoned since the 1950s. Soils are classified as *Eutric Leptosols* according to FAO (2014). Table I summarizes the main features of the experimental site.

A meteorological station was installed in the experimental site in order to register natural rainfall events, measured with a tipping-bucket rain gauge with an accuracy of 0.2 mm per tip. The maximum rainfall intensities (I_{15}) of each event were calculated based on the 15-min intervals. This interval was selected because it was that given by the meteorological station.

In order to characterize the rainfall erosivity during the study period, the rainfall erosivity (R) factor index of the Revised Universal Soil Loss Equation (Morgan, 2001) was calculated. The original method to calculate the erosivity values (R factor) for a storm event requires pluviographical records (Wischmeier & Smith, 1978). This kind of information is difficult to obtain in many parts of the world, and its processing is time-consuming (Bertoni & Lombardi, 1990).

Using similar equations as Abu Hammad *et al.* (2004) and Diodato (2006), R factor was estimated by Equation 1 and 2:

$$R = E * I_{15_{\max}} \quad (1)$$

where E is the total energy for a storm and $I_{15_{\max}}$ is the maximum 15-min intensity. Total energy for a storm is computed from Equation 2:

$$E = \sum_{k=1}^m e_k \Delta V_k \quad (2)$$

Table I. Main features of the experimental site and plots

		Rainfall (mm)	589
Climate			
	Temperature (°C)		18
Topography	Slope angle (°)		4
	Aspect (°)		170
Geology		Alluvial fan (calcareous)	
Land use		Shrubland and pine forests	
Fire history		1991; 2011 (experimental fire)	
Vegetation	Species	<i>Rosmarinus officinalis</i> L., <i>Lavandula stoechas</i> L., <i>Cistus chusii</i> L., <i>Thymus mastichina</i> L., <i>Stipa tenacissima</i> L., <i>Chamaerops humilis</i> L., <i>Pinus halepensis</i> L..	
	Pre-fire VC (%)		70
	Post-fire VC (%)		<20
Soil	Gravel (%)		>55
	Texture	Sandy-loam	
	OM (%)	Pre: 7.3/Post: 8.7	
	pH	Pre: 7.7/Post: 7.7	
	Type of soil structure	Granular	
	Aggregate stability (%)	Pre: 50.0/Post: 60.0	

VC, vegetation covers previous to and after the experimental fire.
Pre: data before experimental fire; Post: data after experimental fire.

where e =unit energy (energy per unit of rainfall), ΔV =rainfall amount for the k period, k =an index for periods during a rain storm where intensity can be considered to be constant, m =number of periods. Unit energy is computed from Equation 3:

$$e = 0.29[1 - 0.72 \exp(-0.082i)] \quad (3)$$

where unit energy e has units of $\text{MJ ha}^{-1} \text{mm}^{-1}$ and i =rainfall intensity (mm/h).

Plots have been widely used in most Mediterranean soil erosion research conducted in burn areas by either wildfires or controlled fires (Shakesby, 2011). Plots predominantly included shrubs and grasses where effects on the burned soil are expected to be greater than in tree plantations as a result of much of the litter and living biomass being consumed (De Luis *et al.*, 2003; Vega *et al.*, 2005; Fernández *et al.*, 2007; Zavala *et al.*, 2010). Nevertheless, according to Ferreira *et al.* (2008), plot results are not necessarily easily upscaled due to problems especially concerning the spatial variability in overland flow and soil erosion controlling factors in Mediterranean environments (Boix-Fayos *et al.*, 2007).

Our study is based on data from six plots: four as burned plots (B) and two control plots (unburned, UB). The size of the plots was equal to 2-m width and 12-m length (24 m²). The plots were oriented parallel to the slope (slope angle=4°) and bounded by 200-mm metal borders. At the foot of each plot, a 2-m-wide collector emptied into tanks of 250 L that collected runoff and sediment produced during natural rain events.

B plots were burned in 2 May 2011. Fire was conducted by the regional firemen forest service of Andalucía. The weather conditions were sunny, no wind, with an air temperature of 16.5°C and a humidity of 74%. Fire was applied at the bottom of the plots and then enhanced with dry plants introduced between the vegetation going up the top of them following the gentle slope gradient. The temperature of fire was not measured but height of flames, ca. 2 m, could be estimated from photos taken during the experimental fire. Following Maia *et al.* (2012), the fire severity was estimated as being low to moderate following three criteria: (i) intact plant stems were found after the fire and even some them conserved totally or partially their aerial system of leaves and stems (for instance, *Chamaerops humilis* L.); and (ii) the ash layer (measured randomly just after fire) did not completely cover the whole area of plots but with a patchy appearance of blackish and greyish patches. Nevertheless, the vegetation cover decreased to less than 25% after the experimental fire.

Vegetation and soil cover within B and UB plots were described in field survey recognition previous to and after the experimental fire. Table I summarizes some of these features. UB plots, including the original vegetation cover, were characterized by Mediterranean shrubs species. Some of these plants partially lose their leaves because of the summer drought (*Cistus chusii* L.), besides the death of annual plants, reducing the vegetation cover at the end of this period of the year. This implied that the vegetation cover of UB plots varied throughout the year (70% ± 5%). The spatial pattern of vegetation provided well-covered soils uniformly distributed within the UB plots. The soil not covered by plant was characterized by high rock fragment cover, mainly disposed on the surface. Locally, rock fragments were embedded into the soil surface. Also, a litter layer (c.a. 2 cm) was observed in soils under shrubs.

As expected, after the experimental fire, B plots registered a remarkable decrease in vegetation cover compared with UB plots. Nevertheless, this difference was not as high as it was expected because the fire was of low intensity. The remaining vegetation cover was below 25%. Most burnt plants persisted as plants with stems connected to the soil surface. The soil not covered previously by plant presented similar conditions to those observed in UB plots. Soil under burned plants and surrounded were covered by ash after the experimental fire, but the ash cover was less than 0.5 mm in depth and spatially heterogeneous. After 2.5 years, vegetation cover ranges from 25 to 50% in the B plots.

The study period was from 02 May 2011 to 31 December 2013. Total overland flow for each erosive rain event was measured through height volumetric calculations, inserting a ruler into the tank, measuring the water depth and converting into volumetric units. Total sediment yield and sediment concentration were measured within the containers at three heights (taking an aliquot at the top, medium and bottom of the deposit) after mixing the water and

multiplying by the water. The sediment weights were obtained in laboratory by drying the overland flow samples at 105°C until water was completely evaporated. These data were used to calculate the total volume (L), rate ($L m^{-2}$) and coefficient of overland flow (%), as well as total sediment yield (Kg), sediment concentration ($g L^{-1}$) and soil loss rate ($t ha^{-1}$).

The statistical analysis was performed using SPSS 21 for Windows. Regression analysis and Pearson's correlation was used to assess the relationship between the measured variables. Once normality and homogeneity of variance using the Kolmogorov–Smirnov test and Levene's test were calculated, the significant differences between the measured variable means from B and UB plots were assessed by means of the Student's *t*-test. In order to analyze the difference in temporal variability of overland flow and soil loss, a two-way repeated-measures ANOVA, using treatment (fire) and time as factors, was calculated.

RESULTS

Events and Erosivity of Rainfalls

During the study period, the recorded rainfall was equal to 1364 mm in the experimental site, occurred in 440 h. The range of rainfall depth per event was from 0.2 to 105.8 mm, whilst that of rainfall duration from 0.25 to 44.3 h. From a total of 67-rainfall registered events, 24 of them (36%) were considered as erosive rainfall events because they generated overland flow. These erosive rainfall events add up 1164 mm: 85% from the total rainfall depth. The average maximum rainfall intensity was of 12.0 mm h^{-1} ranging from 0.8 to 99.2 mm h^{-1} . Table II shows the greatest rainfall events in depth and I_{\max} registered in the experimental site because the experimental fire was conducted. Six of the ten major events in depth and rainfall intensity occurred from the end of August to November.

Also, R index was calculated for every rainfall event. As the previous table shows, the highest rainfall intensities did not always imply the highest R factor because this also depends on the total event duration. The R factor average was equal to $90.2 \pm 251.0 \text{ MJ ha}^{-1} \text{ mm}^{-1}$ and ranging from 0.02 to $1672.3 \text{ MJ ha}^{-1} \text{ mm}^{-1}$. Regression analysis was performed for duration, depth and intensity of rainfalls versus R factor (Figure 2). As it was expected, rainfall intensity



Figure 2. Photographs from the plots just before (A), during (B) and after 3 years (C) since the experimental fire was conducted. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

showed the best lineally regression ($R^2=0.77$, $p < 0.05$). Also, rainfall depth obtained a statistically significant correlation coefficient ($R^2=0.53$, $p < 0.05$). In opposition, rainfall duration was characterized by the lower correlation with R factor ($R^2=0.17$, $p < 0.05$), indicating what was pointed out previously: the longest rain events not always being the highest erosive ones.

Overland Flow and Soil Loss

Table III shows overland flow data recorded in all of the plots during the study period. The mean total overland flow generated per erosive event was equal to $23.7 \pm 1.8 L$ and $11.2 \pm 4.9 L$ in B and UB plots, respectively. The burned/unburned ratio of total overland flow was up-to 4.8 times higher in B plots respect to UB. The student's *t*-test indicated that there were significant differences among total overland flow, overland flow rate and runoff coefficient: $t=0.86$; $t=1.01$; $t=0.98$, respectively ($p < 0.05$). B plots were characterized by similar hydrological responses. In the case of UB plots, there were significant differences between the two unburned plots, as UB-1 produced nearly twice as much overland flow as UB-2. Likewise, the two-way repeated-measures ANOVA indicated that overland flow was significantly different in time when that measured in B plots was compared to UB ones for every rain event ($p \text{ value} = 0.000$; $p < 0.05$).

Figure 3 shows the temporal variability of overland flow and sediment yield regarding rainfall events from the start of study period, respectively. Rain events in autumn registered highest depths and intensity and, thus, overland flow volume and increments were also the highest ones. During winter the recorded overland flow diminished until early spring when a second maximum but minor than those in autumn was measured. Most of time overland flow

Table II. Ten major rainfall events in depth and 15-min rainfall intensity (I_{\max}) registered during the study period (2/May/2011–31/Dec/2013)

Date	Rainfall depth(mm)	R factor($\text{MJ ha}^{-1} \text{ mm}^{-1}$)	Date	$I_{\max}(\text{mm h}^{-1})$	R factor($\text{MJ ha}^{-1} \text{ mm}^{-1}$)
18/Nov/2012	105.8	972.3	30/Sep/2012	99.2	1672.3
30/Sep/2012	103.8	1672.3	29/Aug/2013	63.2	629.0
5/Nov/2011	95.6	397.2	18/Nov/2012	52.8	972.3
4/May/2011	85.8	319.1	22/Nov/2011	38.4	331.0
12/Mar/2013	82.2	121.4	4/May/2011	29.6	319.1
26/Oct/2012	76.2	234.6	11/May/2011	29.6	0.5
7/Nov/2012	75.8	72.4	5/Nov/2011	28.8	397.2
25/Dec/2013	73.4	214.8	19/Jan/2013	28.8	122.4
22/Nov/2011	61.4	331.0	5/Apr/2013	25.6	81.3
29/Aug/2013	45.6	629.0	7/Sep/2013	25.6	132.3

Table III. Mean data of overland flow registered during the study period in the burned (B) and unburned (UB) plots

	B-1	B-2	B-3	B-4	UB-1	UB-2
T (L)	656.6a	587.7a	644.1a	689.2a	303.9b	168.7b
r (L m ⁻²)	1.2 ± 1.5a	1.0 ± 1.3a	1.1 ± 1.4a	1.2 ± 1.5a	0.6 ± 0.4b	0.3 ± 0.3b
Max r (L m ⁻²)	6.2	6.5	6.3	6.5	6.6	0.9
c (%)	3.2 ± 3.7a	2.5 ± 2.2a	2.9 ± 3.1a	2.4 ± 2.5a	1.2 ± 1.4b	1.0 ± 1.1b
Max c (%)	14.6	8.7	11.7	8.7	6.4	4.4

T, total overland flow (L); r, overland flow rate (L m⁻¹); c, overland flow coefficient (%). Means within a row for each microenvironment that do not have a common letter are significantly different using Student's *t*-test (*p* < 0.05). ± indicates standard deviation.

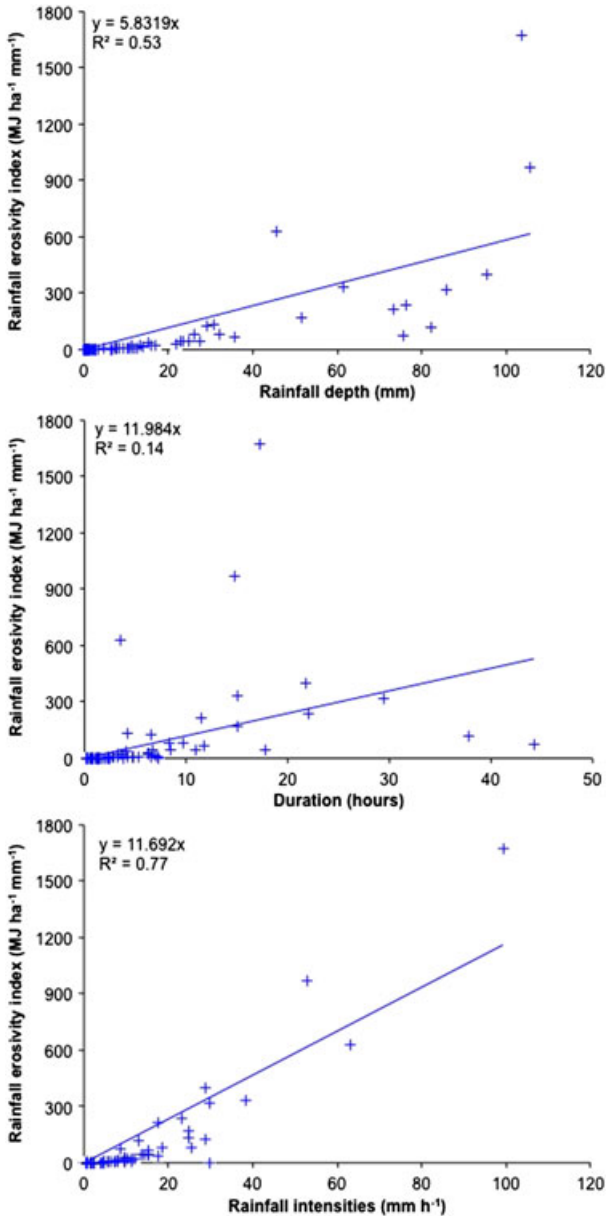


Figure 3. Scatter-plots and regression analysis of rainfall duration, depth and intensity versus rainfall erosivity index.

generated in burned plots was higher than that measured in the unburned ones. It is remarkable the event registered in 30/09/2012 (depth = 103.2 mm; I_{max} = 99.2 mm h⁻¹), which

generated more than 150L of overland flow in B and UB plots. Other important events also occurred from September to November, but total overland flow remained below 60L for B plots and even less than 20L in UB plots. Regarding these data it was observed that overland flow from B plots nearly was duplicated when I_{max} ranged from 30 to 60 mm h⁻¹ (Figure 4). Above 60 mm h⁻¹, only two events were registered and they differed completely not being possible to draw a trend.

Table IV shows the general soil loss data. During the study period, a mean value of total sediment yield equal to 123.5 ± 29.2 Kg and 16.1 ± 17.0 Kg was measured in B and UB plots, respectively. The mean sediment concentration was 74.3 ± 113.4 gL⁻¹ in the B plots and 27.8 ± 51.3 gL⁻¹ in the UB ones, more than two times higher in the former than in the latter. Respect to the mean soil loss rate, B plots

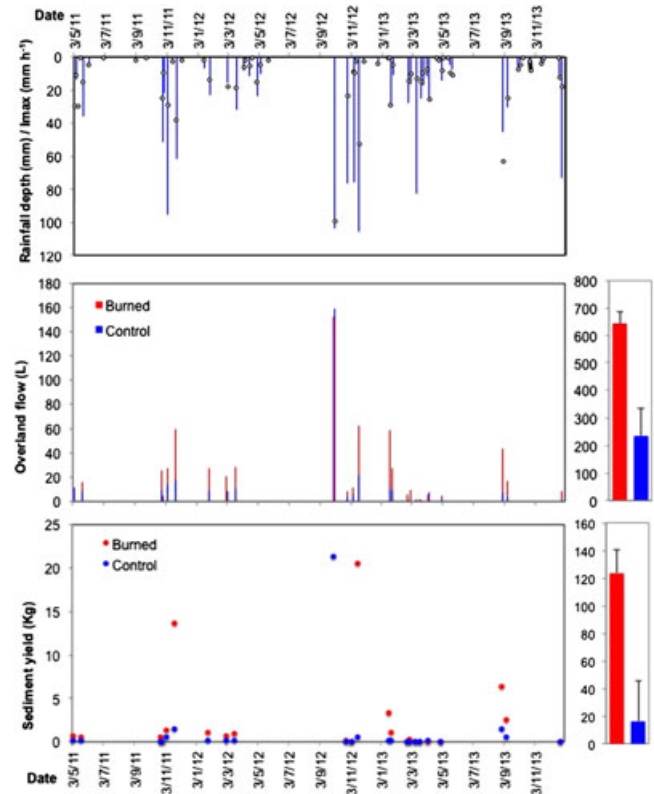


Figure 4. Temporal variability of rainfalls, overland flow and sediment yield during the study period. The graphs on the right indicate the total overland flow and sediment yield registered.

Table IV. Mean soil loss data registered during the study period in the burned (B) and unburned (UB) plots

	B-1	B-2	B-3	B-4	UB-1	UB-2
T (Kg)	129.8a	114.9a	89.8a	159.6a	28.2b	4.1b
SC (g L ⁻¹)	81.3 ± 156.7a	78.0 ± 109.1a	65.8 ± 87.6a	75.6 ± 146.9a	36.3 ± 57.5b	27.8 ± 47.4b
Max SC(g L ⁻¹)	668.9	465.7	309.9	705.2	199.0	157.4
SL (t ha ⁻¹)	2.5 ± 5.6a	2.1 ± 6.2a	1.6 ± 4.2a	2.9 ± 9.4a	0.6 ± 2.0b	0.1 ± 0.2b
Max SL(t ha ⁻¹)	20.3	30.2	19.6	45.7	8.9	0.8

T, total sediment yield; SC, mean sediment concentration; SL, soil loss rate.

Means within a row for each microenvironment that do not have a common letter are significantly different using Student's *t*-test ($p < 0.05$).

± indicates standard deviation.

registered $2.3 \pm 6.3 \text{ t ha}^{-1}$, and UB generated $0.3 \pm 1.1 \text{ t ha}^{-1}$, nearly 8-times lower in the natural vegetation condition. For B and UB plots, the most erosive events were: 29.0 and 8.9 t ha^{-1} (30/Sep/2012), 8.6 and 0.13 t ha^{-1} (18/Nov/2012), and 5.7 and 0.60 t ha^{-1} (22/Nov/2012), respectively. The considered erosive variables followed a parametric distribution regarding to Levene's test. Subsequently, Student's *t*-test showed there were significant differences between B and UB plots with regard to total sediment, sediment concentration and soil loss rate: $t=0.98$; $t=0.51$; $t=1.01$, respectively ($p < 0.05$). Similarly to overland flow, the two-way repeated measures-ANOVA indicated that soil loss was significantly different in time comparing B and UB plots for every rain event (p value = 0.000 ; $p < 0.05$).

Regarding the temporal variability of total sediment yield, UB plots seemed to register a slight increment in the emission of sediments throughout the study period. In the case of B plots, this temporal variability in sediment yield followed a seasonal pattern: coinciding with the major rainfall intensity events, higher peaks in autumn and decreasing towards spring. Similar temporal patterns were observed in the case of sediment concentration and soil loss rates registered in B plots.

Nearly 3 years after the experimental fire, burned plots still produced a major volume of runoff and, subsequently, higher soil losses. The mean soil loss rates of B plots were equal to 0.91 , 3.30 and 1.24 t ha^{-1} in the first, second and beginning of third year, respectively. In the case of UB plots, these values were of 0.12 , 0.41 and 0.29 t ha^{-1} . If the most erosive events (30/Sep/2012) are not considered, those mean values in B plots decreased to 0.97 and 0.54 t ha^{-1} in the second and third year, whilst the UB ones were of 0.03 and 0.12 t ha^{-1} . Both erosive rain events contributed 55 and 16%, respectively, to the total soil loss measured in the UB plots during the study period. Comparing overland flow and soil loss from B and UB plots, it can be assumed the window of disturbance is still functioning and the B plot ecosystems are not recovered from the experimental fire impact 2.5 years after.

The effect of rainfall parameters on overland flow and soil loss was also assessed (Figure 5). The lineal regression models of burned plot data show overland flow and soil loss were always greater than that for the unburned plots. Total overland flow and, especially, soil loss were significantly well correlated with I_{15} and R factor.

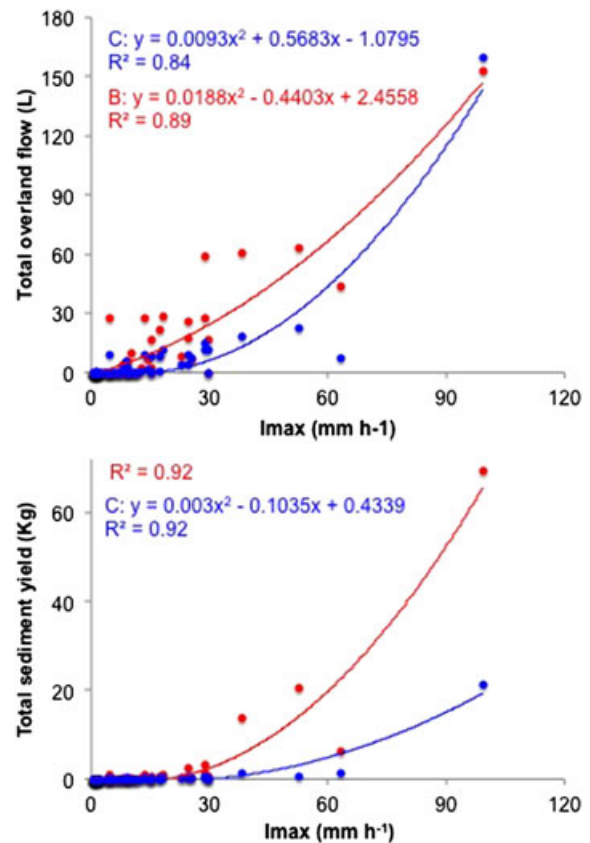


Figure 5. Theoretical increment of overland flow and sediment yield with maximum rainfall intensity (I_{max}). Abbreviations: B, burned plots; C, control plots; I_{max} , maximum rainfall intensity in 15 min.

However, no significant results were obtained when overland flow and soil loss data were correlated with rainfall depth (Figure 6).

DISCUSSION

Rainfall Erosivity

Among the empirical coefficients used to calculate potential erosion, rainfall erosivity represents a natural environmental constraint on soil erosion that limits and conditions land use and management (Angulo-Martínez & Beguería, 2009). Different authors have also pointed out that the irregularity of precipitation is the main factor responsible for the temporal irregularity of erosion rates in the Mediterranean environment (Renschler *et al.*, 1999).

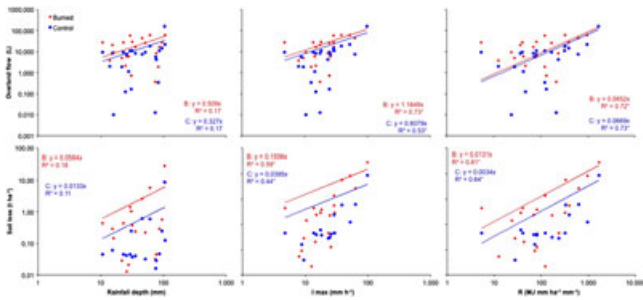


Figure 6. Scatter-plot and regression analysis of sediment concentration versus rainfall depth (A), rainfall intensity (B) and R factor (C) considering the whole database. Asterisk indicates that the correlation coefficient (R^2) is statistically significant for $p < 0.05$. Abbreviations: B, burned plots; C, control plots.

The rainfall parameters that characterized the site during the study period indicate in general one rainfall regime typical of Mediterranean climate. Rainfall periods were concentrated from September to May followed by another dry of at least 3-month duration. Likewise, the major rainfall events in depths, I_{\max} and thus R factor generally occurred from the end of August to November. Longer rain events in duration did not register the greatest depths, but the shorter than 20 h. It seemed that rainfall events longer than 24 h tended to be less intense, likely influenced by their origin. Longer period of rains but less intense in time used to be normally related to Atlantic fronts in South of Spain. In opposition, shorter but more intense rains are related to deep low pressures activated in the Alborán Sea (Western Mediterranean Sea) at the end of summer and during the autumn (DeBano *et al.*, 2005; Ruiz-Sinoga *et al.*, 2011). This is a more common feature of rainfall events in Mediterranean climate.

The magnitude and frequency of I_{\max} and R factor were similar to those registered by other authors in studies conducted under Mediterranean climatic conditions. González-Pelayo *et al.* (2010) addressed rainfall intensities ranging from 2.2 to more than 90 mm h^{-1} . With regard to R factor, obtained from less than 100 to nearly $2000 \text{ MJ mm ha}^{-1} \text{ h}^{-1}$ in South of Spain. The temporal variability observed in our results of rainfall erosivity showed the major values concentrated after summer months, decreasing towards winter and reaching another peak of erosivity in spring season, but shorter. This is in accordance with the same trends observed in other investigations in the Iberian Peninsula (Angulo-Martínez & Beguería, 2009; De Luis *et al.*, 2010).

Effect of Rainfall Erosivity and Intensity on Overland Flow and Soil Loss

MacDonald *et al.* (2008) indicate that stronger rainstorms (high rainfall intensities in 30 min) can initiate post-fire erosion even when there is relatively little bare soil. Studies in Mediterranean areas have identified the first two rainy seasons as the most critical periods for post-fire flooding and sedimentation (Robichaud *et al.*, 2000). Some authors registered the major soil losses during the first rain event after the experimental fire (Soto *et al.*, 1994; González-Pelayo

et al., 2010). However, in this study, the highest soil loss was not recorded during the first rain event once the experimental fire was conducted, only 2 days after. Indeed, several rain events with significant depths ($>20 \text{ mm}$), maximum rainfall intensities ($>15 \text{ mm h}^{-1}$) and R factor ($>300 \text{ MJ mm ha}^{-1} \text{ event}^{-1}$) were recorded at the end of 2012 summer and in the subsequent autumn. This reflects the high variability in rainfall intensity and annual totals in the Mediterranean and the often slow rate of vegetation recovery such that soils can still be relatively devoid of a protective vegetation cover and susceptible to erosion for years rather than months after a wildfire (Shakesby, 2011).

The studied parameters of rainfall regime during the study period were rainfall depth, maximum rainfall intensity in 15 min and rainfall erosivity factor (calculated). The first one did not match well relations when compared with overland flow and soil loss either burned plots or unburned ones. However, the other parameters seemed to clearly express their influence on the activation of hydro-geomorphic processes. Other authors observed similar relationships in burned plots and in Mediterranean conditions (Cerdà & Lasanta, 2005; González-Pelayo *et al.*, 2010).

The I_{\max} and R factor highly experimental overland flow and soil loss as data registered after the four major events indicated: the highest rainfall intensity, the highest overland flow and soil loss in burned plots. The increment in both parameters was exponential as it is assumed in Figure 4: there was an increment of 2 and 1.5 times in overland flow and soil loss when 30 mm h^{-1} was exceeded. After the second threshold, overland flow and soil loss showed very variable response, although only two events were registered beyond it. Other authors have reported similar trends but differing in magnitude. González-Pelayo *et al.* (2010) indicated that one I_{30} of 2.2 mm h^{-1} was enough to generate overland flow in burned plots (but slope gradient was higher than that measured in our study), and Inbar *et al.* (1998) observed this threshold was much lower than 10 mm h^{-1} . Moody and Martin (2001b) also defined an I_{30} threshold of 10 mm h^{-1} to generate runoff, but it depended on a wide range of factors such as vegetation cover, slope angle and elapsed time since fire.

Effect of the Experimental Fire on Overland Flow and Soil Loss

After the experimental fire, soil loss magnitude can be quantified in terms of the change in hydrological and erosive processes from that found under the unburned pre-fire conditions. Previous works have found that the hydrologic processes affected by fire increase for a short time until a maximum rate is reached, and later, during the recovery period the rates decrease (Cerdà & Lasanta, 2005). The length of these two periods constitutes the relaxation or recovery time (Moody & Martin, 2001a, 2001b). Considering the short period of this study, the burned plots showed similar short-term responses during the first 2.5 years of the relaxation–

recovery time. Peaks of overland flow and soil loss were reached on the burnt plots 16 months after the fire because of the maximum rainfall event (30/Sep/2012), which produced high soil losses (even in unburned plots) but significantly different among plots. Differentially, on an oak scrub plot in the Catalan Coastal Ranges of north-east Spain subject to low-severity fire, Soler and Sala (1992) reported >16 times more sediment removed during 7 months of post-fire monitoring compared with an unburned control plot.

Nearly 3 years after the experimental fire, soil loss in burned plots is one order of magnitude higher than in unburned ones. Thus, the window of disturbance (recovery time) is still functioning and the burned plots have not recovered from the experimental fire impact. From an erosional point of view, the recovery time can range from a few years to a few decades. A relaxation time of 3 years was reported in some studies from the USA (Rowe *et al.*, 1954; Brown, 1972; Moody & Martin, 2001a). Under simulated rainfall in southeastern Spain, Cerdà (1998) found steady-state conditions 2 years after the fire for summer conditions and 4 years for winter conditions. Cerdà and Lasanta (2005) found diverse erosive response on the Aísa Experimental Station, with some burnt plot showing a relaxation time of 2 years, whilst another one did not reach the steady-state conditions after 7 years.

The mean soil loss rate ranged from 1.6 to 2.9 t ha⁻¹ in burned plots, and from 0.1 to 0.6 t ha⁻¹ in unburned ones. These results are in accordance with others registered in burned and control plots under Mediterranean climatic conditions (Inbar *et al.*, 1998; Campo *et al.*, 2006; Mayor *et al.*, 2007). Likewise, the soil loss rate is also in the same order of magnitude than those observed under more humid conditions in the Pyrenees (Cerdà & Lasanta, 2005) and in North of Portugal (Prats *et al.*, 2012). For instance, on *Ulex europaeus* scrub subject to low-severity and moderate-severity experimental fires in north-west Spain, Soto *et al.* (1994) reported 2-year post-fire plot-scale soil losses 1.6–4.5 times higher than on equivalent unburned scrub. Significantly, the annual erosion rates (c. 1–4 t ha⁻¹) during these two years were actually higher than some reported following Mediterranean wildfires (Pausas *et al.*, 2008). It is remarkable that 55 and 75% of the total soil loss were produced by the most erosive events in the burned and unburned plots, respectively, whilst the second most erosive events only 16 and 2.5%. This shows that erosive events with the highest rainfall erosivity are more influential in the soil loss dynamic of unburned plots than in the burned ones. The latter shows a major and constant contribution to soil process with rainfalls less erosive due to the lack of vegetation cover.

However, not only the absence of vegetation is crucial for the burned response in overland flow and sediments. Some factors likely played a key role explaining this delay in the highest magnitude erosive event. The absence of overland flow and thus soil loss as consequence of the rain events following the experimental fire, in 2011 May, might be related to the ash cover effect. Although ash was not covering completely soil surface after the fire, Bodí *et al.* (2014)

pointed out the layer of ash on the top of the soil is considered to act as a two-layer system. In some cases, ash was found to reduce overland flow rates and in other cases the opposite (Pereira *et al.*, 2015). Indeed, some authors have suggested that assumptions about soil and infiltration theories may need reconsideration because of the presence of a layer of ash (Moody *et al.*, 2013).

Subsequent rain events after 2011 summer (and very probably the wind) washed off ash from the soil surface. Burned plots had less vegetation cover, especially leaves, but some aerial parts or stems connected to soil surface still remained (thus, facilitating water infiltration into the soil). Besides, soils from the experimental site and surrounded area are characterized by high rock fragment contents in their profiles, enhancing percolation, but also on soil surface slowing overland flow velocity down and, thus, increasing water infiltration into the soil (Poesen & Lavee, 1994; Ruiz-Sinoga *et al.*, 2010). Despite burned conditions within the plots, following Shakesby (2011), erosion in such conditions tends to be supply limited: once ash or charred debris have been removed by overland flow, there is a limited amount of additional surface material available for detachment and transportation in the thin stony soils, common in Mediterranean environments, previously cultivated, abandoned and recolonized by vegetation before being burned. Only soil loss becomes highly significant when an extreme and erosive rainfall event occurred as that registered in 30/Sep/2012 (depth: 103.8 mm; maximum rainfall intensity in 15 min: 99.2 mm h⁻¹; R factor: 1672.3 MJ mm ha⁻¹ mm⁻¹) and not only in the case of burned plots but for the unburned ones too.

Our study deals with a key question in the Mediterranean region where wildfires commonly occurred during summer months. It is necessary to keep in mind the huge social, economical and cultural changes occurred since the 1950s in countries from the Mediterranean region with the consequence of an abandonment of lands and the encroachment of vegetation. This has been addressed as one of the main causes in the increment of the number of wildfires per year. Many of them can be rapidly controlled and do not usually affect to very small areas (Vadilonga *et al.*, 2008). Nevertheless, forest structure has changed with the recolonization of vegetation in old cultivated and grazed lands, which became more prone to huge forest fires with intensified burn severities, increasing the hazard of a few huge forest fires. Because of this, prescribed burning should be a fire-controlling method more and more introduced as a method for the prevention of forest fires with the aim of creating forest structures with reduced fuel loads. Although, our research deals with an experimental fire, it can be considered as an experiment, which effects can be expected and similar after a prescribed fire in field conditions. Indeed, similar hydrological and erosive responses were found after prescribed fires in similar environment conditions in Catalonia (Vadilonga *et al.*, 2008): low runoff generation and erosion just after the prescribed fire.

CONCLUSIONS

Generally, overland flow and soil loss were higher in the plots affected by the experimental fire than in the control ones, especially after the summer when rainfall events were more extreme in depth and intensity. The greatest response of overland and soil loss was highly dependent on maximum rainfall intensity and could be well explained by the RUSLE rainfall erosivity factor. Overland flow and soil loss from burned plots was one order of magnitude higher than that of the control ones. Increments in rainfall intensity up to 60 mm h^{-1} caused increases of two-folds in overland flow and soil loss, with regards mainly to the burned plots. An only one exception was observed with the highest erosivity (100 mm h^{-1}), which produced an extreme response in the control plots. The most erosive event was delayed 1.5 years. This delay might be related to ash cover but also to soil surface conditions, namely, to rock fragment cover and disposition on surface. Thus, rock fragments could act protecting soil when there is a lack of vegetation after a fire and avoiding extreme overland flow and, especially, soil loss.

In summary, our study, which deals with experimental fire, obtains similar hydrological and erosive results to those from prescribed fire. Thus, it can be concluded that the reduction of fuel storage in forest and rangelands to prevent and reduce wildfire hazard by means of prescribed fires could be considered as a useful tool in Mediterranean ecosystems.

ACKNOWLEDGEMENTS

This study was carried out in the framework of the P09-RNM-5057 research project, funded by the Regional Government of Andalusia and supported by the Campus Andalucía Tech. The authors are also grateful to the reviewers who highly improved this article with their revisions, comments and suggestions.

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