Prescribed fire impacts on soil properties, overland flow and sediment transport in a Mediterranean forest: A 5 year study

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Abstract

Prescribed fire is a common management practice in Mediterranean region to reduce the amount of fuel and to decrease the wildfire risk. The objective of this study is to assess the effect of a prescribed fire on some soil properties, hydrological response and vegetation recovery in experimental plots 5 years after. The results showed that: i) with the exception of electrical conductivity, the prescribed fire did not affect the analyzed soil properties, and ii) overland flow and sediment transport were increased during the first two years, returning to levels pre-fire, 5 years post-fire. The rainfall threshold for overland flow generation was lower during the following months after the prescribed fire owing to the depletion of the vegetation cover. Immediately after the fire, the vegetation cover was of 1.9%, being the three main soil surface components that dominated the hydrological response: charcoal and decayed wood; blackish and greyish ash, and bare soil. However, these areas decreased very rapidly during the second year following the fire, principally, owing to the regrowth of herbaceous plants and shrubs. In addition, the vegetation cover in burned plots was 16.1% higher than that measured in the unburned ones. Overall, the prescribed fire only had an impact on runoff and sediment transport in the two years post~~-~~-fire, as consequence of vegetation removal.

Keywords: Prescribed fire; Mediterranean; ~~f~~Forestry management; ~~s~~Soil properties; ~~r~~Runoff; ~~e~~Erosion

~~1.~~1 Introduction

Wildfires are a natural phenomenon of the ecosystems (Cerdà, 1998; DeBano et al., 2005; Outeiro et al., 2008(Pereira et al., 2014)). However, they have an important impact on the ecosystems, as reported in previous works (Neary et al., 2005; Buhk et al., 2007; Alcañiz et al., 2016). Cerdà and Mataix-Solera (2009) noted that wildfires are a particularly serious problem for areas having a Mediterranean climate because the warm summers and drought conditions provide ideal conditions for fires to occur and spread. The configuration and structure of Mediterranean landscapes (the large amounts of fuel accumulation and the continuity between forested areas) can result in very severe fires that spread rapidly and are difficult to extinguish, especially those reaching the forest canopy (Outeiro et al., 2008; Alcañiz et al., 2016). Determining methods to minimize the incidence and effects of forest fires and to reduce their spread is a critical issue for Mediterranean ecosystems (Piqué et al., 2011). The effects of wildfires on the ecosystem depend on the vegetation type, topography, soil type and moisture content, fire intensity and severity, and post-fire meteorological conditions (Certini ~~et al.~~, 2005).

At landscape scale, forest management needs to focus on the vulnerability to fire, which depends on the type and regime of fire (Cerdà and Mataix-Solera, 2009; Martínez-Murillo et al., 2016). Vélez (2000) noted that maintaining forest structures having low levels of fuel and substantial resistance to fire spread, requires preventive forestry practices.~~-~~ The most common are surface vegetation, pruning and removal of vertical fuel, which create clear areas that reduce fire spread, and planting species with reduced flammability and less vulnerable to fire(Fernandes and Rigolot, 2007).

Prescribed burning has been defined as the planned use of fire to achieve precise and clearly defined objectives, representing a more appropriate and less risky approach than unregulated traditional agricultural burning (Outeiro et al., 2008). Initially, this practice was used to renew the farm land and hunting grounds (Cerdà and Mataix-Solera, 2009). Nowadays, prescribed burning is being used to reduce hazard and fire risk, to achieve wildlife habitat maintenance, to control fire regimes by managing fuel and to remove the biomass produced during the land management practices (Alcañiz et al., 2016). The regeneration of plants, habitats improvement, the promotion of recreational uses, and the enhancement of animal grazing are some of the positive effects of prescribed fires (Afif and Oliveira, 2006; Fonseca et al., 2011; Fontúrbel et al., 2016; Francos et al., 2016). However, fire can affect most of the soil physical, chemical, and biological properties (Certini, 2005; Mataix-Solera et al., 2012). Fire severity is commonly a main factor in the post-fire dynamic (González-Pérez et al., 2004; Mataix-Solera et al., 2009). This parameter is directly related to the burned biomass and the vegetation recovery as well as to the hydro-geomorphic processes after fire; generally, low recovery vegetation and hi~~d~~gh erosion rates are associated to fires of high severity (Doerr et al., 2006; Gimeno-García et al., 2007; González-Pelayo et al., 2010; Moody et al., 2013).~~-~~ Prescribed burning is therefore undertaken under favorable temperature, soil and fuel moisture conditions and, where the topography is appropriate (Molina, 2009), is ensured the low impact in the soil (Vega et al., 2005). In this regard, Vélez (2000) proposed the basic rule of 30-30-30, which means that relative humidity under 30%, surface wind speed higher than 30 km h^{-1} and temperatures higher than 30 °C facilitate the increase of fire spread.

The effects of prescribed fires on soil vary from site to site (Guinto et al., 2001; Aroncena and Opio, 2003; Bennett et al., 2014). For example, a significant increase in soil pH immediately following a prescribed fire has been observed in some studies, whil~~e~~st not in other studies (Afif and Oliveira, 2006). Both electrical conductivity and nutrient availability increase following prescribed fires (Granged et al., 2011; Scharenbroch et al., 2012). In the latter case, both short- and long-term studies have indicated that changes occurred because of the incorporation of ash into the soil (Úbeda et al., 2005; Brye, 2006; Outeiro et al., 2008; Scharenbroch et al., 2012). The effects of prescribed fire on soil showed that prior to fire soils beneath vegetation cover have higher levels of soil organic carbon (SOC), greater aggregate stability, and in some cases larger aggregates (O'Dea, 2007; Are et al., 2009). In the case of SOC an incremental increase has been reported following a fire of low severity, because of incomplete combustion of the incorporation of charred material into soil profile (Knicker, 2007; Mataix-Solera et al., 2012). However, others have shown a decrease in SOC following a prescribed fire (Armas-Herrera et al., 2016). Soil hydrophobicity increases after low/moderate severity fires and this can have implications on hydrological and geomorphological process (e.g. infiltration, runoff, soil erosion) (DeBano et al., 1976; Doerr et al., 2000; Zavala et al., 2010; González-Pelayo et al., 2015; Malvar et al., 2016). Fire impact on catchment runoff and sediment yield in Mediterranean drylands may be amplified by drought periods delaying plant recovery (Andreu et al., 2001; Mayor et al., 2007). The recovery of vegetation is one of the most important factors to reduce post-fire land degradation (Inbar et al., 1998; De Luis et al., 2001; Beyers, 2004; Cerdá and Doerr, 2005).

Because prescribed fires can be used to prevent severe wildfires and reduce wild-fire frequency, further researches are necessary to increase the understanding of the use and effects of prescribed fires in different environments (Hubbert et al., 2006). Few studies have addressed the long-term impacts of prescribed fires (Alcañiz et al., 2016). The present study was conducted in an experimental area within the Mediterranean rangelands, where wild-fires are frequent. We investigated the effect of a prescribed fire as a forest management tool in a dry-Mediterranean mountainous forest. We hypothesized that the use of a prescribed burning would have both short- and long-term effects on soil properties, vegetation cover, and hydrological and erosive response of the eco-geomorphological system. The main objectives are to study the impacts on: (i) on some soil properties, (ii) overland flow and sediment transport, and (iii) assess eco-geomorphological system resilience in a period of 5-years following the prescribed burning. The results will contribute to improve the Mediterranean forest and forestry management to reduce the risk and magnitude of wild-fires.

~~2.~~2 Material and ~~M~~methods

~~2.1.~~2.1 Study area

The study was conducted in the El Pinarillo experimental site (X: 424.240 m, Y: 4.073.098 m; UTM30N/ED50), located within the Sierra Tejeda, Almijara y Alhama Natural Park, in southern Spain. The area is characterized by a dry-Mediterranean climate (mean annual temperature: 18 °C; mean annual rainfall: 589 mm year^{-1}), and very steep calcareous mountains. The study site is located in an alluvial fan. Until the 1950s the area was cultivated with cereals. Since then it was abandoned and naturally recolonized by Mediterranean shrub species, in particular *Chamaerops humilis* L., *Cistus albidus* D., *Cistus clusii* D., *Stipa tenacissima* L., *Rosmarinus officinalis* L., *Thymus capitatus* L., and *Rhamnus alaternus* L. Soils are classified as Eutric leptosols (IUSS, 2014) that have a high proportion of surface rock fragment cover (> 50%), gravel content in the profile (total gravel content: 56%; gravel content > 10 mm: 31%; gravel content 2f mm: 10%; gravel content 5f 1 mm: 15%), and a sandy–loam texture (sand: 60%; silt: 32%; clay: 8%). Table 1 shows the eco-geomorphological features of the study site.

~~Table 1.~~Table 1 General characteristics and soil properties (October 2010) under natural conditions at the El Pinarillo experimental site. CEC: cationic exchangeable capacity; TC: total carbon; TN: total nitrogen; C/N: carbon/nitrogen ratio; EC: electrical conductivity; SOC: organic carbon content; SWC: soil water content.

alt-text: Table 1

		Field site
Annual rainfall	(mm year^{-1})	589
Climatic regime		Dry-Mediterranean
Main vegetal species		*Chamaerops humilis, Cistus albidus*~~,~~

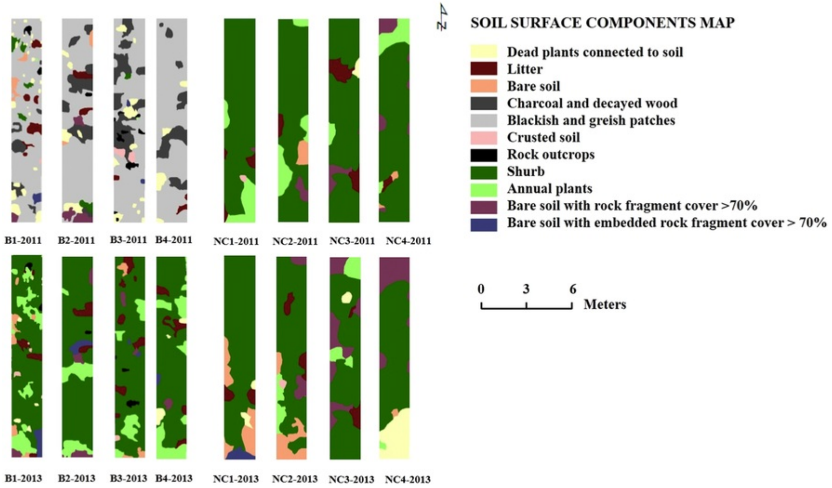
		Cistus clusii~~,~~
		Rosmarinus officinalis~~,~~
		Stipa tenacissima
Slope gradient	(%)	7.5
Aspect		170°N
Coordinates (X;Y)	(UTM30N/ED50)	424.240 m; 4.073.098 m
Soil properties		
Gravel	(%)	56
Sand	(%)	60
Silt	(%)	32
Clay	(%)	8
Field capacity SWC	(%)	25.2
Wilting point SWC	(%)	6.4
Available water	(%)	18.8
Aggregate stability	(%)	51
CEC	meq 100 g^{-1} soil	120.4
TC	(%)	12.5
TN	(%)	0.2
C/N	-	74
SOC	(%)	1.9
pH	-	8
EC	(μS cm^{-1})	501

~~2.2.~~2.2 Experimental design

The experimental site, considering its homogeneous slope gradient (7.5%) and aspect (170°N), involved two treatments: (i) prescribed fire (B) and; (ii) natural condition (NC). Specifically, the study included four burnt plots (replicas: B1, B2, B3 and B4) and four natural control plots (replicas: NC1, NC2, NC3 and NC4) arranged in a complete randomized block design (total number of plots: 8; plot size: 2 m × 12 m; 24 m^2). Each plot was enclosed using steel strips (50 cm height × 1 m wide). A 250 L container placed at the lowest point in each plot was used to collect overland flow and sediment. A tipping-bucket rainfall gauge (accuracy: 0.2 mm from Decagon) linked to an event data logger (HOBO Pendant Event Data Logger, ONSET) was installed in the experimental area in April 2011.

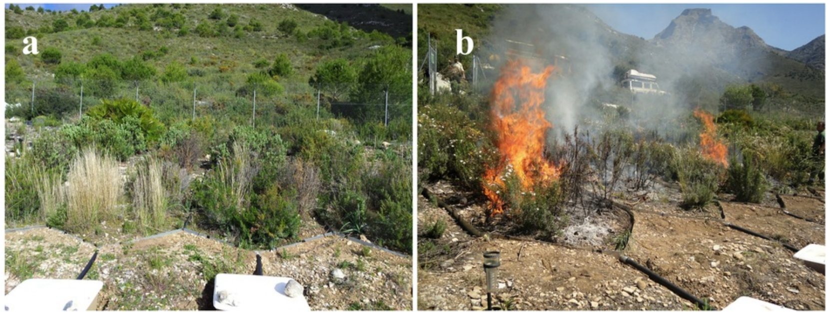
~~2.3.~~2.3 Prescribed fire

The prescribed fire was performed at the end of the Mediterranean rainy season, being the vegetation cover of approximately 80% (Fig~~ure.~~ 1). In 02/May/2011, the B plots were burnt by the Andalusian forest service (ICONA). In each plot the fire was initiated at the bottom and run upward (Fig~~ure.~~ 2). Regarding the meteorological conditions, the weather was sunny with no wind, the air temperature was 16.5 °C and humidity was 74%. The fire temperature above soil surface was not measured, but the flame height reached approximately 2 m, as estimated from photographic images taken during the fire. The fire severity was estimated to be low to moderate based on the two criteria from Maia et al. (2012): (i) there were intact plant stems after the fire, and some plants fully or partially retained their aerial system of leaves and stems (e.g., *Chamaerops humilis* L.); and (ii) the ash layer, measured randomly immediately following the fire, did not completely cover the entire area of each plot, but left blackish and greyish patches (Table 2).



~~**Figure 1.**~~**Fig. 1** Soil surface component maps from the four prescribed fire plots (B1, B2, B3 and B4) and the four natural conditions plots (NC1, NC2, NC3 and NC4) in May 2011 and May 2013.

alt-text: Fig. 1



~~**Figure 2.**~~**Fig. 2** View of the natural condition plot (a) and the burned plot during the prescribed fire (b).

alt-text: Fig. 2

~~**Table 2.**~~**Table 2** Spatio-temporal analysis of changes in percent cover by different classes in natural condition (NC) and prescribed fire (B) plots. Measurements were taken: three days after fire (wet season 2011) and two years after (wet season 2013). Class 1 (C1), dead plants connected to soil; class 2 (C2), litter; class 3 (C3), bare soil; class 4 (C4), charcoal and decayed wood; class 5 (C5), blackish and ~~grayish~~greyish; class 6 (C6), crusted soil; class 7 (C7), rock outcrops; class 8 (C8), shrubs; class 9 (C9), annual plants; class 10 (C10), bare soil with rock fragment cover of ~~more than~~ ≥70%; class 11 (C11), bare soil with embedded rock fragment cover of ~~more than~~ ≥70%. Where Games-Howell and Tukey~~’~~'s test: ^{a} indicates significant difference among NC2011 and NC2013 ($p \leq 0.05$); ^{b} indicates significant difference among B2011 and B2013 ($p \leq 0.05$); ^{c} indicates significant difference among NC2011 and B2011 ($p \leq 0.05$); ^{d} indicates significant difference among NC2013 and B2013 ($p \leq 0.05$).

alt-text: Table 2

Treatment	Data		C1	C2	~~-~~C3	~~-~~C4	C5	C6	C7	C8	C9	C10	C11
NC	2011	Replica 1	0.0	3.9	0.8	0.0	0.0	0.0	0.0	79.7	15.6	0.0	0.0
		Replica 2	0.0	3.1	4.2	0.0	0.0	0.0	0.0	73.3	16.1	3.3	0.0
		Replica 3	2.8	10.4	0.0	0.0	0.0	0.0	0.0	75.5	4.6	6.7	0.0
		Replica 4	0.0	1.9	1.7	0.0	0.0	0.0	0.0	78.2	11.3	6.9	0.0

		Mean	0.7^{c}	4.8	1.7	0.0^{c}	0.0	0.0^{a,c}	0.0^{c}	76.7^{c}	11.9^{a,c}	4.2	0.0^{c}
		SD±	1.4	3.8	1.8	0.0	0.0	0.0	0.0	2.8	5.3	3.3	0.0
	2013	Replica 1	2.6	6.5	16.4	0.0	0.0	0.0	0.0	67.2	0.0	7.3	0.0
		Replica 2	0.0	6.4	12.6	0.0	0.0	1.2	0.0	61.0	12.1	6.7	0.0
		Replica 3	3.8	4.4	0.0	0.0	0.0	0.0	0.0	58.3	14.6	18.9	0.0
		Replica 4	16.1	0.0	1.2	0.0	0.0	0.0	0.0	63.3	1.3	18.1	0.0
		Mean	5.6	4.3	7.6^{d}	0.0	0.0	0.3^{a}	0.0^{d}	62.5^{a}	7.0	12.8^{d}	0.0^{d}
		SD±	7.2	3.0	8.2	0.0	0.0	0.6	0.0	3.8	7.4	6.7	0.0
B	2011	Replica 1	7.3	7.1	5.2	9.2	58.8	1.1	2.6	4.1	0.3	1.9	2.4
		Replica 2	6.4	4.4	3.9	17.5	57.4	0.4	1.1	2.1	0.0	6.8	0.0
		Replica 3	8.7	0.9	0.0	21.4	58.6	5.3	2.9	0.9	0.2	0.0	1.1
		Replica 4	7.9	3.3	0.0	18.9	69.9	0.0	0.0	0.0	0.0	0.0	0.0
		Mean	7.6^{b,c}	3.9	2.3	16.8^{b,c}	61.2^{b,c}	1.7^{c}	1.7^{c}	1.8^{b,c}	0.1^{b,c}	2.2	0.89^{c}
		SD±	1.0	2.6	2.7	5.3	5.8	2.4	1.4	1.8	0.2	3.2	1.1
	2013	Replica 1	2.1	3.5	3.7	0.0	0.0	1.3	1.4	66.1	17.6	1.5	2.8
		Replica 2	0.0	4.4	0.0	0.0	0.0	0.0	0.7	71.4	15.7	5.2	2.6
		Replica 3	0.0	5.6	5.1	0.0	0.0	0.8	1.7	70.0	14.9	1.4	0.5
		Replica 4	3.7	5.1	0.0	0.0	0.0	0.0	0.0	71.1	16.0	2.2	1.9
		Mean	1.5^{b}	4.7	2.2^{d}	0.0^{b}	0.0^{b}	0.5	0.95^{d}	69.5^{b}	16.1^{b}	2.6^{d}	2.0^{d}
		SD±	1.8	0.9	2.6	0.0	0.0	0.6	0.8	2.4	1.1	1.8	1.0

~~2.4.~~2.4 Soil sampling and analysis

Soil from the B and CN plots was randomly sampled in spring 2011 (two days after the fire) and in spring 2016 (five years after the fire). On each sampling occasion 12 soil samples were collected from a depth of 0–5 cm in each plot (total = 48 per treatment). This sampling procedure was based on previous studies that suggested fire effects on soil are negligible below 5 cm (Aznar et al., 2013; Badía et al., 2014a, 2014b; Alcañiz et al., 2016; Armas-Herrera et al., 2016). Samples were taken to the laboratory and soil was air dried and sieved to 2 mm. The soil properties analyzed were: i) pH, which was measured in a deionized water suspension of the soil (2.5:1) using a Crisol GLP 21 pH meter; ii) electrical conductivity (EC), using a deionized water suspension of soil particles (5:1) using a Crisol Micro CM 2200 conductivity meter (ISRIC, 2002); iii) SOC, determined using the Walkley-Black method (Walkley and Black, 1934); iv) soil aggregate stability (AS), using the wet sieving method (Kemper and Rosenau, 1986) for aggregates sieved to 2 mm; v) cation exchange capacity (CEC), using ammonium acetate extraction (Knudsen et al., 1986) and measured with absorption spectrophotometry; and (vi) soil water repellency (SWR), determined with the ~~the~~ ethanol percentage test (EPT; Watson and Letey, 1970; Letey et al., 2000). The EPT classes considered were: very wettable (0.0% ethanol), wettable (3.0%), slightly water repellent (5.0%), moderately water repellent (8.5%), strongly water repellent (13.0%), very strongly water repellent (24.0%), and extremely water repellent (36.0%) (Doerr et al., 2002).

~~2.5.~~2.5 Overland flow and sediment transport measurement

Rainfall, overland flow and sediment were measured from the studied plots between May 2011 and December 2014. At the bottom of each plot, a container of 250 L was installed for collecting overland flow and sediment. Total overland flow after each overland flow event was measured by inserting a ruler into the containers. Overland flow samples (1 L) were collected in the container after each event, for laboratory analysis, to determine sediment concentration. Sediments were measured at three heights within each container following mixing of the water, and multiplied by the volume of water, in order to calculate the sediment yield.

~~2.6.~~2.6 Soil surface components

The effect of the prescribed fire on vegetation recovery was evaluated by means of the monitoring of soil surface components. This was conducted at the end of the wet seasons in 05/May/2011 (three days after the prescribed fire) and two years later, in 07/May/2013 (Fig~~ure~~. 1 and Table 2). The measurements were made using the method described by Calvo-Cases et al. (2005), Arnau-Rosalén et al. (2008) and Hueso-González et al. (2018a). A grid of 4~~x~~ × 2 m defined within each was marked and photographed using a camera placed 6 m above the center of each grid. A global navigation satellite system (Leica GPS1200) was used to geo~~-~~reference the grid knots. The ArcGis 10.2 georeferencing tool was used to orto-rectify the images. Afterwards, following the method described by Ruiz-Sinoga and Martínez-Murillo (2009), the images were used to map the vegetation and soil surface components considering their behavior regarding the rainfall and overland flow generation: as sink areas, bare soil with embedded rock fragments and no crust accounting for >~~-~~70% of cover, with cover including shrubs, litter, dead plants, and annual plants; and as source areas rock outcrops and bare soil areas having on-top rock fragment and no crust accounting for >~~-~~70% of cover, with cover including charcoal and decayed wood, blackish and greyish patches, and crusts.

~~2.7.~~2.7 Statistical analysis

Normal distribution and homogeneous variance were verified using the Kolmogorov–Smirnov and Levene's tests, respectively. Differences in soil properties were determined using a one-way analysis of variance (ANOVA). For non-homoscedastic data (Levene's test: $p \leq 0.05$) the nonparametric Mann-Whitney U test was used. If statistical significances were observed at a $p \leq 0.05$, a Tukey HSD or a Games-Howell test was carried out. In both treatments, regression analysis was used to assess the relationship between rainfall and overland flow ($p \leq 0.05$). All statistical analyses were performed using SPSS software (version 21) for Windows (IBM Corp., 2012).

~~3.~~3 Results and discussion

~~3.1.~~3.1 Effects on soil properties

The soil properties analyzed immediately following the prescribed fire and 5-years later are shown in Table 3. Two days after the fire, the SOC in the B plots increased slightly relative to the NC plots (Table 3; B2011 = 4.5% ± 2.2%, NC2011 = 4.2% ± 0.9%), although the changes were not statistically significant (Table 4, $p = 0.88$). Five years later the fire the mean SOC in B2016 increased to 5.0 ± 1.6% (Table 3), although this increment was also not statistically significant compared to NC2016 (Table 4, $p = 0.34$). The absence of differences in SOC in the B plots respect to the NC plots suggests that after 5-years the increase may be owing to the effect of inter-annual variability in SOC under Mediterranean climatic conditions (Bulluck et al., 2002; Adekalu et al., 2007; Mulumba and Lal, 2008; Hueso-González et al., 2014) rather than because of the effect of fire which was considered of low to moderate severity (Maia et al., 2012). Our findings are consistent with those of Nave et al. (2011) and Fernandes et al. (2013) who demonstrated that low severity fires may not have impacts on SOC, explaining the lack of statistical differences.

~~Table 3.~~**Table 3** Mean and standard deviation (SD±) of soil properties at the natural condition plot (NC) and burnt plot (B), two days (2011) and five years (2016) after the prescribed fire. Where: n, number of samples, SOC, soil organic carbon (%); EC: electrical conductivity (µS cm^{-1}); CEC: cationic exchangeable capacity (meq 100 ~~gr~~ g soil^{-1}); AS~~,~~ (aggregates stability (%)), hydrophobicity and percentage of ethanol class (EPT).

alt-text: Table 3

Soil properties	n	2011				2016			
		NC		B		NC		B	
		Mean	SD±	Mean	SD±	Mean	SD±	Mean	SD±
SOC	48	4.2	0.9	4.5	2.2	5.7	2.1	5.0	1.6
pH	48	7.7	0.1	7.7	0.1	8.1	0.1	8.1	0.1
EC	48	347.3	31.9	450.5	49.1	335.6	7.8	356.3	27.2
CEC	48	28.0	8.3	26.3	1.9	26.3	7.3	26.1	5.1
AS	~~-~~	~~-~~	~~-~~	~~-~~	~~-~~	~~-~~	~~-~~	~~-~~	~~-~~
<0.053 mm	48	62.5	17.5	53.4	2.0	70.7	6.6	67.1	7.4
0.053~~-~~–0.125 mm	48	55.3	15.1	52.0	4.7	65.6	9.6	63.2	6.2
0.125~~-~~–0.5	48	27.9	15.6	12.0	4.6	52.1	14.9	37.0	8.4
0.5~~-~~–1 mm	48	20.3	17.9	4.5	0.9	28.2	3.0	18.5	12.9
1~~-~~–2 mm	48	6.7	4.3	2.1	1.6	15.5	8.0	13.2	13.7

>2 mm	48	91.9	1.9	81.3	11.7	90.3	8.0	93.1	13.7
EPT	48	6.3	1.0	6.5	1.0	6.3	1.0	6.3	0.0

~~Table 4.~~Table 4 Mann-Whitney U test results. Where: SOC = soil organic carbon; EC = electrical conductivity; CEC = cationic exchangeable capacity; AS = aggregates stability; B = burnt plot; NC = natural conditions plot.

alt-text: Table 4

Soil properties	B2011-NC2011	B2011-B2016	B2016-NC2016
SOC	0.88	0.68	0.34
pH	0.88	0.23	1.00
EC	0.04*	0.03*	0.28
CEC	0.08	1.00	1.00
AS	~~-~~	~~-~~	~~-~~
<0.053 mm	0.34	0.89	0.34
0.053~~-~~–0.125 mm	0.88	0.08	1.00
0.125~~-~~–0.5	0.06	0.11	1.11
0.5~~-~~–1 mm	0.13	0.15	0.34
1~~-~~–2 mm	0.20	0.15	0.48
>2 mm	1.12	0.09	1.10

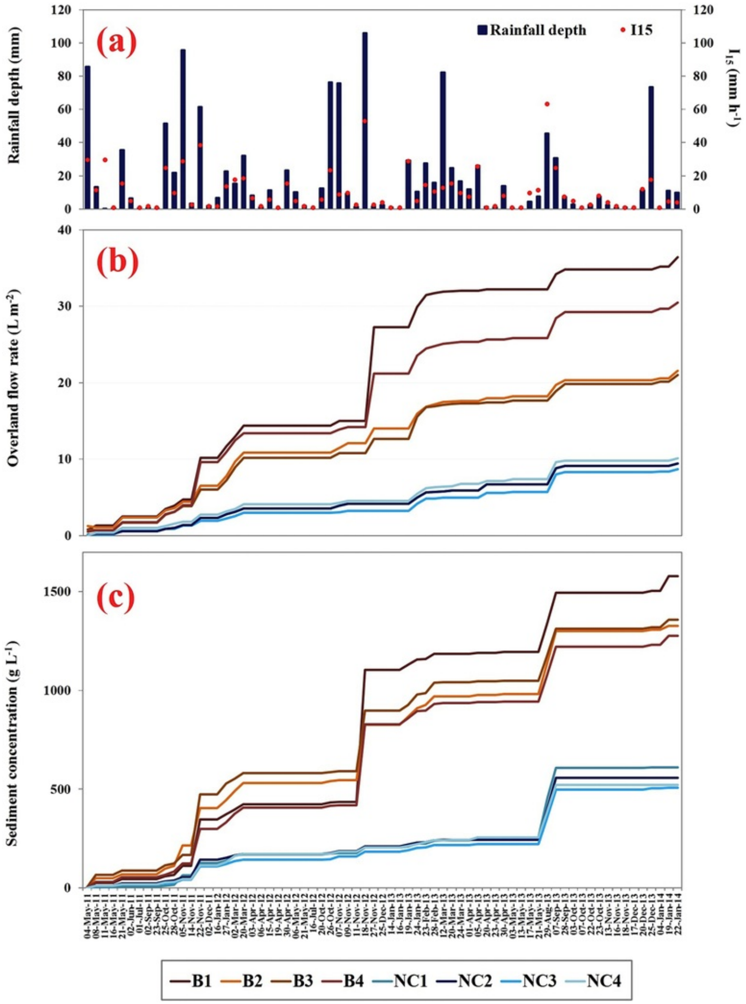
* Indicates significant differences among the treatment ($p \leq 0.05$).

Fire affects SWR, these effects can be highly variable, depending on the type of organic matter consumed, soil heating regime and the amount of oxygen available during burning (Doerr et al., 2009; Malvar et al., 2015). Understanding the extent and relevance of SWR is crucial to understand the impacts of prescribed fire as a land management tool. Varela et al. (2005) reported that the pre-fire SWR dictates the changes it undergoes upon burning. In our study, SWR was observed in all plots and classified as strong severity (Table 3). After the prescribed fire, SWR was modified neither in a short nor long term (Table 3). Probably, this occurred due to the low severity of fire not producing sufficient heating to destroy repellency at the soil surface, which was also observed by Doerr et al. (1998) for pre-fire strong repellent soils in eucalypt stands in Portugal and by Rodríguez-Alleres et al. (2012) for pine stands of NW Spain.

The AS values between B2011 and NC2011 were not statistically significant (Table 4; $p \geq 0.05$), similar to the SOC and SWR (Table 3). Two factors may explain why no changes in AS were observed. First~~,~~, according to Badía and Martí (2003), because of low intensity fires are ineffective in disrupting organic cements agents of the soil aggregates, the structural stability is not expected to decrease. Secondly, because in this study the prescribed fire did not change the hydrophobicity of the soil at the upper soil surface layer (Table 3; strong hydrophobicity in both the B and NC plots). According to Mataix-Solera and Doerr (2004), in calcareous soil exposed to low intensity fires, the increment in soil structural stability is mainly associated with the formation of a hydrophobic film on the external surfaces of aggregates. However, the evaluation of the long-term effects of the prescribed fire showed that all aggregate fractions slightly rise but this increase was not significant in the B2016 plots compared with B2011 (Tables 3 and 4; $p > 0.05$). In the B treatment the vegetation cover (shrub and annual plants) had significantly increased within two years after the burning (Table 2; $p < 0.05$). Thus, this slight increase can be explained by the liberation of cementing agent during post-fire vegetation recovery (Marcos et al., 2000; Granged et al., 2011). This is consistent with the results presented for the soil surface component maps (Fig~~ure~~. 1).

Table 3 shows that the pH did not change significantly following the prescribed fire (Tables 3 and 4; $p \geq 0.05$). Furthermore, the soil pH remained relatively stable throughout the study period, indicating that the prescribed fire did not have a long-term effect in the soil pH (Table 3; pH = 8.1 ± 0.1 in B2016 and NC2016). Although the differences were minor, slightly lower pH values were found in B2011 and NC2011 than in B2016 and NC2016. Ruiz-Sinoga et al. (2012) showed that during the Mediterranean wet seasons, higher amounts of rainfall might modify the lixiviation process in soils and produce a slight decrease in the concentration of cations. This finding was also consistent with the absence of changes in SOC (Table 3) and associated rather to the inter-annual variability in rainfalls than the long-term effects of fire on soil (Hueso-González et al., 2014). The absence of differences in pH between the B and NC plots (Table 4; $p > 0.05$) may be explained by the low severity of the prescribed fire. Previous works demonstrated an increase in soil pH following a fire is mainly because of the oxidation of the organic matter and by the ash incorporation (Úbeda et al., 2005; Mataix-Solera et al., 2009; Úbeda and Outeiro, 2009; Granged et al., 2011; Bodí et al., 2014; Pereira et al., 2013(It should be: Pereira et al., 2014)). Similar to pH, CEC values for the NC2011 and B2011 plots were very similar (Table 3; 28.0 ± 8.3 meq 100 g soil^{-1} and 26.3 ± 1.9 meq 100 g soil^{-1}, respectively). In addition, no differences were observed in CEC values over the study period (Table 4; $p = 1.00$), which can be explained by the low severity of the prescribed fire. Certini (2005) observed that increases in CEC only occurred when high temperatures are reached during the ignition (>450–500~~°C~~ °C). Our findings are also consistent with those of Brye (2006), who reported non-significant increases in cations after a low intensity prescribed burning.

The trend in EC was slightly different respect to the other soil properties. Table 3 shows that the mean EC value increased significantly after the prescribed fire, rising from 347.3 ± 31.9 μS cm^{-1} in NC2011 to 450.5 ± 49.1 μS cm^{-1} in B2011 (Table 4; $p = 0.04$). An increase in EC after prescribed fire has also been reported by Granged et al. (2011). Such an increase is generally expected owing to the incorporation of ash into the soil (Certini, 2005; Cerdá and Doerr, 2005). In contrast, 5-years after the prescribed burning, the average EC value in B2016 plots showed a significant decline compared to B2011 (to 356.3 ± 27.2 μS cm^{-1}). According to Badía and Martí (2008) reduction in EC in post-fire periods are usually results of the overland flow increase (Fig~~ure~~. 3). Thus, no significant difference from the NC2016 value was observed (Table 4; $p = 0.28$). The reduced EC values in B2016 regarding B2011 can be also attributed to the leaching of soil ions during the five-year study period (Úbeda et al., 2005; Scharenbroch et al., 2012).



~~Figure 3.~~**Fig. 3** (a) Rainfall depth (bars, mm), maximum intensity in 15 min (red dot, I_{15}, mm h^{-1}); (b) cumulative overland-flow rate (L m^{-2}) and; (c) cumulative sediment concentration (g L^{-1}). Where: B1, prescribed fire (plot 1); B2, prescribed fire (plot 2); B3, prescribed fire (plot 3), B4; prescribed fire (plot 4); NC1, natural conditions (plot 1); NC2, natural conditions (plot 2); NC3, natural conditions (plot 3); NC4, natural conditions (plot 4). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

alt-text: Fig. 3

~~3.2.~~3.2 Effects on overland flow and sediment yield

In this study, the hydrological and erosive responses of B and NC plots showed differences throughout the study period (Fig~~ure~~. 3 and Table 5). A total of 64 events occurred from 04 May 2011 to 31 December 2014 (Fig~~ure~~. 3). The recorded rainfall was equal to 1~~,~~281 mm registered in 430.8~~ hours~~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~~ hours~~h. Fig~~ure~~. 3 shows the greatest rainfall events in depth and maximum rainfall intensity in 15~~ minutes~~min (I_{15}) registered in the experimental site since the prescribed fire was conducted.

~~Table 5.~~**Table 5** Overland flow rate (L m^{-2}) and sediment concentration (g L^{-1}) characteristics for prescribed fire (B) and natural conditions (NC) plots. n: number of plots per treatment; N: number of rainfall events that generated overland flow and sediment yield; SD: standard deviation; Max: maximum.

alt-text: Table 5

		n	N	Average	SD±	Max	Accumulated
Overland flow rate (L m^{-2})	NC	4	16	0.1	0.3	2.3	9.4
	B	4	24	0.4	0.5	12.3	27.9
Sediment concentration (g l^{-1})	NC	4	16	17.1	3.4	154.6	409.5
	B	4	24	54.3	38.0	668.9	1302.3

Quantifying the impacts of prescribed fires on overland flow and sediment yield is essential (Thomaz and Fachin, 2014; Martínez-Murillo et al., 2016). Although factors responsible for post-fire effects in both variables are well documented (DeBano et al., 1976; Inbar et al., 1998, Johansen et al., 2001; Pierson et al., 2001, Shaskesby and Doerr, 2006), prescribed fire planning must address site-specific impacts and the spatial and temporal scale of fire effects. In B plots, from a total of 64-rainfall registered events, 24 of them (38%) were considered as erosive rainfall events because they generated overland flow (Fig~~ure~~. 3 and Table 5), whilst only 16 of them in NC plots (Fig~~ure~~. 3 and Table 5). According to Hueso-González et al. (2015) this fact implied that the rainfall threshold for overland flow generation might be lower for areas subjected to prescribed fires. Specifically, these 8 extra events listed in B plots were recorded in the first two years following the prescribed burning being influence by the rainfall depth and I_{15} (Fig~~ure~~. 3). The differences between B and NC plots were clear in the overland flow thresholds: whil~~e~~st the NC plots needed a minimum rainfall depth and intensity of 21.6 mm and 15.2 mm h^{-1}, respectively, to generate overland flow, the B plots only 10.6 and 8.8 mm h^{-1} (Fig~~ure~~. 3).

Similarly to these results, other studies conducted in Mediterranean areas have identified the first two years as the most critical periods for post-fire flooding and sedimentation (Robichaud et al., 2000). Specifically, some authors registered the major soil losses during the first rainfall event after the experimental fire (Soto et al., 1994; Campo et al., 2006; González-Pelayo et al., 2010). Other authors observed the greatest overland flow volumes three years after fire related to a low plant recovery due to Mediterranean drought period (Mayor et al., 20~~1~~07). In this study, the highest overland flow and sediment yield rates were not recorded during the first rain event once the experimental fire was conducted and occurred just two days after. Indeed, the major overland flow and sediment concentration were recorded at the end of summer, 5-months after the prescribed burning (Fig~~ure~~. 3). This reflects the high variability in rainfall regime in the Mediterranean climate and the often slow rate of vegetation recovery such that can be susceptible to erosion for years rather than months after a wildfire (Shakesby, 2011). In order to identify the relation between rainfall regime and hydrological and erosive response from plots, a regression analysis was performed comparing duration, depth and intensity of rainfalls vs. overland flow (Table 6). In B plots, I_{15} showed the best fitted lineal equation and was statistically significant ($R^2 = 0.44$, $p < 0.05$). However, neither rainfall depth nor duration were statistically significant correlated ($R^2 = 0.26$; $R^2 = 0.02$, $p > 0.05$). Consequently, I_{15} mainly controlled overland flow and sediment yield from B plots as corroborated their major overland flow rates (Fig~~ure~~. 3). Examples of events occurring this were those registered in 22/Nov/2011 (rainfall depth = 61.4 mm; I_{15} = 38.4 mm h^{-1} and duration = 15.1 h) and 18/Nov/2012 (rainfall depth = 105.1 mm; I15 = 58.8 mm h^{-1}~~-1~~ and duration = 14.5 h). On contrary, in NC, none of the rainfall variables were characterized by a statistically significant correlation coefficient ($R^2 = 0.03$; $R^2 = 0.02$, $R^2 = 0.27$, respectively; $p < 0.05$). This lack of significant correlation was explained by the presence of vegetation in the NC plots, which may change the overland flow generation mechanisms (Inbar et al., 1998; Alegre et al., 2004; Boix-Fayos et al., 2007).

~~Table 6.~~Table 6 Regression analysis of overland flow rate versus rainfall depth, rainfall intensity (I_{15}) and rainfall duration considering the whole database. Asterisk indicates that the correlation coefficient (R^2~~2~~) is statistically significant for $p < 0.05$. Where: B, prescribed fire; NC, natural condition.

alt-text: Table 6

		Linear regression	R^2~~2~~
B	Rainfall depth	y = 0.0481 x	0.26
	I_{15}	y = 0.1170 x	0.44*
	Duration	y = 0.0804 x	0.02
NC	Rainfall depth	y = 0.0061 x	0.02
	I_{15}	y = 0.0279 x	0.27
	Duration	y = 0.0062 x	0.03

Significant differences were observed between B and NC plots were observed (Fig~~ure~~. 3). At the end of the study period, B plots registered major rates than the NC ones (NC = 9.4 L m^{-2}, B = 27.9 L m^{-2}; Table 5). Statistical differences were also observed in the maximum overland flow, recorded in the B plots (Fig~~ure~~. 3 and Table 5; B1 = 12.3 L m^{-2}) (Fig~~ure~~. 3). However, the approximately sigmoid shapes of the overland flow response curves for the monitoring period showed the initial overland flow rate and sediment concentration progressively declined with time after the fire (Fig~~ure~~. 3). Subsequently, in B plots, 84% of the total overland flow was registered at the beginning of the third year following the burning (Fig~~ure~~. 3; May 2013), whilst, in NC plots, only 60%. There was a strong similarity between the trend of the curves described for overland flow rate and sediment yield concentration in burned and unburned plots (Fig~~ure~~. 3). The B plots showed higher amounts of sediment concentration (NC = 409.49 g L~~-~~$^{−1}$, B = 1~~,~~302.34 g L~~-~~$^{−1}$; Table 5). Here, 74.6% of the total sediment was registered at the beginning of the third year after the prescribed fire. In NC plots only 43.0% (Fig~~ure~~. 3). Soler and Sala (1992) reported that after a low severity prescribed fire a high increase (>16 times) of sediment removed during the 7 months of post-fire compared to the control plot. Soto et al. (1994) observed that two-year after an experimental fire, the soil losses were 1.6–4.5 times higher than the control. In addition, two years after the prescribed fire, the overland flow rate and the sediment concentration generated per event from the fire-exposed plots were similar to the flow and sediment produced in the NC plots (Fig~~ure~~. 3). This is related of the high resilience of Mediterranean vegetation to fire (Inbar et al., 1998; Giovannini et al., 2001).

~~3.3.~~3.3 Vegetation recuperation, system hydrodynamics and resilience

Immediately after the prescribed fire and during the following two years the overland flow and sediment yield increased (Fig~~ure~~. 3 and Table 5). Previous studies found that overland flow and erosion rates may be increased after the fire, though both of them decreased as the post-fire vegetation recovery is observed (Andreu et al., 2001; Cerdà and Lasanta, 2005). Thus, the length of these two periods constitutes the relaxation or recovery time and is one of the key factors to control the soil loss (Moody and Martin, 2001a, 2001b(, Hueso-Gonzalez et al., 2018b)). Two days after the burning there were significant differences in vegetation cover comparing B and NC plots (Table 2 and Fig~~ure~~. 1). As expected, just after the prescribed fire, the mean cover of still alive vegetation (classes 8 and 9) was significantly reduced in B2011 (Table 2, $p \leq 0.05$) being the vegetation cover equal to 1.9% whil~~e~~st NC plots showed one of 88.6%. Immediately after the fire, the values for the three main soil surface components that dominated the hydrological response in B plots were: charcoal and decayed wood (16.8 ± 5.35%); blackish and greyish areas (61.2 ± 5.8%); and bare soil (7.9 ± 1.0%). This implies that >85.0% of the total area was acting as a source area for runoff, causing the higher overland flow rates found in the initial two years in the B plots (Fig~~ure~~. 3). This was evident during the rapid response of overland flow to extreme rainfall events (Fig~~ure~~. 3), including those registered on 22/Nov/2011 (rainfall depth: 61.4 mm; I_{15}: 38.4 mm h$^{−1}$) and 18/Nov/2012 (rainfall depth: 105.8 mm; I_{15}: 52.8 mm h$^{−1}$). This indicated that the overland flow, and thus the major erosion rates, was initially generated owing to rainfall excess (~~h~~Hortonian model) (Horton, 1933; Lavee et al., 1998; Ward and Robinson, 2000; Beven, 2002; Calvo-Cases et al., 2003; Cammeraat, 2004; Latron et al., 2007; Hueso-González et al., 2015).

Following a prescribed fire, the rate of vegetation recovery plays an essential role in minimizing negative impacts in the eco-geomorphological system (Inbar et al., 1998; De Luis et al., 2001; Beyers, 2004; Cerdá and Doerr, 2005; Mayor et al., 2007). Pardini et al. (2004) noted that the three years immediately following a fire are the most critical for reconstruction of adequate soil and plant mantles. A relaxation time of three years was reported in some studies from USA (Brown, 1972; Moody and Martin, 2001a). 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 reached the steady-state conditions after 7 years. In our study, two years after the burning, the vegetation cover in B plots significantly increased in B2013 compared to B2011 (Table 2; mean class 8 and 9: 85.6%). Even the average soil surface coverage by shrub and annual plants was 16.1% higher in B2013 than in NC2013. Besides, the burning with low fire severity triggered changes in the plants communities increasing the richness of annual and perennial herbaceous species. Specifically, annual plants covered the 9% of the total area of B plots with regard to NC2013 (Table 2). Similarly, Caturla et al. (2000) and Vilà et al. (2001) demonstrated the germination of herbaceous plants, increase after the fire. All this implied that, in the medium and long term, prescribed fire prevented the risk of severe wildfires and enhanced vegetation growth relative to unburnt areas (Heydari et al., 2016). This also explained the change in the trend in overland flow for B plots at the beginning of the third rainy season (October 2013; Fig~~ure~~. 3). Thus, after this period, the overland flow generation was similar to that registered in NC plots. Our results are similar to those of Pausas (1999) who reported that, approximately 50% and 60% of recovery in a burnt area, occurred after one and three years, respectively. Núñez et al. (2008) found that the percentage of bare soil decreased very rapidly during the first year following a fire, principally as a consequence of herbaceous growth, and three years after the fire in the case of woody species. These results manif~~i~~ested the extraordinary resilience of Mediterranean vegetation in overcoming the impact of a low intensity prescribed fire.

~~4.~~4 Conclusion

The prescribed fire studied did not changed the majority of the soil properties studied. However, the hydrological and erosive responses of the burned plots were changed by fire. In the first months following the fire, the threshold for overland flow generation in the burnt plots is lower considering both rainfall depth and intensity. In addition, the 74.6% of the total soil loss is recorded at the beginning of the third year after the burning. This can be explained because initially ~~more than~~ >85.0% of the total area of the burnt plots is acting as source area for infiltration. Nevertheless, the source area percentage decreases very rapidly during the second year following the fire, principally owing to the regrowth of herbaceous plants and shrubs, even being the vegetation covers a 16.1% of soil surface higher in the burnt plots than in the natural condition plots. This was rendered in similar values of overland flow and sediment after two years of study with regard to those registered in natural conditions. Finally, these results support the effectiveness of prescribed fires to decrease the risk and negative effects of intense wildfire in Mediterranean ecosystems, as it can be applied as management tool for reducing fuels and maintaining, even improving, the vegetation cover.

Uncited references

Cerdà et al., 1995

Eaton et al., 2008

Ghimire et al., 2017

Hueso-González et al., 2018b(This reference has been placed)

Pereira et al., 2014(This reference has benn placed)

Rowe et al., 1954

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Sarah, 2005

Acknowledgments

The study was funded by the P09-RNM-5057 research project (Autonomous Government of Andalusia, Spain) ~~as well as by the Campus Andalucia Tech~~. Also, authors thank to TRAGSA Company their technical support during the experimental site set-up.

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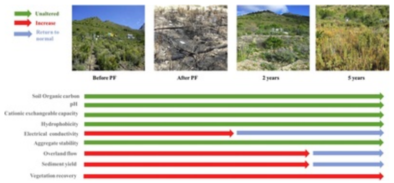
Graphical abstract



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Highlights

- Prescribed fire ~~are~~is a common management practice in Mediterranean regions.
- Addressing the systemic response following prescribed fire helps us to prevent wildfire.
- Prescribed fire could provide long term systemic benefits to Mediterranean forests.
- Low intensity prescribed fire not reported significant changes in soil properties~~.~~
- In long term, low intensity prescribed fire enhances post-fire vegetation recovery.

Queries and Answers

Query:

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Answer: Table 4. Mann-Whitney U test results. Where: SOC = soil organic carbon (%); EC = electrical conductivity (µS cm-1); CEC = cationic exchangeable capacity (meq 100 g soil^{-1}); AS = aggregates stability (%); B = burnt plot; NC = natural conditions plot. *Indicates significant differences among the treatment ($p \leq 0.05$).

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