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Impact of an intense rainfall event on soil properties following a wildfire in a Mediterranean environment (North-East Spain)

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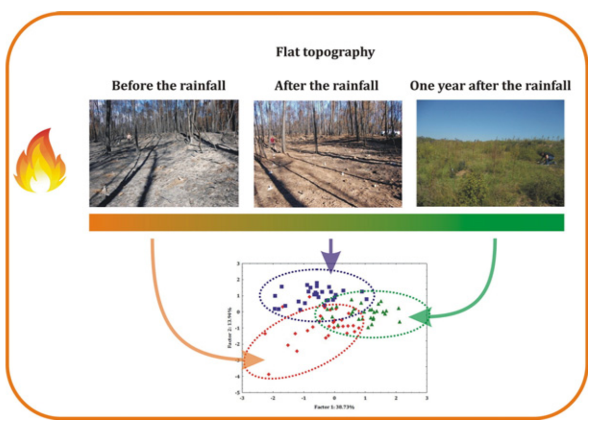
HIGHLIGHTS

- Ash resulting from severe fire episode reduces raindrop impact on soil aggregates.
- Management, vegetation regrowth and soil chemistry decrease soil aggregate stability.
- Intense rainfall on fire-affected soils does not affect soil TN and TC levels.
- Intense rainfall increases cations, phosphorous and SPAR in soil solution.

GRAPHICAL ABSTRACT



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ABSTRACT

Intense rainfall events after severe wildfires can have an impact on soil properties, above all in the Mediterranean environment. This study seeks to examine the immediate impact and the effect after a year of an intense rainfall event on a Mediterranean forest affected by a high severity wildfire. The work analyses the following soil properties: soil aggregate stability, total nitrogen, total carbon, organic and inorganic carbon, the C/N ratio, carbonates, pH, electrical conductivity, extractable calcium, magnesium, sodium, potassium, available phosphorous and the sodium and potassium adsorption ratio (SPAR). We sampled soils in the burned area before, immediately after and one year after the rainfall event. The results showed that the intense rainfall event did not have an immediate impact on soil aggregate stability, but a significant difference was recorded one year after. The intense precipitation did not result in any significant changes in soil total nitrogen, total carbon, inorganic carbon, the C/N ratio and carbonates during the study period. Differences were only registered in soil organic carbon. The soil organic carbon content was significantly higher after the rainfall than in the other sampling dates. The rainfall event did

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Aggregate stability
Major cations
SPAR

increase soil pH, electrical conductivity, major cations, available phosphorous and the SPAR. One year after the fire, a significant decrease in soil aggregate stability was observed that can be attributed to high SPAR levels and human intervention, while the reduction in extractable elements can be attributed to soil leaching and vegetation consumption. Overall, the intense rainfall event, other post-fire rainfall events and human intervention did not have a detrimental impact on soil properties in all probability owing to the flat plot topography.

1. Introduction

Intense rainfall episodes are common in the Mediterranean area (Pereira et al., 2015a), especially during the autumn following warm, dry summers that are responsible for severe wildfires (Versini et al., 2013). Extreme autumn rainfall is expected to increase in the future due to climate change in the Mediterranean basin (Kysely et al., 2012), generating flash floods, with a highly detrimental impact for fire-affected areas (Shakesby, 2011; Ferreira et al., 2015).

Fire is a natural phenomenon in many ecosystems and has obviously been fundamental to human evolution (Vélez, 2000). However, in recent times, as a consequence of land abandonment and climate change, fire regimes have changed and fire intensities and severities have increased, all of which has had major social, economic and environmental implications (Dale et al., 2001; Clark et al., 2014). Indeed, fire has even been described as a global 'herbivore' (Bond and Keeley, 2005). Since the 1950s, Mediterranean environments have become especially vulnerable to summer wildfires for three main reasons: first, the rural exodus, the gradual abandonment of forest management practices and, consequently, an increase of fuel accumulation; second, the industrial plantation of monospecific, flammable tree species; and, third, more frequent and more intense summer heat-waves and droughts, which have increased the meteorological and climate risks of the occurrence of forest fires (Mataix-Solera and Cerdà, 2009; Shakesby, 2011; San-Miguel-Ayanz et al., 2013). These high severity wildfires bring about the destruction of vegetation cover (Úbeda et al., 2006; Tessler et al., 2015), the volatilization and evacuation of nutrients by ash (Bodí et al., 2014; Pereira et al., 2015b,c), and an increase in soil and water loss through erosion and runoff (Cerdà and Lasanta, 2005; Cerdà and Doerr, 2008; Gimeno-García et al., 2008), which can have a negative impact on rivers and other water bodies (Smith et al., 2011; Brown et al., 2015; Estrany et al., 2015).

Previous studies of Mediterranean ecosystems observed that severe wildfires can make major changes to a soil's physical and chemical properties (Kutiel and Naveh, 1987; Knicker et al., 2005; Arcenegui et al., 2008; Certini et al., 2013; Badía et al., 2014; Inbar et al., 2014). Soil aggregate stability can be severely affected by fire (Cerdà, 1993; Cerdà et al., 1995). According to Mataix-Solera et al. (2011), the impact of fire on soil aggregates depends on how the fire affects other soil properties (including its mineralogy, water repellency, organic matter content and microbiology). Additionally, the impact will depend on associated geographical variables, such as aspect (Andreu et al., 2001), on the type of fire (Mataix-Solera et al., 2002) and on the soil type. The studies reported to date fail to provide a consensus, with some identifying an increase (Campo et al., 2006; Arcenegui et al., 2008), a decrease (Mataix-Solera et al., 2002; Kavdir et al., 2005) or no impact (Varela et al., 2010) on soil aggregate stability after severe wildfires. Indeed, Mataix-Solera et al. (2011) report that depending on many factors, fires can result in a disaggregation, owing to the consumption of organic matter, or in an aggregation, owing to the recrystallization of some iron and aluminum oxyhydroxides.

Wildfires have also been shown to change other essential soil chemical properties, albeit temporarily (Bento-Goncalves et al., 2012). Typically, nitrogen and carbon levels decrease after a severe wildfire due to low-temperature volatilization at around 200 °C (Hernandez et al., 1997; Grogan et al., 2000; Johnson et al., 2004; Badía et al., 2014). The nitrogen and carbon fractions that are not volatilized, but present in the ash, are transformed by the heat from the fire (e.g., black carbon, black nitrogen and carbonates) (Knicker, 2007; Gonzalez-Perez et al., 2004), and later incorporated into the soil profile (Knicker et al., 2013; Boot et al., 2015). The pyrolyzed material incorporated into the soil profile has a low C/N ratio, given that nitrogen is mineralized more rapidly than carbon (Baird et al., 1999). This process of mineralization increases the short-term availability of soluble forms of nitrogen and carbon (Prieto-Fernándeze et al., 2004), soil pH, electrical conductivity (EC) and the major extractable elements (Kutiel and Inbar, 1993; Murphy et al., 2006). The ease of solubility of these elements is critical for the regeneration of vegetation. However, at the same time, the type and amount of nutrients released depend heavily on the severity of the fire and the type of forest affected (Raison and McGarity, 1980; Úbeda et al., 2009; Pereira et al., 2012, 2014).

All in all, the disturbance induced by fire in both the type and the amount of available nutrients, with some being more soluble than others, affects the ratios between these nutrients. Typically, in the immediate post-fire period, an increase is recorded in the major extractable nutrients and a reduction is seen in the minor elements as a consequence of the rise in soil pH (Pereira et al., 2011). Studies conducted elsewhere have shown that solutions richer in extractable sodium and potassium in relation to the levels of calcium and magnesium can increase clay dispersion and reduce aggregate stability (Sarah, 2004, 2005; Igwe, 2005; Bagarello et al., 2006), which in turn may make soils more vulnerable to erosion after a fire. Normally, soil extracts from fireaffected areas and ash slurries are rich in sodium and potassium (Khanna et al., 1994; Liodakis et al., 2009; Pereira et al., 2014). The increase in the amount of monovalent cations in burned soils can increase the potential effect of soil solute chemistry in the soil structure. This is especially relevant in recently burned areas, because it is when the soils are most vulnerable to erosion, owing to litter combustion and vegetation removal (White et al., 1996; Duguy et al., 2012). The presence of a layer of ash, rich in sodium and potassium, can release solutions that act as dispersants of soil particles after the first rainfalls, or when incorporated into the soil profile. This additional disturbance may increase the vulnerability of soils to erosion. The study of the sodium and potassium adsorption ratio (SPAR) is important to understand this impact. Very few studies, to date, have assessed the impact of fire on SPAR. To the best of our knowledge, the only study examining the effects of fire on the SPAR was conducted by Pereira et al. (2014) in ash extracts. Here, the authors identified a significant increase in the SPAR in relation to litter solutions in ash slurries. Other studies in fire-affected areas have examined the sodium adsorption ratio (SAR) in soils, but ignoring the contribution of extractable potassium (Blank et al., 2003; Inbar et al., 2014). However, it is important to consider extractable potassium as a potential dispersant, especially in fire-affected areas, where ash and burned soil release considerable amounts of this element in solution (Blank and Zamudio, 1998; Badía and Martí, 2003; Murphy et al., 2006).

The recovery of the burned areas depends on both the topography (e.g., aspect and slope) of the fire-affected area and the meteorological conditions, especially the wind, and the amount and intensity of rainfall. In the immediate post-fire period, wind and rain can (re)distribute ash and the nutrients available for plant recovery across the burned area (Moody et al., 2013; Pereira et al., 2013, 2015b). Meteorological variables are a critical aspect in post-fire environments. The interaction between extreme rainfall episodes and wildland fires is complex, with the fire severity variability being a key factor at the microplot scale (De Luis et al., 2003). Indeed, extreme rainfall events after wildland fires are the cause of high rates of soil erosion, and water and nutrient losses in Mediterranean environments (Inbar et al., 1998; Shakesby, 2011).

Given the impact of torrential rainfall events on areas affected by wildfires, it is clearly important to determine their effects on soil properties. In particular, it is interesting to monitor the significance of the changes attributable to a single event and the soil conditions in the medium-term (one year). The objective of this study is to examine the impact of an intense rainfall event on the soil properties of a recently burned area and to compare these results with data collected one year later.

Fig. 1. Ash layer covering the studied plot before the rainfall event.

2. Materials and methods

2.1. Study area

The study area is located in Colomers, Girona (42°05′17.6″ N - 2°59′ 36.6″ E 38 masl) in North-East Spain. The fire started in Camallera, on 12 November 2013 and burned a total of 550 ha of *Pinus halepensis* Miller, *Quercus ilex* L. and *Eucaliptus globulus* Labill. The geological substratum of the burned area is composed mainly of sedimentary rocks from the lower Bartonian. Soils were classified as Fluventic Haploxerept (Soil Survey Staff, 2014). The main soil properties of the studied area are shown in Table 1. The mean annual temperature of the studied area is 15 °C and the average annual rainfall ranges between 600 and 800 mm (Pacheco, 2010).

2.2. Experimental design and field sampling

Three days after the fire, a 72 m^2 experimental plot (18 × 4 m, with a grid with 2 m spacing between sampling points) in a flat area (slope < 1%) was designed inside the burned area. Fire severity in this experimental plot was classified as high according to Úbeda et al. (2009) and Pereira et al. (2012), given that three crown had combusted and the soil was covered with a layer of gray and white ash (Fig. 1). A total of 30 soil samples (0–5 cm) were collected in the aforementioned grid, 3 days after the fire and before the rainfall event. The second sampling campaign was carried out 4 days after the start of the intense rainfall event (163.7 mm during 2 days), that is, 7 days after the fire. Rainfall data were registered at the meteorological station of Bisbal d'Empordà (41°97′ N - 03°04′ E. 29 masl). The last sampling period was one year after the fire. The total rainfall between the second and third sampling dates was 538.6 mm. The samples were stored in plastic bags and taken to laboratory for analysis.

Table 1
Characteristics of the soils (0–5 cm depth) of the studied area.

	Value
Aggregate stability (% of disaggregation)	2.42
Total nitrogen (%)	0.46
Organic carbon (%)	8.47
Inorganic carbon (%)	2.2
C/N ration	18.14
Carbonates (%)	10.71
pH	7.19
EC (μS/cm)	337
Extractable calcium (ppm)	32,122
Extractable magnesium (ppm)	733
Extractable sodium (ppm)	194
Extractable potassium (ppm)	313
Available phosphorous (ppm)	34.84
SPAR	0.991

2.3. Laboratory methods

Soil samples were dried to constant weight at room temperature (approx. 23 °C) during 7 days. To analyze pH, electrical conductivity (EC) and amounts of extractable elements (calcium, magnesium, sodium and potassium) the samples were sieved using a 2-mm mesh sieve. To analyze aggregate stability, the samples were sieved using a 4.8-mm mesh sieve. For each sample, ten air-dried aggregates (between 4 and 4.8 mm) were collected. The ten drop impact (TDI) method (Low, 1954) was used to study aggregate stability. The method involves placing a 2.8-mm sieve over the aggregates and subjecting them to the impact of ten drops of deionized water, from a droplet placed at a height of 1 m. Each drop had a weight of 0.1 ± 0.001 g and a diameter of 2.8 mm. Aggregates were weighed before the test and the disaggregated material, which passed through the sieve during the test, was also weighed after drying at 105 °C for 24 h. The results are expressed as a percentage of the disaggregated weight.

Soil organic carbon, inorganic carbon and carbonates were measured using the loss-on-ignition (LOI) method described in Heiri et al. (2001). For each sample, 1 gr of soil was pulverized and dried in a muffle furnace at 105 °C during 24 h. To estimate soil organic carbon, the dried samples were exposed to a temperature of 550 °C during 4 h. Finally, to calculate soil inorganic carbon, the samples were subjected to a temperature of 950 °C during 2 h. The results were expressed as percentages. Total carbon and total nitrogen contents were analyzed in the pulverized samples using gas chromatography combustion-reduction with a thermal conductivity detector Flash EA 112 Series (Thermo-Fisher Scientific, Milan). Data acquisition and calculations were carried out using Eafer 300 software (Thermo-Fisher Scientific, Milan) (Pereira et al., 2012).

Soil pH [1:2.5] and EC [1:2.5] were analyzed following extraction with deionized water. Available phosphorus was analyzed using the Olsen Gray method (Olsen et al., 1954). Soil cations (calcium, magnesium, sodium, and potassium) were extracted from samples using ammonium acetate (Knudsen et al., 1986). The extractable cation content was analyzed by inductively coupled plasma mass spectrometry (ICP-MS), using a PerkinElmer Elan-6000 Spectrometer, and by optical emission spectrometry (OES), using a PerkinElmer Optima-3200 RL Spectrometer. Soil SPAR was calculated according to Sarah (2004) (extractable sodium + extractable potassium) / (extractable calcium + extractable magnesium)$^{1/2}$.

2.4. Statistical analysis

Prior to data comparison, data normality and homogeneity of variances were tested using the Shapiro–Wilk and the Levene tests, respectively. None of the data respected the Gaussian distribution or heteroscedasticity. Aggregate stability, total nitrogen, organic carbon, exchangeable magnesium and exchangeable potassium met assumptions of normality and homogeneity of variances after a logarithmic transformation. Available phosphorous only met the assumptions of data normality and homogeneity after a square root transformation. The remaining variables did not meet these requirements, even after a Box-Cox transformation. For those variables that satisfied assumptions of normality and heteroscedasticity, statistical comparisons among sampling dates were conducted using the parametric one-way ANOVA on the transformed data. If significant differences were found, a Tukey HSD test was applied. For the variables that did present normality after all the transformations, the non-parametric Kruskal–Wallis ANOVA (KW) was used. If significant differences were identified, the multiple comparison post-hoc test was applied. Principal component analysis (PCA) was conducted with a varimax rotation based on the correlation matrix (using log-transformed data) to identify the relations among the variables studied and their association according to the different sampling periods. Statistical analyses were conducted using Statistica 10.0.

3. Results

3.1. Aggregate stability

Significant differences were identified in the soil aggregate stability on the three sampling dates ($F = 208.93$, $p < 0.001$). A decrease in soil aggregate stability (i.e., an increase in the percentage of the disaggregated sample) was observed with time. Soil aggregate stability was significantly lower one year after the fire (Fig. 2).

3.2. Total nitrogen, total carbon, organic carbon and inorganic carbon, C/N ratio and carbonates

No significant differences were observed in total nitrogen ($F = 1.57$, $p > 0.05$), total carbon ($KW = 3.80$, $p > 0.05$), inorganic carbon ($KW = 4.96$, $p > 0.05$), C/N ratio ($KW = 1.73$, $p > 0.05$) and carbonate content ($KW = 3.98$, $p > 0.05$) between the three sampling dates (Table 2). Significant differences were only observed in organic carbon content ($F = 4178$, $p > 0.001$), the amount being significantly higher immediately after the rainfall event than before the event and one year after the fire (Table 2).

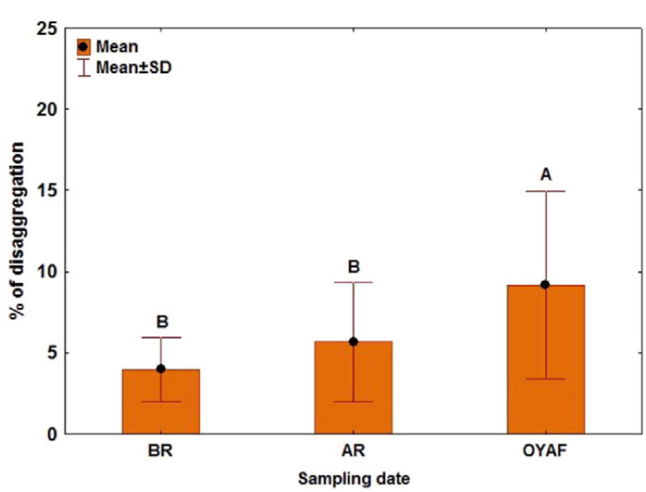

Fig. 2. Mean and standard deviation of the % of soil disaggregation. Different letters represent significant differences at a $p < 0.05$. BR (Before the rainfall), AR (after the rainfall) and OYAF (one year after the fire). N = 90.

Table 2
Descriptive statistics of total nitrogen, total carbon, organic carbon, inorganic carbon, C/N ratio, and carbonates. Different letters represent significant differences at a $p < 0.05$. N = 90.

		Mean	SD	Min	Max	p Value
Total nitrogen (%)	Before rainfall	0.32	0.08	0.17	0.52	n.s[b]
	After rainfall	0.34	0.10	0.15	0.55	
	One year after fire	0.30	0.08	0.17	0.47	
	All	0.32	0.09	0.15	0.55	
Total carbon (%)	Before rainfall	7.58	2.14	4.85	17.21	n.s[a]
	After rainfall	7.69	1.78	3.50	11.73	
	One year after fire	7.08	1.59	4.90	10.94	
	All	7.45	1.85	3.50	17.21	
Organic carbon (%)	Before rainfall	5.20b	1.28	2.86	8.23	***[b]
	After rainfall	6.03a	1.48	3.77	9.72	
	One year after fire	4.58b	1.10	2.91	7.44	
	All	5.27	1.42	2.86	9.72	
Inorganic carbon (%)	Before rainfall	3.49	0.40	2.21	4.42	n.s[a]
	After rainfall	3.43	0.22	2.87	3.97	
	One year after fire	3.55	0.20	3.12	3.93	
	All	3.49	0.29	2.21	4.42	
C/N ratio	Before rainfall	24.20	4.50	18.76	44.13	n.s[a]
	After rainfall	23.33	2.53	19.55	30.19	
	One year after fire	24.43	3.40	20.05	37.45	
	All	23.99	3.56	18.76	44.13	
Carbonates (%)	Before rainfall	16.61	3.02	4.33	21.71	n.s[a]
	After rainfall	16.73	1.12	13.69	19.41	
	One year after fire	17.33	1.11	15.12	19.35	
	All	16.89	1.97	4.33	21.71[c]	

[a] Original data.
[b] log transformed data.
[c] Square-root transformed data.

3.3. pH, electrical conductivity, major cations and available phosphorous and SPAR

Significant differences were observed in soil pH ($KW = 43.89$, $p < 0.001$) and EC ($KW = 64.52$, $p < 0.001$) between the sampling dates. Soil pH and EC values were significantly higher before the rainfall event than on both occasions after the intense rainfall episode. In the case of EC, a decrease was observed with time (Table 3).

Extractable calcium ($KW = 70.72$, $p < 0.001$), extractable magnesium ($F = 42{,}802.06$, $p < 0.001$) and available phosphorous ($F = 790.18$, $p < 0.001$) also differed significantly between the different sampling dates. The amounts of these three elements were significantly higher immediately after the rainfall event than on the other two sampling dates. Significant differences were identified in extractable sodium ($KW = 30.62$, $p < 0.001$) and extractable potassium ($F = 27{,}283.18$, $p < 0.001$) levels, with both being significantly higher before the rainfall event. Finally, significant differences were also observed in the SPAR ($KW = 43.05$, $p < 0.001$), with values being significantly higher both immediately after the rainfall event and one year after the fire (Table 3).

3.4. Multivariate analysis

The PCA carried out identified five factors that at least account for one variable. These first five factors explained a total of 79.21% of the total variance. The first two factors explained 38.73 and 15.24% of the variance, respectively. The intersection of these factors allowed us to identify four different groups of factors: the first comprised EC, total nitrogen, total carbon, organic carbon, extractable calcium, magnesium, sodium, potassium and available phosphorous; the second was integrated solely by the SPAR; the third comprised the aggregate stability, inorganic carbon, carbonates and C/N ratio; and finally, the fourth was integrated by just the soil pH (Fig. 3a). The variables in group 1 were negatively correlated with the variables in groups 2, 3 and 4. The variable in group 2 was negatively correlated with the sole variable in group 4. The variables in group 3 were positively correlated with the

Table 3
Descriptive statistics of pH, electrical conductivity (EC), extractable calcium, extractable magnesium, extractable sodium, extractable potassium, available phosphorous and SPAR. Different letters represent significant differences at a $p < 0.05$. N = 90.

		Mean	SD	Min	Max	p Value
pH	Before rainfall	8.52a	0.28	7.90	9.05	***[1]
	After rainfall	7.99b	0.09	7.84	8.21	
	One year after fire	8.19[a]	0.27	7.69	8.73	
	All	8.24	0.32	7.69	9.05	
EC (μS/cm)	Before rainfall	533.95a	390.40	155.40	2280.00	***[1]
	After rainfall	272.08b	123.93	146.80	687.00	
	One year after fire	113.71c	37.00	71.40	265.00	
	All	306.58	293.65	71.40	2280.00	
Extractable calcium (ppm)	Before rainfall	26,064.15b	6825.92	17,649.47	45,245.41	***[1]
	After rainfall	47,483.94a	11,145.48	31,279.83	70,433.55	
	One year after fire	17,142.14c	2775.97	13,742.49	24,454.36	
	All	30,230.08	14,903.23	13,742.49	70,433.55	
Extractable magnesium (ppm)	Before rainfall	711.47b	231.17	411.12	1157.09	***[2]
	After rainfall	967.37a	304.23	424.90	1762.25	
	One year after fire	346.20c	78.86	214.27	526.19	
	All	675.02	339.56	214.27	1762.25	
Extractable sodium (ppm)	Before rainfall	367.17b	170.00	77.50	925.22	***[1]
	After rainfall	508.36a	222.15	168.09	1036.97	
	One year after fire	328.16b	746.68	62.40	4230.07	
	All	401.23	401.23	62.40	4230.07	
Extractable potassium (ppm)	Before rainfall	431.56a	251.76	251.76	1550.88	***[2]
	After rainfall	408.90a	408.90	115.54	733.44	
	One year after fire	174.27b	174.27	44.10	261.00	
	All	338.24	338.24	198.29	1550.88	
Available phosphorous (ppm)	Before rainfall	45.11b	30.80	2.28	140.61	***[3]
	After rainfall	65.54a	37.21	5.37	161.92	
	One year after fire	19.78c	6.29	2.90	29.48	
	All	43.47	33.58	2.28	161.92	
SPAR	Before rainfall	0.984b	0.007	0.952	0.990	***[1]
	After rainfall	0.991a	0.002	0.985	0.994	
	One year after fire	0.990a	0.002	0.986	0.993	
	All	0.988	0.005	0.952	0.994	

[1] Original data.
[2] log transformed data.
[3] Square-root transformed data.

variable in group 2 and uncorrelated with the variable in group 4. The analysis of the cases showed that when considering all the variables there were no major differences between the sampling periods (Fig. 3b).

4. Discussion

4.1. Aggregate stability

The intense rainfall episode reduced soil aggregate stability immediately after the event, but not significantly; significant differences in soil disaggregation were only observed one year after the fire. Thus, despite the high severity of the fire, which consumed three crown layers, it seems likely that the ash layer reduced raindrop impact on the soil surface and protected soil aggregates (Fig. 4a). The ash layer has been shown to be the first and most effective soil protector in the immediate post-fire period (Pereira et al., 2015b), acting as natural mulch, reducing runoff and soil erosion, and increasing water storage and infiltration (Cerdà and Doerr, 2008; Woods and Balfour, 2008; Bodí et al., 2012; León et al., 2013). Given the vulnerability of burned soils to raindrop impact and particulate detachment, the protection afforded by the ash is of major importance (Gabet, 2014).

This means that the significant differences noted a year after the fire could well be related to the reduction in this source of protection (i.e., as a result of ash erosion, Fig. 4b), as well as to the post-fire management program, in which six months after the fire trees were cleared (Fig. 4c), and to vegetation recovery. According to Velasco and Úbeda (2014), the length of time that the soil is exposed to raindrop impacts is more important than the temperature reached by the fire. Post-fire management represents an additional disturbance in fire-affected soils, in some instances more severe than the fire itself. For example, Mataix-Solera et al. (2015) report that salvage logging reduces soil aggregate stability in burned areas. Likewise, it has been observed that the recuperation of the vegetation can reduce aggregate stability, despite the fact that soil infiltration is high (Cerdà et al., 1995; Velasco and Úbeda, 2014). Fattet et al. (2011) reported that grass and shrub regrowth induces an initial soil disaggregation in the first centimeters of the soil due to root development. Here, it is highly likely that the type of vegetation cover influenced soil aggregate stability. Cerdà (1998) observed, for example, that soil aggregates under shrub vegetation (*Rosmarinus officinalis*, *Thymus vulgaris*, *Ulex parviflorus* and *Anthyllis cystisoides*) were less resistant than those under mature forests (*Quercus ilex*). Soil aggregate stability response to fire is complex and depends on the type of soil affected, the temperature and severity of the fire, the topography of the burned area, the post-fire meteorological conditions, and the degree of vegetation recovery and management (Mataix-Solera et al., 2011). In the present study, it seems likely that the reduction in soil aggregate stability results from the interaction of all these variables and the soil's chemical properties, as we explain below.

4.2. Total nitrogen, total carbon, organic carbon and inorganic carbon, C/N ratio and carbonates

The intense rainfall event did not have any significant impact on the soil's total nitrogen, total carbon, inorganic carbon, C/N ratio and carbonate levels. In the period immediately after the event this can be attributed to two factors. First, the total elimination of ash from the plot (see Fig. 4b) reduced the amount of ash nutrients that could be incorporated into the soil profile. Indeed, previous studies have attributed the increase in nitrogen and carbon pools in fire-affected soils to ash (Gonzalez-Perez et al., 2004; De Marco et al., 2005). Badía et al.

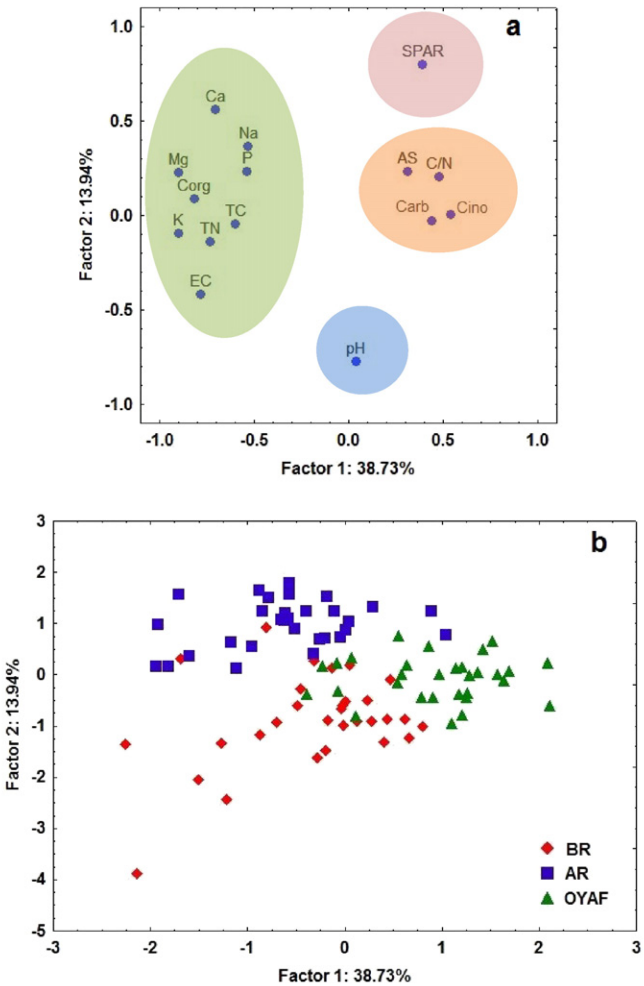

Fig. 3. Relation between Factor 1 and 2, a) variables and b) cases. BR (before the rainfall), AR (after the rainfall) and OYAF (one year after the fire). Aggregate stability (AS), total nitrogen (TN), total carbon (TC), organic carbon (Corg), inorganic carbon (Cino), carbon/nitrogen ratio (C/N), carbonates (Carb), electrical conductivity (EC), extractable calcium (Ca), extractable magnesium (Mg), extractable sodium (Na), extractable potassium (K) and sodium and potassium adsorption ratio (SPAR).

(2014) observed that after a severe wildfire the topsoil (0–1 cm) organic carbon was reduced significantly. One year after, the soil organic carbon of the burned soil was similar to that identified in the unburned plot. The authors attributed this to the incorporation of ash and new inputs derived from reblooming, which begins after the fire. However, ash is a highly mobile material, especially in high severity fires, because of its low density and, therefore, its light specific weight. It has been shown that ash produced at high temperatures loses most of its mass (Úbeda et al., 2009) and that it is easily transported by wind and water (Pereira et al., 2015c). The second factor was the severity of the fire. Nitrogen and carbon are volatilized at low temperatures (Fisher and Binkley, 2000), and so it seems highly likely that the ash deposited on the surface of the study area was poor in these elements. Light colored ash (see Fig. 1) is an indication of high severity fires. Pereira et al. (2012) observed that the total nitrogen and total carbon of ash fell significantly with increasing fire severity. Overall, the intensity of the precipitation, wind and the severity of the fire may have limited the contribution of ash to the soil's total nitrogen and carbon content.

Ash produced at high temperatures contributes primarily to the soil's inorganic compounds and carbonates (Bodí et al., 2014). However, here, no differences were recorded in their respective levels in the burned soils before and after the rainfall event. As discussed, ash produced at high temperatures is light weight and easily transported. Moreover, white ash, rich in inorganic compounds and carbonates

Fig. 4. Study area a) immediately after the fire, b) after the intense rainfall and c) one year after the fire.

(Goforth et al., 2005; Pereira et al., 2012), is the first to be transported or incorporated into the soil profile (Pereira et al., 2013). Pereira et al. (2015c) observed that after a severe wildfire the white ash (rich in carbonates and other inorganic material) was easily transported by wind. They reported that 15 days after the fire, in a period without rainfall, the % area covered in light gray and white ash was reduced. Similar results were noted by Pereira et al. (2013) after a grassland fire where the ash cover reduction was especially important at points where the ash was light gray and white in color. In this study, it seems probable that most of the inorganic compounds and carbonates present in the ash produced at high severity were eroded by wind, because as Úbeda et al. (2009) observed they are more readily transported (light weight). Water may have had some small influence in ash erosion as the study plot was flat. Nevertheless, we did observe a significant increase in the amount of organic carbon after the rainfall episode, indicating that some material not completely combusted in situ was incorporated into the first few centimeters of the soil. Despite the severity of the fire, not all the organic matter was combusted, and some small particles of charcoal were visible (see Fig. 1). Unlike white ash, black ash is rich in organic material (Dlapa et al., 2013) and more resistant to transport (being heavier than white ash), and may remain in the soil surface for several weeks after a fire (Pereira et al., 2013). This, and the fact that the studied area was flat, may have favored the maintenance of charcoal fragments on the soil surface, which were incorporated after the rainfall period. However, in areas affected by high severity fires, ash is extremely mobile, while it is also possible that such particles are deposited from other areas (Pereira et al., 2015c). Here, both processes are likely to have coincided during the rainfall event, but we are unable to identify the main contributor to the increase in soil organic carbon.

A year after the fire, the soil's organic carbon decreased and showed similar values to those observed before the rainfall event. This decrease can be attributed to the incorporation of this material in deeper soil profiles (Woods and Balfour, 2010), microbiological decomposition (Knicker et al., 2013), erosion in subsequent precipitation events (Novara et al., 2011) and post-fire management.

4.3. pH, electrical conductivity, major cations, available phosphorous and SPAR

Soil pH and EC decreased significantly after the intense rainfall event, a reduction that can be attributed to the transport of elements in overland flow and/or leaching into the soil profile. These results are in line with previous studies that report a decrease in soil pH and EC after periods of rain (Kutiel and Naveh, 1987). Overall, a decrease was identified with time, so that a year after the fire, soil pH and EC were lower than on the previous two sampling dates. All the extractable cations (with the exception of potassium), available phosphorous and the SPAR were significantly higher in the period after the rainfall event. This increase can be attributed to the leaching of ash nutrients (Raison and McGarity, 1980; Pereira et al., 2014). Badía et al. (2014) also observed that extractable calcium, magnesium and phosphorous increased one week after the fire. The changes observed were attributed to the heat released during the fire, which decreased the soil organic carbon, but mineralized the organic matter, increasing the solubility of calcium, magnesium and phosphorous. Despite the fact that soil pH and EC presented their highest levels prior to the rainfall event, these elements were released in greater amounts in the sampling period after the precipitation event. We hypothesize that this may be a consequence of the fact that:

1. Soil pH was too high for the optimal solubility of some of these elements. The optimal solubility of extractable calcium and magnesium is around pH 7–8 (Neary et al., 2005), while available phosphorous is extractable at a pH ranging from 6.5 to 7.5 (Varennes, 2003). In the period before the rainfall event, soil pH presented an average value of 8.52, thus limiting the solubility of these elements. After the intense period of precipitation, soil pH fell to 7.99, thus increasing the probability that these elements could be extracted. Extractable sodium and potassium are highly soluble at a pH above 7.5 (Troeh and Thompson, 2005), a level that was observed both before and after the rainfall period. Despite this, we observed that levels of extractable sodium were significantly higher in the period after the rainfall event, while no differences were observed in those of extractable potassium. It seems probable that the ash, which was incorporated into the soil profile, significantly increased the amount of extractable sodium in the soil. These results are in line with previous reports that observed an increase in the major extractable elements and in available phosphorous after a fire (Murphy et al., 2006; Galang et al., 2010).
2. Soil EC was significantly higher before the rainfall event than it was after, despite the fact that the major cations presented the opposite dynamic. This high level of conductivity may reflect the contribution of other chemical elements not considered in this study, such as anions (including, nitrites, nitrates, sulfides, chlorides). Anion leaching makes a major contribution to water ionic composition (Kitamura, 2009); indeed, previous studies have shown that large amounts of anions can be leached from soils affected by wildfires (Kutiel and Inbar, 1993; Gimeno-García et al., 2008; Thomas et al., 2000; Ferreira et al., 2005; Lasanta and Cerdà, 2005; Murphy et al., 2006).

A year after the fire, soil pH had increased significantly (compared to the value recorded after the rainfall event), while EC, and the amounts of all the extractable elements, had fallen in relation to the results recorded in the previous sampling period. This can be attributed to further losses in the overland flow generated by subsequent rainfall events, soil leaching, post-fire management and plant consumption (Neary et al., 2005; Murphy et al., 2006; Badía et al., 2014). The latter can be verified in Fig. 4c, which shows that vegetation covered 100% of the burned plot.

The SPAR index was significantly higher after the rainfall event and one year after the fire than in the period before the intense precipitation. Soil solutions with a high SPAR in these last two sampling periods may have increased the vulnerability of soils to erosion because of their high clay dispersion capacity (Sarah, 2004, 2005). This increase in the index after the rainfall event is probably the consequence of the incorporation of some elements of ash into the soil profile (Pereira et al., 2014). To our knowledge no previous studies have examined SPAR levels in fire-affected soils, and further studies need to be conducted in order to understand the impact of soil solution chemistry on soil structure. Soil solutions with a high SPAR can have a negative impact on soil structure (Sarah, 2005). The decrease in soil aggregate stability was significantly higher one year after the fire, when the SPAR values were high. In combination with the factors discussed above, the increase in SPAR values may well have had a negative impact on soil aggregate stability.

4.4. Overall discussion and implications for post-fire management

Intense rainfall events can have a negative impact on recently burned soils, given that they are greatly exposed to erosion agents. This is especially significant in mountainous areas where steep slopes facilitate soil erosion. In such instances it is recommended that some post-fire restoration strategies be applied in order to reduce the vulnerability of soils to degradation, as has been observed in other areas of the Mediterranean (Castro et al., 2011; Shakesby, 2011; Badía et al., 2015). In the present case, the torrential rainfall did not have an extremely negative impact on the burned area, since much of the vegetation recovered, as can be observed in Fig. 4c. This can be attributed to the fact that the study area was flat, which reduced the impact of this precipitation event and other post-fire meteorological factors. Mediterranean ecosystems are highly resilient to fire and can recover rapidly without any need for restoration measures (Cerdà and Doerr, 2005; López-Poma et al., 2014). This was the case here, despite the disturbances induced by tree removal.

The intense rainfall event had different impacts on some soil properties and it seems probable that these can be connected to the ash layer that had formed after the fire. Thus, the ash layer reduced raindrop impact and soil aggregate degradation, but because it resulted from a high severity combustion event it did not modify total nitrogen and total carbon levels significantly (given that these elements appear in very low amounts in white ash). However, despite its severity, the fire did not consume all the organic material and these charred remains increased the soil's organic carbon content following the rainfall event. Ash is rich in cations and phosphorous, which volatize at higher temperatures than carbon and nitrogen (Bodí et al., 2014). These elements are easily soluble, especially at their optimum pH.

Post-fire management is well documented as having a marked impact on soil properties (Gomez-Rey et al., 2013; Powers et al., 2013; Wagenbrenner et al., 2015); however, here, the degradation of soil structure cannot be attributed solely to human intervention, as other variables – including ash and soil erosion, vegetation recuperation and soil chemical properties – are also influential. Further studies are needed to identify the direct impact of each of these variables. The initial increase in nutrients in soil solution had been reversed one year after the fire, as a result of erosion, leaching and plant consumption. Taking all the elements studied into consideration — the intense rainfall episode, other natural post-fire events and human management, no major differences were recorded in the soils in relation to their initial values (i.e., before the rainfall) and we did not identify any clear groups in the PCA analysis. The location of the sampling points in the graph does not point to any clear differences between them (Fig. 3b). This can be attributed to the lack of significant differences in many of the variables analyzed, including total nitrogen, total carbon, inorganic carbon, the C/N ratio and carbonate content, which may have had an influence on this result. The effects of wildfires on the soil properties of burned areas have been well described (Murphy et al., 2006; Caon et al., 2014), and, given the values recorded in Table 1, it is apparent that our study area experienced a similar impact; however, here, the overall effects were not significant.

Ash is a valuable protector of soils in post-fire environments, as highlighted in many studies (Onda et al., 2008; Bodí et al., 2012, 2014; Cerdà and Doerr, 2008; Jordán et al., 2015; Pereira et al., 2013, 2015a), and it is also a major source of soil nutrients (Pereira et al., 2014). However, to fulfill these roles, it is essential that the ash remains in the soil layer undisturbed by human intervention. Disturbance exposes soils to erosion agents and increases the mobility of ash, especially in areas affected by high severity fires (Pereira et al., 2015b) as the one experienced here. Intense rainfalls, though, are a normal occurrence in Mediterranean environments and so the protection against erosion agents is frequently destroyed (Cerdà and Doerr, 2008). The erosion of ash reduces the capacity of the vegetation to recover after a fire, and so it is in these environments in particular that salvage logging should be avoided, given the additional disturbance it represents to the soil ecosystem. Clearly, therefore, the fire management program (including tree removal) carried out in this area was not the most appropriate for an area affected by a high severity fire, since it almost certainly constituted an additional disturbance to the soil. In this study, we have not been able to identify the specific impact of tree removal and to isolate its effects from the other variables; however, it may have contributed to soil structure deterioration one year after the fire. Overall, despite this impact and the incorrect management, the topographic characteristics of the study plot may have facilitated the rapid recuperation of the ecosystem and mitigated the effects of human intervention. However, these practices on slopes, and especially with certain soil types, can lead to soil erosion and degradation (Mataix-Solera et al., 2015).

5. Conclusions

Significant impacts were only observed one year after the fire as a consequence of ash and soil erosion, tree removal, vegetation recuperation and changes in soil chemical properties. Overall, this study highlighted that:

a) This intense rainfall period did not have a significant impact on soil aggregate stability in this area affected by a high severity fire. Significant impacts were only observed one year after the fire as a consequence of ash and soil erosion, tree removal, vegetation recuperation and changes in soil chemical properties such as SPAR.
b) The fire did not have an impact on total nitrogen, total carbon, inorganic carbon, the C/N ratio or carbonate levels. However, particles of charred material, either transported from other areas or which were more resistant to erosion, may have contributed to a significant increase in organic carbon.
c) Extractable cations and available phosphorous increased after the rainfall event as a consequence of a favorable pH. SPAR values were also significantly higher after the rainfall event, indicating that it may have contributed to the decrease in soil aggregate stability.
d) One year after the fire, a significant decrease was observed in aggregate stability and extractable elements. This was probably due to the high SPAR levels (in the case of the decrease in soil aggregate stability), human intervention and soil leaching provoked by other rainfall events and vegetation consumption.

Thus, based on the results of the analyses conducted in this study, the intense rainfall event and other post-fire processes (attributable to natural or human causes) did not greatly modify the soil properties as recorded before the intense rainfall episode.

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