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Long-term impact of wildfire on soils exposed to different fire severities. A case study in Cadiretes Massif (NE Iberian Peninsula)

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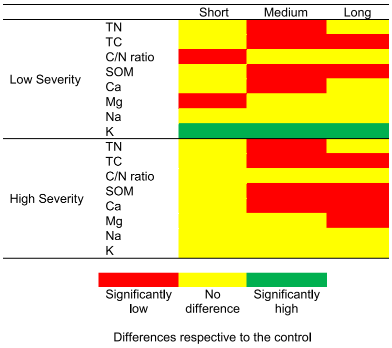
HIGHLIGHTS

- Severe wildfires affect soil properties to long-term.
- Soil nutrients responded differently to time and to fire severity.
- Soils need more time to recover its properties in high- than in low-severity areas.

GRAPHICAL ABSTRACT



		Short	Medium	Long
Low Severity	TN	🟨	🟥	🟨
	TC	🟨	🟥	🟥
	C/N ratio	🟥	🟨	🟨
	SOM	🟨	🟥	🟥
	Ca	🟨	🟥	🟨
	Mg	🟥	🟨	🟨
	Na	🟨	🟨	🟨
	K	🟩	🟩	🟩
High Severity	TN	🟨	🟥	🟨
	TC	🟨	🟥	🟥
	C/N ratio	🟨	🟨	🟨
	SOM	🟨	🟥	🟥
	Ca	🟨	🟥	🟥
	Mg	🟨	🟨	🟥
	Na	🟨	🟨	🟨
	K	🟨	🟨	🟨

🟥 Significantly low
🟨 No difference
🟩 Significantly high

Differences respective to the control

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ABSTRACT

Wildfires affect ecosystems depending on the fire regime. Long-term studies are needed to understand the ecological role played by fire, especially as regards its impact on soils. The aim of this study is to monitor the long-term effects (18 years) of a wildfire on soil properties in two areas affected by low and high fire severity regimes. The properties studied were total nitrogen (TN), total carbon (TC), C/N ratio, soil organic matter (SOM) and extractable calcium (Ca), magnesium (Mg), sodium (Na) and potassium (K). The study was carried out in three phases: short- (immediately after the wildfire), medium- (seven years after the wildfire) and long-term (18 years after the wildfire). The results showed that in both fire regimes TN decreased with time, TC and SOM were significantly lower in the burned plots than they were in the control in the medium- and long-terms. C/N ratio was significantly lower at short-term in low wildfire severity area. Extractable Ca and Mg were significantly higher in control plot than in the burned plots in the medium-term. In the long-term, extractable Ca and Mg were significantly lower in the area exposed to a high severity burning. No differences were identified in the case of extractable Na between plots on any of the sampling dates, while extractable K was significantly higher in the plot exposed to low wildfire than it was in the control. Some restoration measures may be required after the wildfire, especially in areas affected by high severity burning, to avoid the long-term impacts on the essential soil nutrients of TC, SOM, extractable Ca and Mg. This long-term nutrient depletion is attributable to vegetation removal, erosion, leaching and post-fire vegetation consumption. Soils clearly need more time to recover from wildfire disturbance, especially in areas affected by high severity fire regimes.

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1. Introduction

Wildfires are a global phenomenon and a natural element of ecosystems, where their impact is dependent upon the fire regime (Bento-Gonçalves et al., 2012; Gill, 1975; González-Pérez et al., 2004). Soils are an essential component of ecosystems, and can undergo substantial modifications because of the direct (e.g. heating) or indirect (e.g. ash) effects of fire; although, they normally return to their pre-fire conditions with time. These effects are largely confined to the first few centimeters of the soil profile. It has been well documented that the impact of fire on soils depends on soil type, fire history, the ecosystem and species burned, the topographical conditions of the affected area, the meteorological conditions during and after the fire and the severity of the fire. Low fire severities can increase soil organic matter (SOM), total nitrogen (TN), total carbon (TC) and total extractable cations, whereas high fire severities consume all the SOM, reduce TN and TC considerably, and substantially increase the amount of major cations in solution. The ability of the burned area to recover its pre-fire levels depends on the ecosystem affected, fire severity, the topography of the fire-affected area and the post-fire meteorological conditions. Soil status in post-fire environments is a key element for ecosystem recovery (Badia et al., 2014; Bodi et al., 2014; Caon et al., 2014; Pereira et al., 2016).

The large majority of studies examining the impact of wildfires on soil focus on their short- (e.g. Romanya et al., 2001; Snyman, 2003; Tessler et al., 2008; Pereira et al., 2017) or medium-term effects (e.g. Lozano et al., 2016; Martinez-Garcia et al., 2017); and owing to constraints of time, logistics and finances, little research has examined their long-term effects. However, long-term studies are essential to gain a good understanding of the ecological role of fire. Most of the long-term studies that have been reported were undertaken in North America (Ojima et al., 1994; Slaughter et al., 1998; Yermakov and Rothstein, 2006; LeDuc and Rothstein, 2010; Johnson et al., 2012), although some data are available from other parts of the world, including South America (Roscoe et al., 2000; Silvana-Longo et al., 2011), Australia (Muñoz-Rojas et al., 2016) and Europe (Kaye et al., 2010). Moreover, while some authors have looked at how soils change up to hundred years after the last known fire (DeLuca et al., 2006; McNamara et al., 2015), they neither monitor the evolution of post-fire soil properties nor record the severity of the fire regime to which they were exposed, a critical parameter in determining the recovery of the ecosystem. As such, there is clearly a pressing need for greater insights into the long-term effects of wildfires on soil properties, especially in fire-prone ecosystems, like the Mediterranean, in order to develop a better understanding of their resilience and capacity to respond to such disturbances. These studies are especially relevant in the current context of climatic change, with predictions that the number and size of fires will increase and that fire regimes will change (e.g. a larger number of high severity fires during longer fire seasons) (Brotons et al., 2013; Turco et al., 2014, 2017).

Although a long-term study of the effects of fire on soil properties in the Mediterranean has been conducted (Kaye et al., 2010), to the best of our knowledge, no study has examined the effects of different fire severity regimes from a long-term perspective. Yet, note that a number of studies have examined the short- and medium-term effects of low (Inbar et al., 2014), moderate (Faria et al., 2015) and high severity fires (Badia et al., 2014; Lombao et al., 2015; Francos et al., 2016b). The importance of long-term studies of the effects of varying fire intensities is that they should shed light on the capacity of soils to respond to different levels of disturbance. This is critical for determining how long low and high fire severity regimes can modify a soil ecosystem. Thus, the aim of the study reported here is to monitor the long-term impact of a wildland fire of different severities on the chemical properties of soil.

2. Materials and methods

2.1. Study area

The study area is located in Cadiretes, Girona, in the north-east of the Iberian Peninsula, at an altitude of between 190 and 250 m a.s.l. (Úbeda et al., 2005) (Fig. 1). The parent material consists of metamorphic rock. The massif is covered by dense Mediterranean vegetation, and includes such species as *Quercus suber* L., *Arbutus unedo* L., *Erica arborea* L. *Pinus pinaster* ssp. Mean annual rainfall ranges between 700 and 800 mm, with an autumn maximum and a summer minimum (Úbeda, 2001). Summer temperatures often exceed 25 °C; while winters are generally mild, rarely below 0 °C. Evapotranspiration exceeds precipitation in summer months, from June to August (Úbeda, 1998). According to US Soil Taxonomy (Soil Survey Staff, 2014), the soils of the control and low severity zone can be classified as Typic Haploxerept while those in the high severity fire zone are classified as Lithic Haploxerept. The area was affected by a fire that broke out on 5 July 1994 burning an area of 55 ha. In 1994, the area was a plantation of *Pinus pinaster* ssp. with potential for *Quercus suber* L. (Francos et al., 2016a). After the wildfire, no restoration measures were carried out in the forest affected area.

2.2. Experimental design and field sampling

One day after the fire, two plots were designed in an area affected by both low and high severity wildfires (henceforth L-S and H-S plots), respectively. Both plots were on south-facing slopes with a gradient of approximately 10%. Fire severity was assessed by means of ash color and the number and diameter of surviving branches. Soils covered with black ash were considered to be indicative of low fire severity, while those covered with grey/white ash were deemed indicative of high fire severity (Moreno and Oechel, 1989). An unburned area was selected as control. All three areas present similar environmental characteristics in terms of their parent material, topography and vegetation. Inside each area, we designed a transect, and we sampled the soils each 2 m. In the first sampling campaign, conducted immediately after the fire, we collected five topsoil samples from each plot (0–3 cm). In the second (seven years after the wildfire) and third (18 years after the wildfire) sample campaigns, we collected a further 10 samples per plot per campaign. In total, we collected 75 soil samples. After the fire, no forestry management measures were implemented. Thus, the only impacts on soil properties were those induced by the wildfire and the post-fire natural plant recovery. Two previous studies have been published reporting the results from the data collected in the short- (Úbeda, 2001) and medium-terms (Úbeda et al., 2005).

2.3. Laboratory methods

Samples were dried in the laboratory at room temperature (±23 °C) for 48 h. Soils were sieved with a < 2 mm mesh to discard the coarser material. TN and TC content were analyzed with a 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). SOM was measured using the loss-on-ignition (LOI) method described in Henri et al. (2001). For each sample, 1 g of soil was pulverized and dried in a muffle furnace at 105 °C for 24 h. To estimate SOM, the dried samples were heated at 550 °C for 4 h. Soil extractable Ca, Mg, Na and K were analyzed with the method proposed by Knudsen et al. (1986).

2.4. Statistical analysis

Statistical comparisons between sampling times and plots were carried out with a two-way ANOVA test. Significant differences were considered at $p < 0.05$. If significant differences were identified, a Tukey HSD post-hoc test was applied. A redundancy analysis (RDA) was

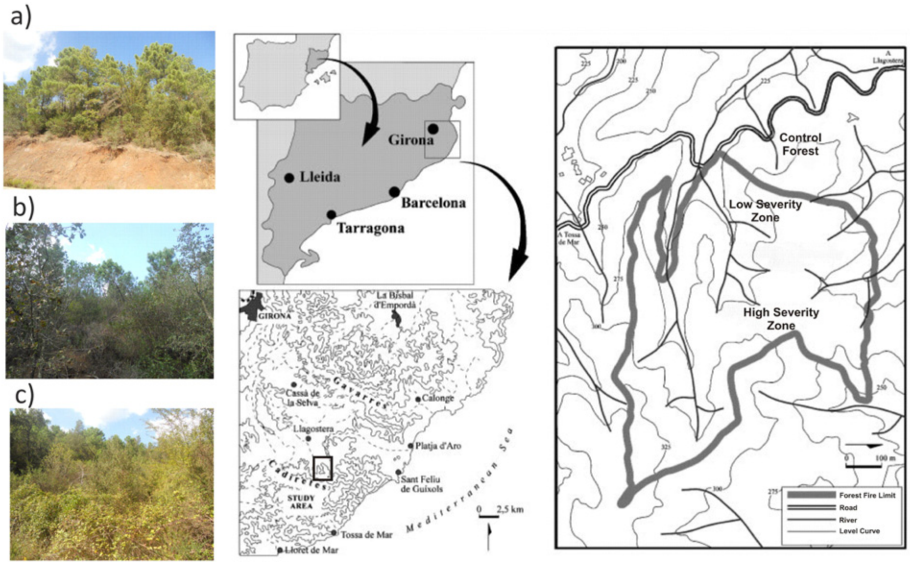

Fig. 1. Location of study area. a) control, b) low severity and c) high severity. Modified from Úbeda, 1998.

carried out to identify the extent to which the variation in one set of variables accounts for the variation in another. Statistical analyzes were carried out using SPSS 23.0 and CANOCO for Windows 4.5 software.

3. Results

3.1. Total nitrogen, total carbon, C/N ratio and soil organic matter

We found significant differences between time, severity and time × severity in the soils TN, TC, and C/N ratio. In the case of SOM, significant differences were only observed between time and severity (Table 1). TN and TC were significantly higher in the plots affected by low and high severity fires in the short-term than they were in the medium- and long-terms. The C/N ratio was significantly lower in both burned plots in the medium-term than it was at the other two sampling times. SOM was significantly higher in the control, L-S and H-S plots in the short-term than it was in the medium- and long-term. In the case of severity, the control plot presented significantly higher TN values in the medium-term. TC content was significantly higher in the control plot compared to corresponding values in the burned plots in the medium- and long-terms. The C/N ratios were significantly lower in the L-S plot than they were in the control plot in the short-term, while SOM was significantly higher in the control compared to the values recorded in the L-S and H-S plots in the medium- and long-terms (Table 2).

Table 1
Two-way ANOVA results. Significant differences at $p < 0.05$*. $p < 0.01$** and $p < 0.001$***. n.s. not significant at a $p < 0.05$.

	Sites	*p*-Value
Total nitrogen (%)	Time	***
	Severity	*
	Sampling × severity	***
Total carbon (%)	Time	***
	Severity	**
	Sampling × severity	*
C/N ratio	Time	***
	Severity	***
	Sampling × severity	**
Soil organic matter (%)	Time	***
	Severity	*
	Sampling × severity	n.s.
Extractable calcium (ppm)	Time	***
	Severity	**
	Sampling × severity	*
Extractable magnesium (ppm)	Time	***
	Severity	*
	Sampling × severity	n.s.
Extractable sodium (ppm)	Time	***
	Severity	n.s.
	Sampling × severity	n.s.
Extractable potassium (ppm)	Time	***
	Severity	***
	Sampling × severity	*

3.2. Soil calcium, magnesium, sodium and potassium

Significant differences were observed in levels of soil extractable Ca and K between time, severity and time × severity. In the case of extractable Mg, significant differences were only identified between time and severity, while in that of extractable Na, significant differences were only observed in relation to time (Table 1). Extractable Ca was significantly higher in the areas affected by low fire severity in the medium- and long-terms compared to levels recorded in the short-term. In the H-S plot, extractable Ca was significantly higher in the medium-term sample period than it was in the others. Extractable Mg and Na levels were significantly lower in all the plots studied in the short and long-term periods compared to the levels reported in the medium-term. Extractable K was significantly higher in the medium-term in the control plot when compared to the values recorded in the short- and long-terms (Table 3).

In the case of severity, levels of soil extractable Ca were significantly higher in the control than they were in the fire affected plots in the medium-term. In the long-term, significantly higher levels were only observed in the case of the H-S plot. Soil extractable Mg content was significantly higher in the control than it was in the L-F plot in the short-term. Extractable Mg was also significantly higher in the control and L-S plots than it was in the H-S plot. Finally, in relation to soil extractable K, we observed significant differences on all the sampling dates. In the short- and long-term, extractable K was significantly higher in the L-S plot than it was in the control. In the medium-term, extractable K content was significantly higher in the L-S plot than it was in the control and the H-S plot.

3.3. Multivariable analysis

Short-term RDA factor 1 explains 41% of the variance, while factor 2 explains 39.6%. In the short- term, the values of TC, TN, SOM, extractable Na and K were highest in the L-S plot. Soil extractable Ca, Mg and C/N presented the highest values in the control plot (Fig. 2a). Medium-term RDA factor 1 explains 45.7% of the variance and factor 2 explains

Table 2
Descriptive statistics for total nitrogen. Total carbon. C/N Ratio. Soil organic matter. Different letters represent significant differences at a $p < 0.05$ between sampling dates (capital letters) and severities (low case letters). Three different severities: control, low severity and high severity. Three different samplings: short-term ($N = 5$), medium-term ($N = 10$) and long-term ($N = 10$).

	Sampling date	Plot	Mean	SD	Min	Max
Total nitrogen (%)	Short-term	Control	0.39	0.38	0.25	0.54
		Low	0.64 A	0.25	0.49	0.79
		High	0.44 A	0.28	0.29	0.59
		All	0.49	0.28	0.25	0.79
	Medium-term	Control	0.49 a	0.26	0.38	0.59
		Low	0.22 bB	0.09	0.12	0.33
		High	0.16 bB	0.84	0.05	0.26
		All	0.29	0.21	0.05	0.59
	Long-term	Control	0.24	0.07	0.14	0.35
		Low	0.18 B	0.08	0.08	0.28
		High	0.18 B	0.05	0.08	0.28
		All	0.20	0.07	0.08	0.35
Total carbon (%)	Short-term	Control	10.54	8.61	7.17	13.9
		Low	13.70 A	5.98	10.33	17.06
		High	9.75 A	2.84	6.39	13.12
		All	11.33	6.07	6.39	17.06
	Medium-term	Control	11.23 a	6.07	8.85	13.61
		Low	5.27 bB	1.99	2.9	7.65
		High	3.05 bB	1.84	0.67	5.43
		All	6.52	5.1	0.67	13.61
	Long-term	Control	6.83 a	1.70	4.45	9.21
		Low	4.25 bB	1.75	1.87	6.63
		High	3.9 bB	1.22	1.52	6.28
		All	4.99	2.02	1.52	9.21
C/N ratio	Short-term	Control	50.11 aA	5.56	40.87	55.23
		Low	29.91 bA	14.76	3.66	38.60
		High	38.78 abA	2.70	35.75	42.79
		All	39.60	12.10	3.66	55.23
	Medium-term	Control	16.54C	9.33	6.62	37.47
		Low	13.98 B	2.17	11.00	18.60
		High	10.84 B	1.94	8.18	13.15
		All	13.79	5.93	6.62	37.47
	Long-term	Control	28.45 B	4.99	31.41	49.57
		Low	23.61 A	5.78	32.02	51.54
		High	20.56 A	4.52	27.30	42.37
		All	38.49	5.22	27.30	51.54
Soil organic matter (%)	Short-term	Control	18.16 A	14.85	13.43	22.90
		Low	19.01 A	13.78	14.28	23.75
		High	16.96 A	4.73	12.28	21.70
		All	18.05	11.15	12.28	23.75
	Medium-term	Control	6.39 aB	1.12	3.05	9.74
		Low	3.06 bB	1.16	0.29	6.41
		High	1.77 cC	1.07	1.58	5.11
		All	3.74	2.26	0.29	9.74
	Long-term	Control	9.44 aB	1.94	6.09	12.78
		Low	6.74 bB	2.29	3.39	10.09
		High	6.32 bB	1.06	2.98	9.67
		All	7.50	2.26	2.98	12.78

Table 3
Descriptive statistics for extractable calcium, magnesium, sodium and potassium. Different letters represent significant differences at a $p < 0.05$ between sampling dates (capital letters) and severities (low case letters). Three different severities: control, low severity and high severity. Three different samplings: short-term ($N = 5$), medium-term ($N = 10$) and long-term ($N = 10$).

	Sampling date	Severity	Mean	SD	Min	Max
Extractable calcium (ppm)	Short-term	Control	1289 B	465	447	2132
		Low	1075 B	253	232	1917
		High	1369C	129	527	2212
		All	1244	244	232	2212
	Medium-term	Control	5170 aA	2032	4574	5766
		Low	3246 bA	669	2650	3842
		High	3248 bA	517	2653	3844
		All	3888	172	2650	5766
	Long-term	Control	3020 aB	678	2425	3616
		Low	2715 aA	1005	2119	3311
		High	1912 bB	289	1316	2508
		All	2549	172	1316	3616
Extractable magnesium (ppm)	Short-term	Control	392 aB	151	200	584
		Low	213 bC	51	21	405
		High	281 abB	28	89	473
		All	296	56	21	584
	Medium-term	Control	912 A	416	776	1048
		Low	878 A	172	742	1014
		High	785 A	243	649	920
		All	858	39	649	1048
	Long-term	Control	620 aAB	139	484	756
		Low	518 abB	211	383	654
		High	419 bB	48	283	555
		All	519	39	283	756
Extractable sodium (ppm)	Short-term	Control	347	205	62	631
		Low	380 B	152	96	664
		High	330 AB	166	46	614
		All	352	164	46	664
	Medium-term	Control	554	540	353	755
		Low	854 A	536	653	1055
		High	562 A	288	361	763
		All	657	475	353	1055
	Long-term	Control	194	98	7	394
		Low	102 B	136	99	303
		High	164 B	112	37	364
		All	153	119	7	394
Extractable potassium (ppm)	Short-term	Control	161 bB	67	95	227
		Low	308 a	110	242	374
		High	278 ab	51	212	344
		All	249	99	95	374
	Medium-term	Control	300 bA	56	254	347
		Low	419 a	119	372	465
		High	252 b	43	205	298
		All	324	105	205	465
	Long-term	Control	216 bB	48	169	262
		Low	307 a	71	261	354
		High	238 ab	71	191	285
		All	254	74	169	354

39.6%. The values of TN, TC, C/N ratio, SOM, extractable Ca and Mg were highest in the control plot, while Na and K were highest in the L-S plot (Fig. 2b). Finally, long-term RDA factor 1 explains 44.4% of the variance and factor 2 explains 33.4%. As for the medium-term sampling period, values of TN, TC, C/N ratio, SOM, extractable Ca and Mg were highest in the control plot. At this sampling date, extractable Na was also highest in the control. Soil extractable K content was still highest in the L-S plot (Fig. 2c).

4. Discussion

4.1. Total nitrogen, total carbon, C/N ratio and soil organic matter

Soil TN content was significantly higher in the short-term than it was on the other sampling dates in both burned sites. This can be attributed to the incorporation of ash and charcoal into the soil profile in the immediate aftermath of the fire (Goforth et al., 2005; Pereira et al., 2011; Dzwonko et al., 2015). With time, there is a reduction in soil TN content, independent of fire severity, because of post-fire erosion, leaching and plant consumption (see Xue et al., 2014). Differences between plots were identified only in the medium-term, reflecting the marked reduction in TN values in the burned plots for the reasons outlined above. Independent of severity, the fire did not have any short-term implications

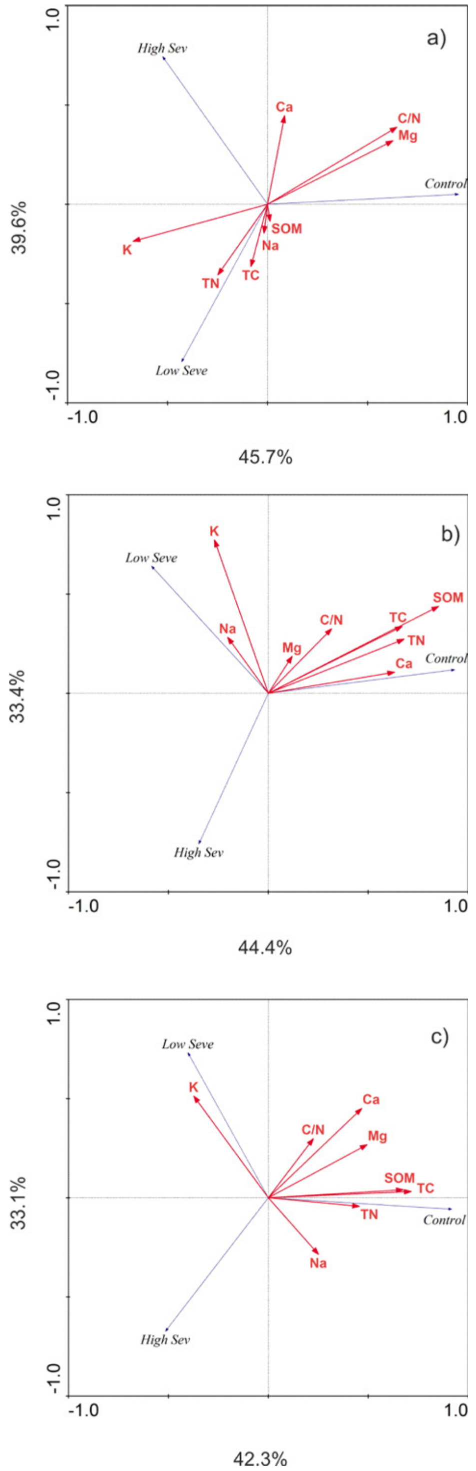

Fig. 2. RDA for the relation between Factors 1 and 2. The environmental variables are TN (total nitrogen), TC (total carbon), C/N (carbon/nitrogen ratio), SOM (soil organic matter), Ca (calcium), Mg (magnesium), Na (sodium), K (potassium). The cases of study are a) short-term sampling, b) medium-term sampling, c) long-term sampling. The three different severities are: Control (unburned), Low Sev (low severity area) and High Sev (high severity area).

on soil TN (despite the non-significant increase in both fire-affected plots in relation to the control). Studies conducted elsewhere report different results: for example, Murphy et al. (2006) and Knoepp et al. (2005) observed a significant decrease in soil TN after a wildfire.

As with TN, soil TC content was significantly lower between the first and second sampling dates, which can be attributed to the same causes described above for TN and to the increasing mineralization rate of carbon in the presence of high amounts of nutrients in solution (Alcaniz et al., 2016). In the medium- and long-terms, the fire-affected areas presented significantly lower TC values than those in the control plot. Kavdir et al. (2005) also observed a significantly lower concentration of soil TC in burned soils compared to that found in controls 12 years after a wildfire. Our results showed that after 18 years, the impacts of the wildfire could still be observed in soil TC content, which had failed to recover their pre-fire levels irrespective of the severity of the regime. Reduced levels of litter deposition meant less carbon was returned to the soils, indicating that in the case of soil TC content, the wildfire represented a long-term disturbance. In burned soils the amount of fresh residues – which are rich in labile and easily decomposable materials – is reduced (Kavdir et al., 2005). Silvana-Longo et al. (2011), Kaye et al. (2010) and Johnson et al. (2005) observed that four, 10 and 20 years after a wildfire, respectively, TC levels failed to return to their pre-fire levels.

The C/N ratio was significantly lower in the medium-term than at the other two sampling dates. The fall in the C/N ratio in the medium-term is the consequence of the mineralization effect of fire. The incorporation of burned material into the soil profile reduces the C/N ratio (Pereira et al., 2011) and in fire-affected soils this reduction is due to the fact that N is immobilized (in contrast to C) in recalcitrant heterocyclic structures. When heated, organic fractions with a low degree of humification increase their relative N content (Badia and Marti, 2003; Certini et al., 2011). This may have contributed to a reduction in the soil C/N ratio reduction in the medium-term (Black and Harden, 1995; Badia and Marti, 2003; González-Pérez et al., 2004). Pyrogenic organic matter is highly recalcitrant and resistant to microbial decomposition and so may remain in the soil profile for a long time (Santin et al., 2016). Knicker et al. (2013) observed a considerable presence of charcoal in the topsoil five years after a severe wildfire. Eighteen years after the fire, the soil C/N ratio had returned to its pre-fire level, which may be a consequence of the decrease in ash and charcoal, and an increase in fresh litter, which slightly increased SOM content. Our results are in line with Roscoe et al. (2000), who did not identify any significant differences in soil C/N ratio 21 years after a wildfire. In contrast, Johnson et al. (2012) observed that C/N ratio was significantly high in the control plot 12 years after a wildfire. Here, the area affected by the low severity fire had a significantly lower C/N ratio, the consequence of the relative enrichment of soil TN as discussed above. The high C/N ratio observed in the area affected by the high severity fire, similar in that respect to the ratio in the control, can be attributed to the decline in TN. Soto et al. (1991) observed that nitrogen losses are low below temperatures of 460 °C, but that they increase at greater temperatures. Úbeda et al. (2009) observed that ash produced at high temperatures had a high C/N ratio as result of the marked decrease in TN content.

SOM content in both burned plots was significantly higher in the short-term than in the medium- and long-terms. As expected, it follows the same dynamic as that observed for TC and TN content, and the reasons for the subsequent drop are as above. Our results are in line with previous studies were a decrease in SOM was observed in both short- (Pereira et al., 2014) and long-term studies (Kloss et al., 2012; Rovira et al., 2012; Xue et al., 2014). After the fire, soil needs a certain time to recover. During the post-fire period, there is a negative SOM balance, despite the input of ash and charcoal into the soil profile. The natural input of SOM is interrupted and is only recovered with the reestablishment of vegetation (Rovira et al., 2012). The effects of wildfire on SOM immediately after a fire vary: some studies report an increase (Mataix-Solera et al., 2002; Muranova and Simanský, 2015), others a decrease (Fernandez et al., 1997; Neff et al., 2005; Murphy et al., 2006), and some, as in our study, report no change (Jordan et al., 2011), independently of the fire severity observed. However, low fire severities typically increase or have no effect on SOM, while high fire severities reduce it (Jordan et al., 2011; Mehdi et al., 2012; Caon et al., 2014). SOM was significantly lower in the burned areas in the medium- and long-terms, as was TC, as a consequence of post-fire erosion, leaching and plant consumption. The fact that SOM was significantly lower in the burned plots in the medium-term is evidence that some erosion may have occurred between the first and second sampling dates. SOM erosion on slopes has been identified previously (Novara et al., 2011). Soil mantle and plant recovery is crucial in the immediate months following a fire to reduce the impact of torrential rainfalls. If this does not happen, erosion may induce a delay in ecosystem reorganization (Pardini et al., 2004).

4.2. Soil calcium, magnesium, sodium and potassium

Levels of extractable Ca and Mg were significantly higher in the medium-term compared to the levels recorded at the other two sampling dates (with the exception of extractable Ca between the medium- and long-terms in the L-S plot). Soils were richer in these elements in the medium-term, coinciding with the lowest C/N ratio, and due in all probability to the incorporation of charcoal rich in these nutrients following the first rainfalls. Despite the fall in TC and SOM, the mineralization induced by fire increases the availability of Ca and Mg in ash (Pereira et al., 2012) and this may explain the increase in these nutrients in the medium-term. It also indicates that some of the combusted material was incorporated into the soil profile in the period between the first two sampling dates. The long-term reduction may be the consequence of vegetation consumption. Several studies observed a significant increase in extractable Ca and Mg after wildfires (Kutiel and Inbar, 1993; Pardini et al., 2004). Compared to the figures for the control plot, no significant differences were observed in extractable Ca in the short-term; however, they were seen in extractable Mg. In both cases, nutrient concentrations were lower in the L-S plot. There is no obvious explanation for this, but we hypothesize that the degree of mineralization associated with the fire in the L-S plot was not as great as that in the H-S plot and, hence, nutrient availability was not as high. Previous studies carried out in areas affected by low severity fires observed a decrease in Mg in relation to levels in the control (Thomaz et al., 2014; Fuentes-Ramirez et al., 2015). In the medium-term, the values of extractable Ca and Mg were higher in the control plot, but only significantly so in the case of Ca. The lower content in relation to that in the control may have been due to nutrient depletion induced by erosion, leaching or vegetation consumption between the first and second sampling dates. Finally, in the long-term, the soils of the plot affected by the H-S fire presented significantly lower values of extractable Ca and Mg, compared to those in the control, showing that in this plot nutrients did not recover to their pre-fire levels. However, in stark contrast, Johnson et al. (2005) observed an increase in extractable Ca and Mg in the long-term.

Levels of extractable Na were significantly higher in the fire-affected plots in the medium-term than they were at the other sampling dates. In this respect, extractable Na followed the same patterns as extractable Ca and Mg, a pattern that can be attributed to the incorporation of combusted material into the soil profile. Studies elsewhere also report an increase in extractable Na after fire (Scarenbroch et al., 2012). There were no significant differences in soil extractable K between sampling dates on the fire affected plots. However, in each sampling period, the concentration of this nutrient was always significantly higher in the L-S plot than that in the control plot. Previous studies have reported an increase in extractable K in fire affected areas compared to unburned areas (Marion et al., 1991; Kutiel and Inbar, 1993; Scarenbroch et al., 2012).

4.3. Overall discussion and implications for management of wildfire affected areas

The wildfire changed the soils' nutrient dynamics. In the short-term, some nutrients were identified at high concentrations in the L-S plot (e.g. TN, TC, SOM, extractable Na and K), while in the H-S plot the concentration of the nutrients studied (with the exception of extractable Ca) was always below that of the nutrients in the other two plots. This points to the heterogeneous impact of the wildfire, which, in the short-term, can increase soil nutrients in some areas but reduce them in another. The low concentration of soil nutrients in plots affected by high severity fires is a consequence of the high temperatures reached, the high impact on the soils and the volatilization of nutrients (Caon et al., 2014). The lack of nutrients in the soil limited the recovery of the vegetation and plant diversity six months after the fire, in a comparative study with an area affected by a low severity fire (Francos et al., 2016a). In the medium-term, with the exception of extractable Na and K, the values of the other elements were high in the L-S plot, a consequence of post-fire erosion, leaching and vegetation consumption. Finally, in the long-term, the concentration of nutrients was very similar to that observed in the medium-term (with the exception of extractable K, all the other nutrients were present in high concentrations in the control plot). The wildfire studied had a long-term effect on some of the soil nutrients studied. Extractable Na was unaffected by fire (compared to levels in the control area) in any of the sampling periods, while TN and the C/N ratio returned to pre-fire levels in both the L-S and H-S plots. Extractable Ca and Mg only recovered in the L-S plot, while TC and SOM failed to recover their pre-fire levels 18 years after the wildfire in both burnt plots. This shows that rates of soil nutrient recovery differ after a fire, and in this case, TC and SOM were the most affected, irrespective of the severity of the fire regime. This finding contradicts previous studies that suggest that fires may contribute to long-term carbon stock pools and increase the soil capacity of carbon storage (Bennett et al., 2014; Santin et al., 2015). Extractable K was always significantly higher in the L-S plot, showing the long-term effect of fire on this nutrient.

Several studies conducted in the Mediterranean environment show that vegetation can recover rapidly after wildfires (Diaz-Delgado and Pons, 2001; Wittenberg et al., 2008; Tessler et al., 2016); however, few studies have examined their impact on soils. Indeed, according to our results, certain soil properties (TC, SOM extractable Ca and Mg) can take many years to return to their pre-fire levels. Here, the fact that the wildfire fire changed the plant composition, from a *Pinus* plantation to a *Quercus suber* forest, may have influenced soil recovery to pre-fire levels. To avoid soil degradation in the immediate post-fire period and to contribute to a faster recovery of soil properties, certain restoration measures – including different types of mulching (Santana et al., 2014), namely: organic amendments (Cellier et al., 2014), hydroseeding (Vourlitis et al., 2017), straw (Vega et al., 2014) or forest residues (Prats et al., 2014) – may be important in avoiding soil erosion, nutrient depletion and the long-term effects of fire on soil properties, especially in areas affected by high fire severities. The difficulties soils face in recovering increase with the frequency of wildfires, as observed by Guenon et al. (2013). Changes in land-use and climate change in the Mediterranean region (e.g. temperature increase and precipitation reduction) will increase wildfire frequency and severity (Turco et al., 2014), and therefore, decrease the capacity of soil recuperation to this disturbance. This may cause at long-term soil and land degradation. However, management techniques should not be implemented in the immediate post-fire period since this is when the soil is most vulnerable to human disturbance. Other post-fire engineering measures are also being used in areas affected by fire. They include hillslope treatments, erosion barriers, road and trail treatments (e.g. armoring, flow directions and water passage structures) and channel treatments (Robichaud, 2009). Salvage logging may not be an appropriate measure due to its negative effects on soil properties (Fernandez and Vega, 2016; Garcia-Orenes et al., 2017).

5. Conclusions

The wildfire studied here had different long-term effects on the soils' chemical properties, indicating that soil nutrients respond differently according to the time since wildfire and severity of wildfire. Levels of extractable Na did not differ from those recorded in the control plot on any of the sampling dates, while TN and C/N recovered to pre-fire levels. Major cations only recovered in the area affected by low fire severity and TC and SOM did not recover in either of the burned areas. The low severity fire also led to a long-term increase in extractable K levels. The lack of recovery presented by the essential soil parameters – including, extractable Ca and Mg (in the area affected by high severity fire), TC and SOM – show that restoration measures may be needed, especially after high severity fires. The inability of nutrients to recover their pre-fire levels is clearly a consequence of the disturbances caused by the fire (e.g. vegetation removal, erosion, leaching) and the subsequent loss of vegetation with time, decreasing overall soil nutrient content. Soils need more time to return to their pre-fire levels, especially in areas affected by high severity fire. However, further research is needed to observe when TC and SOM return to pre-fire levels as here this may have been influenced by the change in vegetation cover.

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