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ORIGINAL PAPER

Effects of wildfire and logging on soil functionality in the short-term in *Pinus halepensis* M. forests

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Abstract

Salvage logging is thought to have negative impacts on soil functionality because it may increase soil compaction and reduce vegetation cover and soil organic matter content. We investigated whether and to what extent burning and subsequent logging initially altered soil functionality of a Mediterranean forest of *Pinus halepensis* M. Soil functionality indicators (e.g. soil enzyme activities, basal soil respiration, glomalin-related soil protein, and microbial carbon) were measured in March and October 2017 in unburned forest plots, nearby plots severely burned by wildfire in July 2016, and nearby burned plots severely burned by wildfire and then logged in December 2016 using a lightweight agricultural tractor. The results showed significant differences among three groups: unburned soils sampled in spring (1) and autumn (2), and burned soils (not subject or subject to logging) sampled in spring and autumn. In unburned plots, seasonality had a significant effect, which disappeared in burned plots regardless of whether they had been logged. The burned plots had higher content of organic matter and total nitrogen than the unburned soils but they were not correlated to higher soil respiration or microbial biomass. There were not any differences in any of the soil functionality indicators between the unlogged and logged burned plots. In addition, the burned plots had a higher glomalin-related soil protein content than the unburned soil in the autumn measurement. Overall, the results suggest a short-term wildfire impact of soil properties whereas logging using a lightweight tractor produced no significant impacts in this sparse Mediterranean pine forest.

Keywords High-severity fire · Mediterranean forest · Salvage logging · Soil respiration · Soil organic matter · Soil enzyme

Introduction

Wildfires are a natural disturbance factor in Mediterranean forests, often enhanced by human activities such as intentional or accidental ignitions (Ruiz-Mirazo et al. 2012; Balch et al. 2017) and altered fire potential related to climate change (Jolly et al. 2015). Fires also alter the timing of vegetation succession (Pausas et al. 2009) and can affect the chemical and biological properties of soils (DeBano 2000; Certini 2005).

Post-fire salvage logging is used primarily to recover timber values but may also be prescribed to reduce possible insect and disease outbreaks and fire recurrence, reduce safety hazards, and for watershed restoration (e.g. to create contour log dams) (Ice et al. 2004; Leverkus et al. 2018). The pros (e.g. economic benefits, reduced fire susceptibility, increased worker safety and access) and cons (e.g. increased soil compaction, increased hydrologic responses, long-term loss of habitat and large downed wood) of salvage logging

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have been debated for years. The debate continues, particularly in the Mediterranean Basin and in other areas with Mediterranean climates where rainy autumns, winters and springs contrast with prolonged summer droughts. Post-fire salvage logging creates a secondary disturbance that can affect vegetation structure (Donato et al. 2006; Boucher et al. 2014; Knapp and Ritchie 2016), macrofauna habitat and populations (Thorn et al. 2018), and the physical properties of soils (Wagenbrenner et al. 2015, 2016; Prats et al. 2019), but little is known about the impacts of fire or post-fire salvage logging on soil microbiological or chemical properties (Ginzburg and Steinberger, 2012; Kishchuk et al. 2014; Leverkus et al. 2018), particularly in Mediterranean ecosystems (Lucas-Borja et al. 2019).

In many cases, salvage logging is carried out in the period immediately after a fire to provide some economic benefit to the owner, since the wood value decreases with time (Akay et al. 2006). Given that a negative influence on the soil hydrological response after post-fire logging has been well-documented (e.g. Wagenbrenner et al. 2015; DellaSala et al. 2006; Lucas-Borja et al. 2018), one might ask whether salvage logging after wildfire may affect the short-term soil functionality of forest ecosystems. More research is needed to evaluate the influence of logging on soil functionality, with particular attention to the Mediterranean forests where soils are especially prone to degradation and the risk of fire is high.

Many experiments done in the USA and Europe have shown that assessment of long-term post-fire impacts and restoration actions are often focused on the macrobiotic components of the ecosystem (Hessburg and Agee 2003; Beschta et al. 2004; Fernández and Vega 2016a, b; Gómez-Sánchez et al. 2019; Lucas-Borja et al. 2019). For these assessments, recovery of native plant communities and habitats, maintenance of plant biodiversity, reestablishment of timber or grazing species and control of invasive weeds have been the most important targets. However, little research has been done regarding the microbiotic impacts of salvage logging within the soil ecosystem itself (e.g. Poirier et al. 2014; Smith et al. 2008; Kishchuk et al. 2014), and there is a critical need to understand the impacts of post-fire salvage logging on soil microbiological and enzymatic responses.

Microbial populations and soil enzymes are of paramount importance for ecosystem processes because they catalyse a host of soil reactions that have biogeochemical significance (e.g. nutrient cycling). Moreover, these microbiological properties are related to the amount and quality of soil organic matter, which can be directly impacted by wildfire and salvage logging (Kishchuk et al. 2014). Once these substantial gaps are filled, land managers will be able to fully evaluate the relative and cumulative effects of fire and post-fire salvage logging on the critical zone processes. Overall, soil functionality plays an important role on soil fertility with a clear influence on growth and reproduction of the microbial mass. Indicators such as enzyme activities specifically related to the cycles of N, P, C and S (urease, alkaline and acid phosphatase, β-glucosidase and arylsulfatase, respectively), and microbial biomass, such as dehydrogenase activity (DHA) and soil respiration (Bastida et al. 2008; Lucas-Borja et al. 2011; Hedo et al. 2015) can be used to assess soil functionality. Moreover, the variations in C/N ratio (Lucas-Borja et al. 2012; Hedo et al. 2015), soil pH (Lucas-Borja et al. 2012), soil texture (Fterich et al. 2014), nutrient status (Burgess and Wetzel 2000; Santa-Regina and Tarazona 2001) and microbiological communities (Wu et al. 2013) are meaningful indicators of soil functionality.

In an earlier investigation in the same study area, noticeable variations in vegetation cover, dead plant matter and bare soil were detected throughout the first year after the wildfire relative to the unburned forest (Lucas-Borja et al. 2019). The added disturbance of post-fire salvage logging led to increases in dry sediment deposition in the first year (Lucas-Borja et al. 2019). However, little research has been done regarding the microbiotic impacts of logging on soil functionality (e.g. Rab 1996; García-Orenes et al. 2017; Pereira et al. 2018). We suspect that the changes in soil vegetation cover and microclimatic conditions induced by the wildfire and salvage logging may have altered the physico-chemical and biochemical soil properties in the short term. This study aims to determine whether and to what extent wildfire and post-fire logging altered short-term soil functionality of a Mediterranean forest of *Pinus halepensis* M. To this aim, several indicators of soil functionality were measured in the spring and autumn in forested areas with and without wildfire and post-fire logging. We hypothesised that logging negatively affected the short-term post-fire soil functionality because it increased soil compaction and reduced vegetation cover and organic matter content, and these impacted the metabolic processes of forest soils.

Materials and methods

Study site

The Sierra de las Quebradas forest (Liétor, Castilla-La Mancha region, province of Albacete, Spain (W1°56′35.02″, N38°30′40.79″; Fig. 1) ranges in elevation between 520 and 770 m, and the study sites have west or southwest aspects. The semiarid climate is categorised as type BSk according to the Köppen classification (Kottek et al. 2006) with a mean annual temperature of 16.6 °C and mean annual precipitation of 321 mm. Soils are classified as *Calcid Aridisols* (USDA Soil Taxonomy 1999) and have a sandy loam texture. The dominant overstory vegetation consists of Aleppo pine (*Pinus halepensis* Mill.*)* and kermes oak (*Querco*

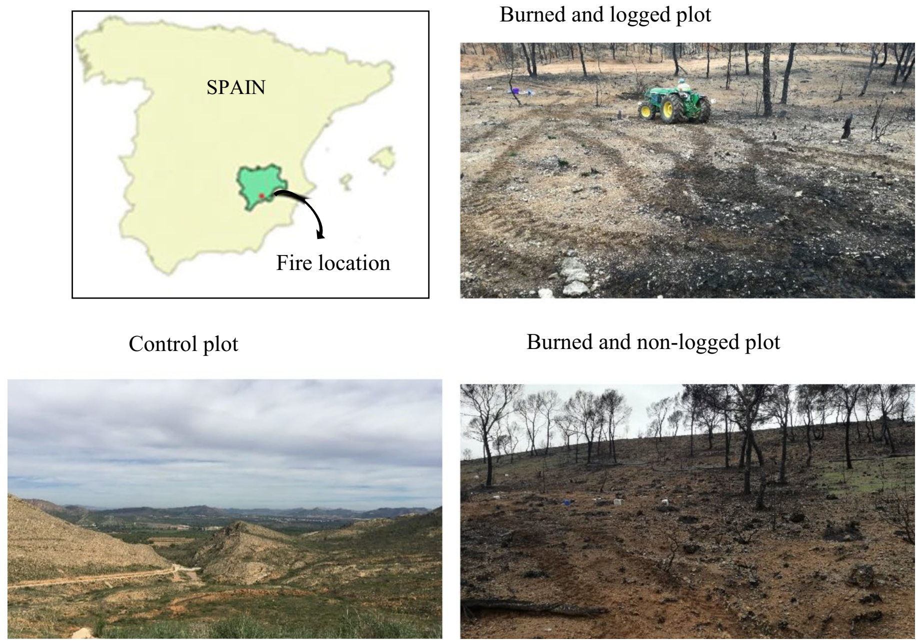

Fig. 1 Location of the study area (Liétor, Castilla La Mancha, Spain) and pictures taken from each experimental condition

cocciferae) (Peinado et al. 2008). Before the wildfire, the stand density ranged from 500 to 650 trees/ha and the tree heights ranged from 7 to 14 m. Additional understory vegetation includes *Rosmarinus officinalis* L., *Brachypodium retusum* (Pers.) Beauv., *Cistus clusii* Dunal, *Lavandula latifolia* Medik., *Thymus vulgaris* L., *Helichrysum stoechas* L., *Stipa tenacissima* L., *Quercus coccifera* L. and *Plantago albicans* L. The economic value of the understory species decreased in the mid-1900s, which led to agricultural abandonment and reforestation by Aleppo pines of natural origin.

In July 2016, a wildfire burned much of the forest. In September 2016, we selected a study catchment (700 ha) which included unburned forest and burned forest where crown fire had occurred and resulted in 100% tree mortality (Fig. 1). A WatchDog 2000 model 2700 weather station (Spectrum Technologies, Inc., Aurora, IL, USA), was installed in the study area and measured precipitation depth and intensity and air temperature. We compared the air temperature and precipitation during the study to climatic records (1978–2012) (AEMET 2015) to assess the site conditions relative to the local climate.

Experimental design

This study was carried out during 2017 within the study catchment, where we established nine randomly-located experimental plots, each extending 20 m downslope by 10 m along the contour and located at least 200 m from the nearest plot. Characteristics such as slope, aspect, pre-fire vegetation, and soil type were relatively uniform among the plots. Three of the nine plots were in unburned forest. The remaining six plots had burned at high severity, which was assessed previous to logging in ten 20 cm × 20 cm quadrats placed at systematically identified points along one placed on the centre of each plot using methods described by Fernández and Vega (2016a, b). Of the six burned plots, three received no additional treatment and three had been logged in December 2016. Salvage logging was conducted using an agricultural adapted tractor with herringbone-tyre pneumatic rubber agricultural wheels (tyre size 18.4R30) (Fig. 1). The tractor was a 4-cylinder model DT9880 (Landini), which can reach a rated power of 94/69.2 C.V. kW^{-1}. The working speed ranges from 6.0 to 8.0 km h^{-1}. The total tractor weight was 4697 kg. Soils in each of the nine plots were sampled in March and October 2017. Hereafter, the treatments are indicated with capital letters (“NB”, non-burned, “B + NL”, burned and non-logged, and “B + L”, burned and logged) and the sampling seasons are indicated by capital letters: “/S” for spring (March 2017); and “/A” for autumn (October 2017). For example, “B + L/S” indicates a burned and logged plot sampled in March 2017.

Soil sampling

We collected one 600-g soil sample from each plot during each sampling period, for a total of 18 samples. Each plot sample was made up of six 100-g subsamples collected from randomly selected points in each plot, to capture the potential variability of soil conditions within the plots. Each soil subsample was at least 5 m from the nearest adjacent subsample and the six subsamples represented different regions of each plot. Moreover, each subsample was collected from the top 10 cm of surface soil after removing the litter layer, then passed through a 2 mm sieve and stored at 4 °C until subsequent analyses could be done the next day.

Physico-chemical soil analyses

On each soil sample particle size distribution was determined using the method of Guitián-Ojea and Carballas (1976). Soil pH and electrical conductivity (EC, μS/cm) were measured in a 1:5 (w/v) aqueous solution with a multiparameter portable device (Hanna Instruments® model HI2040-02, Gipuzkoa, Spain). Organic matter content (OM, %) was determined using the potassium dichromate oxidation method (Nelson and Sommers 1996), and organic carbon (OC, %) was calculated by multiplying the OM by 0.58 (Lucas-Borja et al. 2018). Total nitrogen (TN, %) was determined using the Kjeldahl method (Bremner and Mulvaney 1982). The C/N ratio was obtained by dividing the organic carbon by the total nitrogen.

Biochemical soil analyses

Collected samples were dried 1 day after sampling during 48 at lab temperature for measuring several biochemical properties. We used a fumigation-extraction method to determine microbial carbon (MC, expressed as mg C kg^{-1} dry soil) (Vance et al. 1987). Basal soil respiration (BSR, expressed as the μg CO_2 h^{-1} g^{-1} of dry soil), was measured with a respirometer (Micro-Oxymax, Columbus Instruments, Inc., OH, USA). Soil dehydrogenase activity was determined by the reduction in p-iodonitrotetrazolium chloride (INT) to p-iodonitrotetrazolium formazan (INTF) following Von Mersi and Schinner (1991) and expressed as μg INTF h^{-1} g^{-1} of dry soil. Urease activity (UA, expressed as μmol N-NH4 + h^{-1} g^{-1} of dry soil) was measured using urea as a substrate and a borate buffer at pH = 10 (Tabatabai 1994; Kandeler and Gerber 1988). The activity of acid phosphatase (acid-PA) and β-glucosidase (BGA), both expressed as μmol p-NP h^{-1} g^{-1} of dry soil, were determined using the methods of Tabatabai and Bremner (1969) and Eivazi and Tabatabai (1977), respectively. Glomalin-related soil protein content (GPRS, expressed as g^{-1} dry soil) was measured with the techniques of Lozano et al. (2016). GPRS was extracted from 0.25 g subsamples with 2 ml citric acid buffer, pH 7.0, at 121 °C for 30 min in an autoclave. After extractions, samples were centrifuged at 3000 revolutions per minute for 15 min to remove soil particles. Protein in the supernatant was determined by a Bradford assay (Wright and Upadhyaya 1996).

Statistical analyses

Statistical differences in physical, chemical and biochemical characteristics of non-burned, burned and non-logged, and burned and logged soil samples obtained in autumn and spring were determined by univariate and multivariate permutational analysis of variance (PERANOVA and PERMANOVA, Anderson 2001) using a three-factor design: (1) fire occurrence (burned/non-burned); (2) logging activities (logging/non-logging); (3) season of the year (spring/autumn). Then, Pearson's matrix was calculated to evaluate the possible correlations among the properties of sampled soil. For the statistical analyses the software PRIMER V 7® with PERMANOVA add-on (Anderson et al. 2008) and Statgraphics Centurion XVI ® (StatPoint Technologies, Inc., Warrenton, VA, USA) were used. We used a significance level of 0.05 unless otherwise indicated.

Results

Air temperature was similar between the reference period (1978–2012) and the study period (November 2016–November 2017). In contrast, precipitation from November 2016 to January 2017 was greater than during the reference period (1978–2012), while the rest of the study year was dry in comparison to the reference period (Fig. 2). Moreover, The PERMANOVA analysis on the suite of physico-chemical and biochemical properties showed significant differences (Pseudo-F: 7.6; $p < 0.001$) between unburned soils and burned soils (subject to logging or not) in both field sampling campaigns (Table 1).

Differences among treatments and temporal changes in physical and chemical soil properties

The soil texture of the NB plots was a sandy clay loam, while both the burned soils (B + NL and B + L) were sandy loams (Table 2). The different textures resulted from higher clay and lower silt contents in the NB plots as compared to the B + NL and B + L plots. The soil pH ranged from 8.45 to 8.73, indicating slight alkalinity, and there was no significant difference in pH among any of the plots or sample periods. In general, the NB plots showed the lowest contents of OC, OM and TN and the highest for the C/N ratio (Table 2). The OC, OM, EC and TN significantly differed between the NB plots and the burned (either logged or not) plots in spring 2017. More specifically, as compared to the NB samples, the B + NL and B + L soils had higher OC and OM (about + 80% and + 140%, respectively for both variables) and much higher TN (at least + 200% for both treatments), which resulted in lower C/N (− 43% and − 23%, respectively). The C/N ratio was significantly different among the spring 2017 samples of the three treatments.

With regard to the seasons, none of the treatments had any differences in any of the physical or chemical properties between the spring and autumn samples except for a

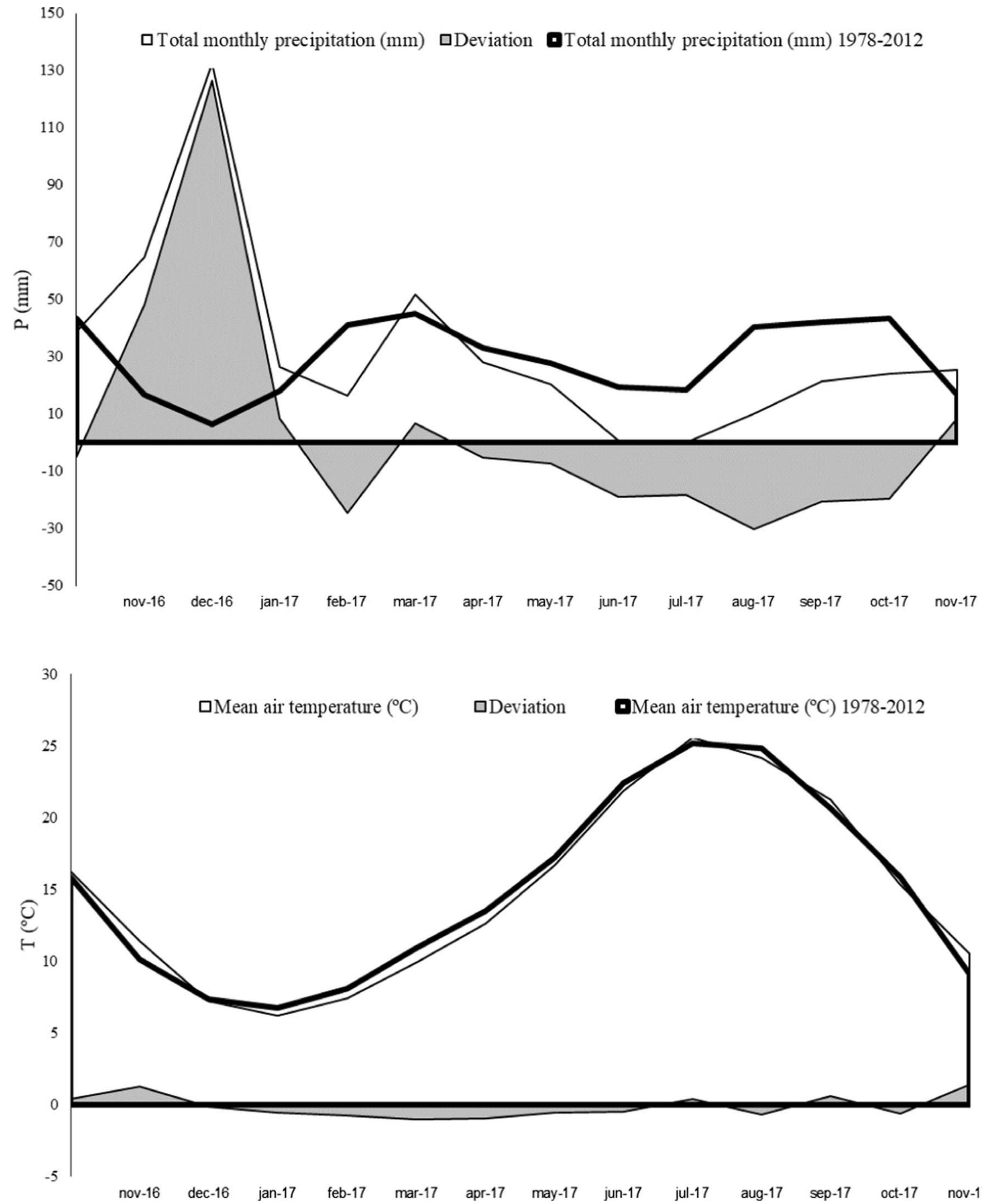

Fig. 2 Climatic data records during the study period compared to the reference period (1978–2012)

significant decrease in C/N ratio (− 58%) in the NB plots and a significant increase in the C/N ratio (+ 20%) in the B + NL plots between spring and autumn (Table 2). The soil properties in the B + NL samples from the autumn field campaign were generally similar to those of the B + L samples in both seasons, and combined, these burned samples had significantly higher OC, OM and TN contents than the NB soils. Similarly, significant decreases in EC between the burned and unburned soils were detected (Table 2).

Differences among treatments and temporal changes in biochemical soil properties

Compared to NB soils in spring 2017 the burned plots (whether subject to logging or not) showed no differences in BGA, UA, Acid-PA, DHA. The BSR was higher and the GPRS was lower in the B + NL plots than the NL and B + L plots, and the MC in B + NL and B + L were higher than the NB (Table 3). Comparing the autumn to spring results from the NB plots showed that BGA, Acid-PA and GPRS decreased significantly, whereas MC increased significantly and there was no change in UA, DHA, or BSR (Table 3). In the burned soils, the GPRS increased in the B + NL plots and there were no significant differences in any of the indices in the B + L plots from spring to autumn (Table 3).

Table 1 One-way permutational multivariate analysis of variance (PERMANOVA) for burn condition ["NB", non-burned soil, "B + NL", burned and non-logged soil, and "B + L", burned and logged soil in both spring (March 2017) and autumn (October 2017)] and applied to physico-chemical and biochemical properties of soil samples collected in this study ($n = 18$) (Liétor, Castilla La Mancha, Spain)

Source	*df*	SS	MS	Pseudo-*F*	*P*(perm)	Unique perms
Burn condition	5	207	41	7.6	0.0001	9928
Residuals	12	65	5.4			
Total	17	272				

df degrees of freedom, *SS* sum of squares, *MS* mean squares, *pseudo-F* MS Burn condition: MS residuals ratio, *P(perm)* threshold for significance in PERMANOVA, *Unique perms* number of unique values of the test statistic obtained under permutation

Table 2 Main physical and chemical properties (mean ± standard error) of soil samples collected in spring (S) and autumn (A) in non-burned (NB), burned and non-logged (B + NL) and burned and logged (B + L) plots ($n = 3$ per treatment/season) (Liétor, Castilla La Mancha, Spain)

Treatment/season	Clay (%)	Silt (%)	Sand (%)	OM (%)	OC (%)	pH	EC (µS/cm)	TN (%)	C/N
NB/S	32.6 ± 0.34(a)	19.9 ± 1.35(c)	47.4 ± 2.23(a)	2.65 ± 0.23(c)	1.54 ± 0.09(c)	8.73 ± 0.13(a)	124 ± 16.2(a)	0.07 ± 0.02(b)	22.1 ± 0.23(a)
NB/A	32.1 ± 0.52(a)	19.1 ± 1.10(c)	48.2 ± 1.02(a)	2.19 ± 0.16(c)	1.27 ± 0.09(c)	8.64 ± 0.21(a)	103 ± 17.7(ab)	0.09 ± 0.01(b)	13.9 ± 0.73(c)
B + NL/S	14.8 ± 1.65(bc)	32.9 ± 0.74(ab)	52.1 ± 2.40(a)	4.75 ± 0.15(ab)	2.75 ± 0.08(ab)	8.47 ± 0.03(a)	90.9 ± 7.2(b)	0.21 ± 0.01(a)	12.6 ± 0.33(d)
B + NL/A	7.71 ± 1.03(b)	41.8 ± 1.96(a)	50.3 ± 3.21(a)	6.20 ± 0.73(a)	3.60 ± 0.42(a)	8.45 ± 0.10(a)	81.4 ± 19.8(b)	0.24 ± 0.03(a)	15.1 ± 0.41(b)
B + L/S	6.99 ± 1.45(b)	42.2 ± 0.37(a)	50.7 ± 2.24(a)	6.45 ± 0.38(a)	3.75 ± 0.15(a)	8.60 ± 0.12(a)	93.3 ± 7.54(b)	0.22 ± 0.01(a)	17.0 ± 0.22(b)
B + L/A	6.68 ± 0.34(b)	42.0 ± 0.03(a)	51.2 ± 1.04(ab)	7.12 ± 0.09(a)	4.14 ± 0.05(a)	8.47 ± 0.07(a)	88.2 ± 6.92(b)	0.25 ± 0.02(a)	16.6 ± 0.25(b)

Different lowercase letters among treatments and seasons indicate statistically significant differences ($p < 0.05$) based on the permanova analyses

OC organic carbon, *OM* organic matter, *EC* electrical conductivity, *TN* total nitrogen

Table 3 Main biochemical properties (mean ± standard error) of soil samples collected in spring (S) and autumn (A) in non-burned (NB), burned and non-logged (B + NL) and burned and logged (B + L) plots ($n = 3$ per treatment/season) (Liétor, Castilla La Mancha, Spain)

Treatment/season	BGA (µmol p-NP h^{-1} g^{-1})	UA (µmol N-NH4 + h^{-1} g^{-1})	Acid-PA (µmol p-NP h^{-1} g^{-1})	DHA (µg INTF h^{-1} g^{-1})	BSR (µgCO_2 h^{-1} g^{-1})	GPRS (µ g^{-1} dry soil)	MC (mg C kg^{-1} dry soil)
NB/S	0.86 ± 0.05(ab)	0.73 ± 0.03(a)	1.16 ± 0.04(a)	0.10 ± 0.01(a)	1.94 ± 0.05(b)	1700 ± 149(b)	56.3 ± 0.52(c)
NB/A	0.59 ± 0.06(c)	0.50 ± 0.11(a)	0.47 ± 0.04(b)	0.11 ± 0.02(a)	1.94 ± 0.11(b)	1030 ± 118(c)	369 ± 20.4(a)
B + NL/S	0.86 ± 0.21(ab)	0.53 ± 0.09(a)	0.77 ± 0.06(ab)	0.12 ± 0.02(a)	3.73 ± 0.73(a)	1394 ± 183(c)	191 ± 9.63(b)
B + NL/A	0.96 ± 0.14(ab)	0.44 ± 0.05(a)	0.93 ± 0.03(a)	0.11 ± 0.06(a)	4.47 ± 0.57(a)	2845 ± 289(a)	204 ± 3.91(b)
B + L/S	1.18 ± 0.47(ab)	0.85 ± 0.40(a)	1.22 ± 0.51(a)	0.14 ± 0.03(a)	2.10 ± 0.24(b)	2278 ± 635(ab)	224 ± 108(b)
B + L/A	1.28 ± 0.01(a)	0.66 ± 0.09(a)	1.35 ± 0.08(a)	0.08 ± 0.01(a)	2.05 ± 1.13(b)	2890 ± 77(a)	195 ± 5.00(b)

Different lowercase letters indicate statistically significant differences ($p < 0.05$) based on the permanova analyses and among treatments and seasons

BGA β-glucosidase activity, *UA* urease activity, *Acid-PA* acid phosphatase activity, *DHA* dehydrogenase activity, *BSR* basal soil respiration, *GPRS* glomalin-related soil protein, *MC* microbial carbon

Relationships among physico-chemical and biochemical soil properties

As might be expected the clay, silt and sand contents were significantly correlated each other ($|r| > 0.56$). As regards the physico-chemical soil properties, strong and significant correlations ($|r| > 0.47$) were identified among OM, TN and C/N. The pH was significantly correlated with the clay and silt fractions of soils ($|r| \geq 0.60$) and negatively with the OM and TN contents ($r \leq -0.52$) (Table 4). Concerning the biochemical soil properties, BGA, Acid-PA and GPRS were significantly correlated with each other ($r \geq 0.74$) and with several physico-chemical soil properties (particularly with OM and TN, $r \geq 0.51$). In more detail, BGA and GPRS each had a large number of positive correlations ($r \geq 0.59$) with the physico-chemical soil properties, and they both were negatively correlated with clay content ($r \leq -0.62$). UA showed significant and positive correlations with BGA and Acid-PA ($r = 0.61$ and $r = 0.74$, respectively), while DHA was only negatively correlated with BSR ($r = -0.46$). No significant correlation was found between the EC or MC and any of the physico-chemical or biochemical soil properties (Table 4).

Discussion

The results of our PERMANOVA analysis showed that wildfire is a significant disturbance factor of soil, as indicated by the remarkable differences between unburned and burned soils, with or without logging at the end of the first post-fire wet season (spring 2017) and at the end of the following dry season (autumn 2017) (Table 2). Others have detected significant changes in soil organic matter and nutrient content in soils affected by wildfire as compared to unburned soils (e.g. González-Pérez et al. 2004; García-Orenes et al. 2017), including nutrient availability and water retention (Certini 2005), increases in pH (Mataix-Solera et al. 2002; Ulery et al. 1993), and reduction in the aggregate stability and soil structure decay (DeBano 2000). Changes in soil texture related to burning have also been identified in previous studies, and attributed to aggregate breakdown with loss of soil organic matter (e.g. Certini 2005; Mataix-Solera and Cerdà 2009). Our results corroborate this fact as our textures clearly differed between NB and burned plots (B + NL and B + L). Moreover, there were no differences in textural properties between the spring and autumn samples, and we attribute this to the short time between sample periods. We attribute the lack of difference between B + NL and B + L to the lightweight machinery used during logging operations. For this research, logging operations were carried out using a single pass of an agricultural tractor with pneumatic tires, resulting in low ground pressure. Fernández et al. (2007) found similarly little impact of post-fire salvage logging on vegetaton recovery.

The monitoring of the physico-chemical properties of the soil showed changes mainly between the non-burned and burned plots (regardless of logging) over time. Differences between the burned and logged and burned and not logged plots occurred only in the C/N ratio, BSR, and GPRS.

Table 4 Correlation matrix among physico-chemical and biochemical properties of soil samples collected in spring and autumn in non-burned, burned and non-logged and burned and logged plots ($n = 18$) (Liétor, Castilla La Mancha, Spain)

Soil property	%Silt	%Sand	pH	EC	OM	TN	C/N	BGA	UA	Acid-PA	DHA	GPRS	BSR	MC
%Clay	**−0.98**	**−0.67**	**0.60**	0.11	**−0.97**	**−0.96**	**−0.60**	**−0.62**	−0.07	−0.43	−0.08	**−0.73**	−0.29	0.02
%Silt		**0.56**	**−0.61**	−0.10	**0.98**	**0.97**	**0.63**	**0.63**	0.06	0.45	0.01	**0.78**	0.33	−0.02
%Sand			−0.28	0.17	**0.54**	**0.58**	0.19	0.37	0.11	0.24	0.37	0.23	−0.01	−0.04
pH				0.27	**−0.53**	**−0.52**	−0.44	−0.37	−0.24	−0.28	−0.20	−0.43	−0.25	−0.01
EC					−0.19	0.13	−0.18	−0.27	−0.21	−0.31	−0.17	−0.15	0.31	−0.11
OM						**0.97**	**0.67**	**0.67**	0.14	**0.51**	−0.03	**0.78**	0.26	−0.01
TN							**0.47**	**0.59**	0.02	0.40	−0.06	**0.71**	0.40	−0.02
C/N								**0.61**	0.43	**0.61**	0.10	**0.69**	−0.26	0.04
BGA									**0.61**	**0.88**	0.09	**0.76**	−0.17	−0.05
UA										**0.74**	0.28	0.25	−0.38	−0.03
Acid-PA											−0.05	**0.74**	−0.17	−0.33
DHA												−0.27	**−0.46**	0.07
GPRS													0.24	−0.14
BSR														−0.04

Values in bold are statistically significant at $p < 0.05$ based on the canonical correlation analysis

EC electrical conductivity, *OC* organic carbon, *OM* organic matter, *TN* total nitrogen, *BGA* β-glucosidase activity, *UA* urease activity, *Acid-PA* acid phosphatase activity, *DHA* dehydrogenase activity, *GPRS* glomalin-related soil protein, *BSR* basal soil respiration, *MC* microbial carbon

Literature shows that soil pH and EC tend to rise after fire (e.g. Pereira et al. 2018), and these properties gradually return to the original pre-fire values due to the washout effect (Mataix-Solera et al. 2009; Munoz-Rojas et al. 2016). In our study, the pH of soil did not respond to burning or burning and logging, possibly due to the buffering capacity of our carbonated soils, which slows or prevents the movement of the acid front and therefore the mobilisation of soil elements (Certini 2005; Mataix-Solera et al. 2009). Conversely, EC of the burned soils in our study initially increased and then decreased relative to the unburned soils as predicted by the earlier studies. The EC was significantly lower in the B + NL and B + L plots relative to the NB plots. The difference in EC may be because of burning, which accumulates ash containing C and other nutrients from burned forest fuel (Caon et al. 2014).

Some of the other physico-chemical properties of soils significantly changed immediately after the wildfire. These changes indicated a shift of burned soils towards a higher content of organic matter and nutrients, thus improving their fertility, and these increases were no different in soils subjected to logging. Moreover, these changes persisted or further increased in the second sample period with a simultaneous increase in the C/N ratio, driven by the slight increase in OC. Of all the physical and chemical soil properties, OM content is one of the most important quality indicators, given its influence on plant growth-related functions such as water retention, nutrient exchange, and soil structure (Mataix-Solera et al. 2011; Munoz-Rojas et al. 2016). The increase in soil organic matter may be due to accumulation of ash, which contains carbon and other nutrients from burned forest fuel (Bodí et al. 2014; Caon et al. 2014). In general, the variability of the C/N ratio was similar across the three treatments, indicating low activity and disintegration speed for OM as well as a low degree of N mineralisation regardless of burning and logging, which may be due to a more recalcitrant chemical composition of litter and low litter quality (Martín-Peinado et al. 2016).

The simultaneous measurement of several enzymatic activities might be useful as an indicator of the bioactivity and biochemical fertility of a soil (Gil-Sotres et al. 1992). Enzymatic activity plays an important role in catalysing biological reactions (Mataix-Solera et al. 2009). This study has confirmed how wildfire can modify enzymatic activity and microbial biomass and how these changes can subsequently vary when soils are subjected to post-fire logging. Enzymes strongly influence both degradative processes in the soil and changes in organic matter (Ceccanti and García 1994) but as Nannipieri et al. (1990) suggested, it would be difficult for one activity alone to be taken as representative of the overall nutrient state of a soil due to the great specificity of individual enzymes for particular substrates. To summarise, we measured significant decreases in BGA, Acid-PA, and GPRS and a significant increase in MC between spring and autumn in the non-burned plots. As indicated by the climatic records, spring 2017 was preceded by a relatively wet period and autumn 2017 was drier than the reference period (Fig. 2). As Merilä et al. (2002) showed, low soil moisture is a major factor in controlling the activity of microbes. Seasonal changes in soil moisture were frequently reported to affect enzymatic activities in forest soils (Baldrian et al. 2010). As Criquet et al. (2004) demonstrated, some enzymatic activities (e.g. urease, phosphatase and β-glucosidade) were substantially reduced in dry seasons. Sardans and Peñuelas (2005) also concluded that forest soil contained less microbial biomass and exhibited reduced enzyme activities in dry periods. However, when burned, either logged or not, differences for sol enzyme activities were hard to find and seasonality was not as an important factor. In this regard, BSR and MC were significantly different between the NB and burned soils. These enzymatic effects detected in NB soils compared to B + NL plots (either logged or not) may be due to the accumulation of organic matter and nitrogen coming from the burned plant material (Rodríguez et al. 2017), which continued until these mineralised materials had been consumed (Munoz-Rojas et al. 2016) and their decomposition in the 7-month monitoring period. This result was further confirmed by the positive correlations between the BGA and Acid-PA on one hand and OM and TN on the other hand.

The lack of variation in DHA observed in the unburned, burned, and burned and logged soils, and the absence of relationship between DHA and all of the physical characteristics and all of the chemical parameters except a negative correlation with BSR, confirms the lack of sensitivity of DHA to seasonality and side effects found in other studies in Mediterranean areas (Lucas-Borja et al. 2011, 2019). The lack of effect could be related to the fact that dehydrogenases are not active as extracellular enzymes in soil, thus presenting a different pattern compared to extracellular soil enzymes such as β-glucosidase, urease and acid phosphatase (Błońska et al. 2017). Thus and according to our results, the usefulness of DHA as an indicator of soil quality in burned areas is low.

Based on our correlation results, an increase in OM in the burned soils did not generate a parallel increase in the DHA, BSR, or soil microbial biomass. In other words, there was an uncoupling of the soil microbial biomass and its activity. This result was also found in an earlier study by Lucas-Borja et al. (2011), who pointed out that the different chemical structure of the litter types (including burned plant material) might be responsible for the low microbial activity in sites with high microbial biomass. Moreover, the uncoupling of the soil microbial biomass and its general activity suggests a stress or disturbance of the soil microbial community (Lucas-Borja et al. 2011). Our study demonstrated that

Glomalin-Related Soil Protein (GPRS) content in B + NL and B + L soils in autumn, approximately 1 year post-fire, exceeded the spring burned measurements and the autumn measurements in the unburned soil. Result also showed that GPRS values were significantly correlated with OM content and the C/N ratio. Burnt plots (either logged or not) favouring higher OM accumulation and C/N ratios would generate GPRS recovery even to higher values compared to unburned plots. The glomalin, which is a glycoprotein produced by Arbuscular Mycorrhizal Fungi (AMF), is an indicator of C and N storage, which in turn play key roles in aggregate stability or water repellence of soils (Lozano et al. 2016). As Rivas et al. (2016) showed, the GPRS level recovery 4 years after fire was due to species' rapid root colonisation and associated arbuscular mycorrhizal fungi colonisation. Overall, it can be said that logging after wildfire affect does not significantly alter soil functionality in the short-term in *Pinus halepensis* M. forests whereas wildfire is an influential factor. However, this is a short period to assess changes and the implications for mid or long-term responses should be correctly addressed. In addition, particular attention should be paid to different types of forest logging machines and forestry equipment.

Conclusions

In order to evaluate whether and to what extent logging alters soil functionality in the short period after a wildfire in a Mediterranean forest of *Pinus halepensis* M., we sampled unburned soils (control), and plots burned and subjected to no logging or logging in March and October 2017 following a severe wildfire in July 2016 and logging in December 2016. Differences in physico-chemical and biochemical properties of soils under the three conditions showed some discrimination between unburned and burned plots (logged or not) 8 months after wildfire and again 15 months after the fire, but few difference 3 and 10 months after post-fire logging. Specifically, the burned (either logged or not) soils had greater organic matter content, greater nitrogen content, and higher basal soil respiration rate than the unburned controls, although the basal soil respiration rate was not significantly higher in the autumn (15 months after fire) measurement. The glomalin-related soil protein content was also greater in the burned plots than the controls in the autumn (15 months after burning). There were no differences in soil pH, sand fraction, urease activity, dehydrogenase activity, or microbial carbon among the unburned, burned, and burned and logged soil conditions. These results led us to reject the initial working hypothesis that logging negatively affects soil functionality immediately after fire in Mediterranean forests. Logging operations using a lightweight tractor produced no significant impacts on logged plots. Overall, the differences between non-burned and wildfire affected plots suggest the important effects of wildfires on soil functionality. In our study, the seasonal differences in some of the indicators of unburned soils were more significant than the differences between the burned plots with and without logging.

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References

Akay AE, Yilmaz M, Tonguc F (2006) Impact of mechanized harvesting machines on forest ecosystem: residual stand damage. J Appl Sci 6:2414–2419

Anderson MJ (2001) A new method for non-parametric multivariate analysis of variance. Aust Ecol 26:32–46

Anderson M, Gorley RN, Clarke RK (2008) PERMANOVA + for primer: guide to software and statistical methods. Plymouth Marine Laboratory, Plymouth, p 214

Balch JK, Bradley BA, Abatzoglou JT et al (2017) Human-started wildfires expand the fire niche across the United States. Proc Natl Acad Sci 114:2946–2951

Baldrian P, Merhautová V, Cajthaml T, Petránková M, Šnajdr J (2010) Small-scale distribution of extracellular enzymes, fungal, and bacterial biomass in Quercus petraea forest topsoil. Bio Fertil Soils 46:717–726

Bastida F, Zsolnay A, Hernández T, García C (2008) Past, present and future of soil quality indices: a biological perspective. Geoderma 147:159–171

Beschta RL, Rhodes JJ, Kauffman JB et al (2004) Postfire management on forested public lands of the western United States. Conserv Biol 18:957–967

Błońska E, Lasota J, Zwydak M (2017) The relationship between soil properties, enzyme activity and land use. For Res Pap 78(1):39–44. https://doi.org/10.1515/frp-2017-0004

Boucher D, Gauthier S, Noël J et al (2014) Salvage logging affects early post-fire tree composition in Canadian boreal forest. For Ecol Manag 325:118–127

Bremner JM, Mulvaney CS (1982) Nitrogen—total 1. Methods Soil Anal Part B Chem Microbiol Prop 2:595–624

Burgess D, Wetzel S (2000) Nutrient availability and regeneration response after partial cutting and site preparation in eastern white pine. For Ecol Manag 138:249–261

Caon L, Vallejo VR, Ritsema CJ, Geissen V (2014) Effects of wildfire on soil nutrients in Mediterranean ecosystems. Earth Sci Rev 139:47–58

Certini G (2005) Effects of fire on properties of forest soils: a review. Oecologia 143:1–10

Criquet S, Ferre E, Farnet AM, Le Petit J (2004) Annual dynamics of phosphatase activities in an evergreen oak litter: influence of biotic and abiotic factors. Soil Biol Biochem 36:1111–1118

DeBano LF (2000) The role of fire and soil heating on water repellency in wildland environments: a review. J Hydrol 231:195–206

DellaSala DA, Karr JR, Schoennagel T, Perry D, Noss RF, Lindenmayer D, Beschta R, Hutto RL, Swanson ME, Evans J (2006) Post-fire logging debate ignores many issues. Science 314:51–52

Donato DC, Fontaine JB, Campbell JL et al (2006) Post-wildfire logging hinders regeneration and increases fire risk. Science 80:311–352

Eivazi F, Tabatabai MA (1977) Phosphatases in soils. Soil Biol Biochem 9:167–172

Fernández C, Vega JA (2016a) Effects of mulching and post-fire salvage logging on soil erosion and vegetative regrowth in NW Spain. For Ecol Manag 375:46–54. https://doi.org/10.1016/j.foreco.2016.05.024

Fernández C, Vega JA (2016b) Modelling the effect of soil burn severity on soil erosion at hillslope scale in the first year following wildfire in NW Spain. Earth Surf Process Landforms 41:928–935

Fernández C, Vega JV, Fonturbel T, Pérez-Gorostiaga P (2007) Effects of wildfire, salvage logging and slash treatments on soil degradation. Land Degrad Dev 20:587–588

Fterich A, Mahdhi M, Mars M (2014) The effects of *Acacia tortilis* subsp. raddiana, soil texture and soil depth on soil microbial and biochemical characteristics in arid zones of Tunisia. Land Degrad Dev 25:143–152

García-Orenes F, Arcenegui V, Chrenkova K et al (2017) Effects of salvage logging on soil properties and vegetation recovery in a fire-affected Mediterranean forest: a two year monitoring research. Sci Total Environ 586:1057–1065

Gil-Sotres F, Trasar-Cepeda C, Ciardi C, Ceccanti B, Leiros MC (1992) Biochemical measures of biological activity in very young minesoils. Biol Fertil Soils 13:25–30

Ginzburg O, Steinberger Y (2012) Effects of forest wildfire on soil microbial-community activity and chemical components on a temporal-seasonal scale. Plant Soil 360:243–257

Gómez-Sánchez E, Lucas-Borja ME, Plaza-Álvarez PA et al (2019) Effects of post-fire hillslope stabilisation techniques on chemical, physico-chemical and microbiological soil properties in mediterranean forest ecosystems. J Environ Manag 246:229–238

González-Pérez JA, González-Vila FJ, Almendros G, Knicker H (2004) The effect of fire on soil organic matter—a review. Environ Int 30:855–870

Guitián-Ojea F, Carballas T (1976) Técnicas de Análisis de Suelos. Pico Sacro, Santiago de Compostela

Hedo J, Lucas-Borja ME, Wic C et al (2015) Soil microbiological properties and enzymatic activities of long-term post-fire recovery in dry and semiarid Aleppo pine (*Pinus halepensis* M.) forest stands. Solid Earth 6:243–252

Hessburg PF, Agee JK (2003) An environmental narrative of inland northwest United States forests, 1800–2000. For Ecol Manag 178:23–59

Ice GG, Neary DG, Adams PW (2004) Effects of wildfire on soils and watershed processes. J For 102:16–20

Jolly WM, Cochrane MA, Freeborn PH et al (2015) Climate-induced variations in global wildfire danger from 1979 to 2013. Nat Commun 6:7537

Kandeler E, Gerber H (1988) Short-term assay of soil urease activity using colorimetric determination of ammonium. Biol Fertil Soils 6:68–72

Kishchuk BE, Thiffault E, Lorente M et al (2014) Decadal soil and stand response to fire, harvest, and salvage-logging disturbances in the western boreal mixedwood forest of Alberta, Canada. Can J For Res 45:141–152

Knapp EE, Ritchie MW (2016) Response of understory vegetation to salvage logging following a high-severity wildfire. Ecosphere 7:e01550

Kottek M, Grieser J, Beck C et al (2006) World map of the Köppen–Geiger climate classification updated. Meteorol Zeitschrift 15:259–263

Leverkus AB, Rey Benayas JM, Castro J et al (2018) Salvage logging effects on regulating and supporting ecosystem services—a systematic map. Can J For Res 48:983–1000

Lozano E, Chrenková K, Arcenegui V et al (2016) Glomalin-related soil protein response to heating temperature: a laboratory approach. Land Degrad Dev 27:1432–1439. https://doi.org/10.1002/ldr.2415

Lucas-Borja ME, Bastida F, Moreno JL et al (2011) The effects of human trampling on the microbiological properties of soil and vegetation in Mediterranean mountain areas. Land Degrad Dev 22:383–394

Lucas-Borja ME, Candel D, Jindo K et al (2012) Soil microbial community structure and activity in monospecific and mixed forest stands, under Mediterranean humid conditions. Plant Soil 354:359–370

Lucas-Borja ME, Zema DA, Carrà BG et al (2018) Short-term changes in infiltration between straw mulched and non-mulched soils after wildfire in Mediterranean forest ecosystems. Ecol Eng. https://doi.org/10.1016/j.ecoleng.2018.07.018

Lucas-Borja ME, González-Romero J, Plaza-Álvarez PA et al (2019) The impact of straw mulching and salvage logging on post-fire runoff and soil erosion generation under Mediterranean climate conditions. Sci Total Environ 654:441–451

Martín-Peinado FJ, Navarro FB, Jiménez MN et al (2016) Long-term effects of pine plantations on soil quality in Southern Spain. Land Degrad Dev 27:1709–1720

Mataix-Solera J, Cerdà A (2009) Los efectos de los incendios forestales en los suelos. Síntesis y conclusiones. Nuevos retos en la investigación y en la gestión. Efectos los Incend For sobre los suelos en España El estado la cuestión visto por los científicos españoles Cátedra Divulg la Ciència Univ València, València 355–383

Mataix-Solera J, Cerdà A, Arcenegui V, Jordán A, Zavala LM (2011) Fire effects on soil aggregation: a review. Earth-Science Rev 109:44–60

Mataix-Solera J, Gómez I, Navarro-Pedreño J et al (2002) Soil organic matter and aggregates affected by wildfire in a *Pinus halepensis* forest in a Mediterranean environment. Int J Wildl Fire 11:107–114

Mataix-Solera J, Guerrero C, García-Orenes F et al (2009) Forest fire effects on soil microbiology. Fire Eff Soils Restor Strateg 5:133–175

Munoz-Rojas M, Erickson TE, Martini D et al (2016) Soil physicochemical and microbiological indicators of short, medium and long term post-fire recovery in semi-arid ecosystems. Ecol Indic 63:14–22

Nannipieri P, Greco S,Ceccanti B (1990) Ecological significance of the biological activity in soil. In: Bollag J-M, Stotzky G (eds) Soil biochemistry, vol 6. Dekker, New York, pp 293–355

Nelson DW, Sommers LE (1996) Total carbon, organic carbon, and organic matter. Methods Soil Anal Part C Cheml Methods 5:961–1010

Pausas JG, Llovet J, Rodrigo A, Vallejo R (2009) Are wildfires a disaster in the Mediterranean basin? A review. Int J Wildl fire 17:713–723

Peinado M, Monje L, Martínez Parras JM (2008) El Paisaje Vegetal de Castilla-La Mancha. Manual de Geobotánica, JCCM, Toledo (España)

Pereira P, Francos M, Brevik EC et al (2018) Post-fire soil management. Curr Opin Environ Sci Heal 5:26–32

Poirier V, Paré D, Boiffin J, Munson AD (2014) Combined influence of fire and salvage logging on carbon and nitrogen storage in boreal forest soil profiles. For Ecol Manag 326:133–141

Prats SA, Malvar MC, Coelho COA, Wagenbrenner JW (2019) Hydrologic and erosion responses to compaction and added surface cover in post-fire logged areas: isolating splash, interrill and rill erosion. J Hydrol 575:408–419

Rab MA (1996) Soil physical and hydrological properties following logging and slash burning in the *Eucalyptus regnans* forest of southeastern Australia. For Ecol Manag 84:159–176

Rivas Y, Canseco MI, Knicker H et al (2016) Variación en el contenido de glomalina relacionada a las proteínas del suelo, después de un incendio forestal en un Andisol en bosques de Araucaria araucana del centro-sur de Chile. Bosque (Valdivia) 37:409–417

Rodríguez J, González-Pérez JA, Turmero A et al (2017) Wildfire effects on the microbial activity and diversity in a Mediterranean forest soil. CATENA 158:82–88

Ruiz-Mirazo J, Martínez-Fernández J, Vega-García C (2012) Pastoral wildfires in the Mediterranean: understanding their linkages to land cover patterns in managed landscapes. J Environ Manag 98:43–50

Santa-Regina I, Tarazona T (2001) Nutrient cycling in a natural beech forest and adjacent planted pine in northern Spain. Forestry 74:11–28

Smith NR, Kishchuk BE, Mohn WW (2008) Effects of wildfire and harvest disturbances on forest soil bacterial communities. Appl Environ Microbiol 74:216–224

Tabatabai MA (1994) Soil enzymes. Methods Soil Anal Part Microbiol Biochem Prop 2:775–833

Tabatabai MA, Bremner JM (1969) Use of p-nitrophenyl phosphate for assay of soil phosphatase activity. Soil Biol Biochem 1:301–307

Thorn S, Bässler C, Brandl R et al (2018) Impacts of salvage logging on biodiversity: a meta-analysis. J Appl Ecol 55:279–289

Ulery AL, Graham RC, Amrhein C (1993) Wood-ash composition and soil pH following intense burning. Soil Sci 156:358–364

Vance ED, Brookes PC, Jenkinson DS (1987) An extraction method for measuring soil microbial biomass C. Soil Biol Biochem 19:703–707

Von Mersi W, Schinner F (1991) An improved and accurate method for determining the dehydrogenase activity of soils with iodonitrotetrazolium chloride. Biol Fertil Soils 11:216–220

Wagenbrenner JW, MacDonald LH, Coats RN et al (2015) Effects of post-fire salvage logging and a skid trail treatment on ground cover, soils, and sediment production in the interior western United States. For Ecol Manag 335:176–193. https://doi.org/10.1016/j.foreco.2014.09.016

Wagenbrenner JW, Robichaud PR, Brown RE (2016) Rill erosion in burned and salvage logged western montane forests: effects of logging equipment type, traffic level, and slash treatment. J Hydrol 541:889–901

Wright SF, Upadhyaya A (1996) Extraction of an abundant and unusual protein from soil and comparison with hyphal protein of arbuscular mycorrhizal fungi. Soil Sci 161:575–586

Wu S, Chang J, Dai Y et al (2013) Treatment performance and microorganism community structure of integrated vertical-flow constructed wetland plots for domestic wastewater. Environ Sci Pollut Res 20:3789–3798