

Università degli Studi Mediterranea di Reggio Calabria

Archivio Istituzionale dei prodotti della ricerca

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

This is the peer reviewd version of the followng article:

Original

Effects of wildfire and logging on soil functionality in the short-term in Pinus halepensis M. forests / Lucas-Borja, M. E.; Ortega, R.; Miralles, I.; Plaza-Álvarez, P. A.; González-Romero, J.; Peña-Molina, E.; Moya, D.; Zema, Demetrio Antonio; Wagenbrenner, J. W.; de las Heras, J.. - In: EUROPEAN JOURNAL OF FOREST RESEARCH. - ISSN 1612-4669. - 139:(2020), pp. 935-945. [10.1007/s10342-020-01296-2]

Availability: This version is available at: https://hdl.handle.net/20.500.12318/59566 since: 2024-11-20T09:26:37Z

Published DOI: http://doi.org/10.1007/s10342-020-01296-2 The final published version is available online at:https://link.springer.com/article/10.1007/s10342-020-

Terms of use:

The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. For all terms of use and more information see the publisher's website

Publisher copyright

This item was downloaded from IRIS Università Mediterranea di Reggio Calabria (https://iris.unirc.it/) When citing, please refer to the published version.

1	This is the peer reviewed version of the following article:
2	
3	Lucas-Borja, M. E., Ortega, R., Miralles, I., Plaza-Álvarez, P. A., González-Romero, J., Peña-
4	Molina, E., & De las Heras, J. (2020). Effects of wildfire and logging on soil functionality
5	in the short-term in Pinus halepensis M. forests. European Journal of Forest Research, 139,
6	<i>935-945</i> .
7	
8	which has been published in final doi
9	
10	10.1007/s10342-020-01296-2
11	
12	(https://link.springer.com/article/10.1007/s10342-020-01296-2)
13	
14 15	The terms and conditions for the reuse of this version of the manuscript are specified in the multishing policy. For all terms of use and more information see the publisher's such as
12	publishing policy. For all terms of use and more information see the publisher's website

16	Effects of wildfire and logging on soil functionality in the short-term in <i>Pinus halepensis</i> M.
17	forests
18	
19	Lucas-Borja, M.E. ^{a,*} , Ortega, R. ^b , Miralles, I. ^b , Plaza-Álvarez, P.A. ^a , González-Romero, J. ^a ,
20	Peña-Molina, E. ^a , Moya, D. ^a , Zema, D.A. ^c , Wagenbrenner, J. W. ^d , de las Heras, J. ^a ,
21	
22	^a Higher Technical School of Agricultural and Forestry Engineering, Castilla-La Mancha
23	University, Campus Universitario s/n, 02071 Albacete, Spain
24	^b Department of Agronomy & Centre for Intensive Mediterranean Agrosystems and Agri-Food
25	Biotechnology (CIAIMBITAL), University of Almeria, E-04120, Almería, Spain
26	^c Mediterranean University of Reggio Calabria, Department AGRARIA, Località Feo di Vito, I-
27	89122 Reggio Calabria, Italy
28	^d USDA Forest Service, Pacific Southwest Research Station, Arcata, California, United States
29	
30	*Email: ManuelEsteban.Lucas@uclm.es
31	
32	Manuel E. Lucas-Borja ORCID: https://orcid.org/0000-0001-6270-8408
33	
34	
35	
36	
37	Effects of wildfire and logging on soil functionality in the short-term in <i>Pinus halepensis</i> M.
38	forests

40	Lucas-Borja, M.E. ^{a,*} , Ortega, R. ^b , Miralles, I. ^b , Plaza-Álvarez, P.A. ^a , González-Romero, J. ^a ,
41	Peña-Molina, E. ^a , Moya, D. ^a , Zema, D.A. ^c , Wagenbrenner, J. W. ^d , de las Heras, J. ^a ,
42	
43	^a Higher Technical School of Agricultural and Forestry Engineering, Castilla-La Mancha
44	University, Campus Universitario s/n, 02071 Albacete, Spain
45	^b Department of Agronomy & Centre for Intensive Mediterranean Agrosystems and Agri-Food
46	Biotechnology (CIAIMBITAL), University of Almeria, E-04120, Almería, Spain
47	^c Mediterranean University of Reggio Calabria, Department AGRARIA, Località Feo di Vito, I-
48	89122 Reggio Calabria, Italy
49	^d USDA Forest Service, Pacific Southwest Research Station, Arcata, California, United States
50	
51	*Email: ManuelEsteban.Lucas@uclm.es
52	
53	Abstract
54	
55	Salvage logging is thought to have negative impacts on soil functionality because it may increase
56	soil compaction and reduce vegetation cover and soil organic matter content. We investigated
57	whether and to what extent burning and subsequent logging initially altered soil functionality of
58	a Mediterranean forest of Pinus halepensis M. Soil functionality indicators (e.g. soil enzyme
59	activities, basal soil respiration, glomalin-related soil protein, and microbial carbon) were
60	measured in March and October 2017 in unburned forest plots, nearby plots severely burned by
61	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 62 differences among three groups: unburned soils sampled in spring (i) and autumn (ii), and burned 63 soils (not subject or subject to logging) sampled in spring and autumn. In unburned plots, 64 seasonality had a significant effect, which disappeared in burned plots regardless of whether they 65 had been logged. The burned plots had higher content of organic matter and total nitrogen than 66 the unburned soils but they were not correlated to higher soil respiration or microbial biomass. 67 68 There were not any differences in any of the soil functionality indicators between the unlogged 69 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-70 71 term wildfire impact of soil properties whereas logging using a lightweight tractor produced no significant impacts in this sparse Mediterranean pine forest. 72

73

Keywords: High-severity fire; Mediterranean forest; salvage logging; soil respiration; soil
organic matter; soil enzyme.

76

77 **1. 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, Ginzberg and Steinberger 2004, Certini 2005).

Postfire salvage logging is used primarily to recover timber values but may also be prescribed to 84 reduce possible insect and disease outbreaks and fire recurrence, reduce safety hazards, and for 85 watershed restoration (e.g., to create contour log dams) (Ice et al., 2004; Leverkus et al., 2018). 86 The pros (e.g., economic benefits, reduced fire susceptibility, increased worker safety and 87 access) and cons (e.g., increased soil compaction, increased hydrologic responses, long-term loss 88 of habitat and large downed wood) of salvage logging have been debated for years. The debate 89 90 continues, particularly in the Mediterranean Basin and in other areas with Mediterranean 91 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 92 93 (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, 94 2016, Prats et al. 2019), but little is known about the impacts of fire or post-fire salvage logging 95 96 on soil microbiological or chemical properties (Ginzburg and Steinberger, 2012; Kishchuk et al., 2015, Leverkus et al., 2018), particularly in Mediterranean ecosystems (Lucas-Borja et al., 97 2019). 98

99

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., Fernandez et al., 2007; Wagenbrenner et al. 2015; DellaSala et al. 2016; 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 Mediterraneanforests where soils are especially prone to degradation and the risk of fire is high.

108

Many experiments done in the United States and Europe have shown that assessment of long-109 term post-fire impacts and restoration actions are often focused on the macrobiotic components 110 of the ecosystem (Hessburg and Agee 2003; Beschta et al., 2004; Fernandez and Vega 2016; 111 Gómez et al., 2019; Lucas-Borja et al. 2019). For these assessments, recovery of native plant 112 113 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, 114 115 little research has been done regarding the micro-biotic impacts of salvage logging within the soil ecosystem itself (e.g., Poirier et al, 2014; Smith et al., 2008; Kishchuk et al. 2015), and there 116 is a critical need to understand the impacts of post-fire salvage logging on soil microbiological 117 118 and enzymatic responses.

119

Microbial populations and soil enzymes are of paramount importance for ecosystem processes 120 because they catalyze a host of soil reactions that have biogeochemical significance (e.g., 121 nutrient cycling). Moreover, these microbiological properties are related to the amount and 122 quality of soil organic matter, which can be directly impacted by wildfire and salvage logging 123 (Kishchuk et al. 2015). Once these substantial gaps are filled, land managers will be able to fully 124 evaluate the relative and cumulative effects of fire and post-fire salvage logging on the critical 125 zone processes. Overall, soil functionality plays an important role on soil fertility with a clear 126 influence on growth and reproduction of the microbial mass. Indicators such as enzyme activities 127 specifically related to the cycles of N, P, C and S (urease, alkaline and acid phosphatase, β-128

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.

135

136 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 reatlive to the 137 138 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, 139 little research has been done regarding the microbiotic impacts of logging on soil functionality 140 141 (e.g., Rab 1996; Garcia-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 142 may have altered the physico-chemical and biochemical soil properties in the short-term. This 143 study aims to determine whether and to what extent wildfire and post-fire logging altered short-144 term soil functionality of a Mediterranean forest of Pinus halepensis M. To this aim, several 145 indicators of soil functionality were measured in the spring and autumn in forested areas with 146 and without wildfire and post-fire logging. We hypothesised that logging negatively affected the 147 short-term post-fire soil functionality because it increased soil compaction and reduced 148 vegetation cover and organic matter content, and these impacted the metabolic processes of 149 forest soils. 150

152 **2. Materials and methods**

153

154 *2.1. Study site*

155

The Sierra de las Quebradas forest (Liétor, Castilla-La Mancha region, province of Albacete, 156 Spain (W1°56'35.02", N38°30'40.79"; Figure 1) ranges in elevation between 520 and 770 m, 157 158 and the study sites have west or southwest aspects. The semiarid climate is categorized as type BSk according to the Köppen classification (Kottek et al. 2006) with a mean annual temperature 159 of 16.6°C and mean annual precipitation of 321 mm. Soils are classified as Calcid Aridisols 160 161 (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 cocciferae) 162 (Peinado et al., 2008). Before the wildfire, the stand density ranged from 500-650 trees/ha and 163 164 the tree heights ranged from 7-14 m. Additional understory vegetation includes Rosmarinus officinalis L., Brachypodium retusum (Pers.) Beauv., Cistus clusii Dunal, Lavandula latifolia 165 Medik., Thymus vulgaris L., Helichrysum stoechas L., Stipa tenacissima L., Quercus coccifera 166 L. and *Plantago albicans* L. The economic value of the understory species decreased in the mid-167 1900s, which led to agricultural abandonment and reforestation by Aleppo pines of natural 168 origin. 169

170

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 (Figure 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.

178

179 2.2. Experimental design

180

181 This study was carried out during 2017 within the study catchment, where we established nine 182 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 183 184 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 185 previous to logging in ten 20 cm x 20 cm quadrats placed at systematically identified points 186 187 along one placed on the centre of each plot using methods described by Fernández and Vega (2016). Of the six burned plots, three received no additional treatment and three had been logged 188 in December 2016. Salvage logging was conducted using an agricultural adapted tractor with 189 herringbone-tyre pneumatic rubber agricultural wheels (tyre size 18.4R30) (Figure 1). The 190 tractor was a 4-cylinder model DT9880 (Landini), which can reach a rated power of 94/69.2 191 C.V. kW^{-1} . The working speed ranges from 6.0 to 8.0 km h⁻¹. The total tractor weight was 4,697 192 kg. Soils in each of the nine plots were sampled in March and October 2017. Hereafter, the 193 treatments are indicated with capital letters ("NB", non-burned, "B+NL", burned and non-logged, 194 and "B+L", burned and logged) and the sampling seasons are indicated by capital letters: "/S" for 195 spring (March 2017); and "/A" for autumn (October 2017). For example, "B+L/S" indicates a 196 burned and logged plot sampled in March 2017. 197

199 2.3. Soil sampling

200

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 sub-samples 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.

208

```
209 2.4. Physico-chemical soil analyses
```

210

On each soil sample particle size distribution was determined using the method of Guitián and 211 Carballás (1976). Soil pH and electrical conductivity (EC, µS/cm) were measured in a 1:5 (w/v) 212 aqueous solution with a multiparameter portable device (Hanna Instruments® model HI2040-02, 213 Gipuzkoa, Spain). Organic matter content (OM, %) was determined using the potassium 214 dichromate oxidation method (Nelson and Sommers 1996), and organic carbon (OC, %) was 215 calculated by multiplying the OM by 0.58 (Lucas-Borja et al., 2018). Total nitrogen (TN, %) was 216 determined using the Kjeldahl method (Bremner and Mulvaney 1982). The C:N ratio was 217 218 obtained by dividing the organic carbon by the total nitrogen.

219

220 2.5. Biochemical soil analyses

Collected samples were dried one day after sampling during 48 at lab temperature for measuring 222 several biochemical properties. We used a fumigation-extraction method to determine microbial 223 carbon (MC, expressed as mg C kg⁻¹ dry soil) (Vance et al. 1987). Basal soil respiration (BSR, 224 expressed as the $\mu g CO_2$ hour⁻¹ g⁻¹ of dry soil), was measured with a respirometer (Micro-225 Oxymax, Columbus Instruments, Inc., OH, USA). Soil dehydrogenase activity was determined 226 by the reduction of p-iodonitrotetrazolium chloride (INT) to p-iodonitrotetrazolium formazan 227 (INTF) following Von Mersi and Schinner (1991) and expressed as μg INTF hour⁻¹ g⁻¹ of dry 228 soil. Urease activity (UA, expressed as μ mol N-NH4+ hour⁻¹ g⁻¹ of dry soil) was measured using 229 urea as a substrate and a borate buffer at pH = 10 (Tabatabai 1994, Kandeler and Gerber 1988). 230 The activity of acid phosphatase (acid-PA) and β -glucosidase (BGA), both expressed as μ mol 231 pNP hour⁻¹ g⁻¹ of dry soil, were determined using the methods of Tabatabai and Bremner (1969) 232 233 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 234 extracted from 0.25 g subsamples with 2 ml citric acid buffer, pH 7.0, at 121 °C for 30 min in an 235 autoclave. After extractions, samples were centrifuged at 3000 revolutions per minute for 15 236 minutes to remove soil particles. Protein in the supernatant was determined by a Bradford assay 237 (Wright and Upadhyaya, 1996). 238

239

240 2.6. 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 244 PERMANOVA, Anderson 2001) using a three-factor design: (i) fire occurrence (burned/non-245 burned); (ii) logging activities (logging/non-logging); (iii) season of the year (spring/autumn). 246 Then, Pearson's matrix was calculated to evaluate the possible correlations among the properties 247 of sampled soil. For the statistical analyses the software PRIMER V 7® with PERMANOVA 248 add-on (Anderson et al. 2008) and Statgraphics Centurion XVI ® (StatPoint Technologies, Inc., 249 Warrenton, VA, USA) were used. We used a significance level of 0.05 unless otherwise 250 251 indicated.

252

253 **3. Results**

Air temperature was similar between the reference period (1978-2012) and the study period (November 2016 to 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 (Figure 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).

261

262 3.1. Differences among treatments and temporal changes in physical and chemical soil263 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 8.45 267 to 8.73, indicating slight alkalinity, and there was no significant difference in pH among any of 268 the plots or sample periods. In general, the NB plots showed the lowest contents of OC, OM and 269 TN and the highest for the C:N ratio (Table 2). The OC, OM, EC and TN significantly differed 270 between the NB plots and the burned (either logged or not) plots in spring 2017. More 271 specifically, as compared to the NB samples, the B+NL and B+L soils had higher OC and OM 272 (about +80% and +140%, respectively for both variables) and much higher TN (at least +200% 273 274 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. 275

276

With regard to the seasons, none of the treatments had any differences in any of the physical or 277 chemical properties between the spring and autumn samples except for a significant decrease in 278 279 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 280 autumn field campaign were generally similar to those of the B+L samples in both seasons, and 281 combined, these burned samples had significantly higher OC, OM and TN contents than the NB 282 soils. Similarly, significant decreases in EC between the burned and unburned soils were 283 284 detected (Table 2).

285

286 3.2. Differences among treatments and temporal changes in biochemical soil properties

287

288 Compared to NB soils in spring 2017 the burned plots (whether subject to logging or not) 289 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).

296

297 3.3. Relationships among physico-chemical and biochemical soil properties

298

299 As might be expected the clay, silt and sand contents were significantly correlated each other $(|\mathbf{r}|$ > 0.56). As regards the physico-chemical soil properties, strong and significant correlations ($|\mathbf{r}| >$ 300 0.47) were identified among OM, TN and C:N. The pH was significantly correlated with the clay 301 302 and silt fractions of soils ($|r| \ge 0.60$) and negatively with the OM and TN contents ($r \le -0.52$) (Table 4). Concerning the biochemical soil properties, BGA, Acid-PA and GPRS were 303 significantly correlated with each other ($r \ge 0.74$) and with several physico-chemical soil 304 properties (particularly with OM and TN, $r \ge 0.51$). In more detail, BGA and GPRS each had a 305 large number of positive correlations ($r \ge 0.59$) with the physico-chemical soil properties, and 306 they both were negatively correlated with clay content (r \leq -0.62). UA showed significant and 307 positive correlations with BGA and Acid-PA (r = 0.61 and r = 0.74, respectively), while DHA 308 was only negatively correlated with BSR (r = -0.46). No significant correlation was found 309 between the EC or MC and any of the physico-chemical or biochemical soil properties (Table 4). 310

311

312 **4. Discussion**

The results of our PERMANOVA analysis showed that wildfire is a significant disturbance 314 factor of soil, as indicated by the remarkable differences between unburned and burned soils, 315 with or without logging at the end of the first post-fire wet season (spring 2017) and at the end of 316 the following dry season (autumn 2017) (Table 2). Others have detected significant changes in 317 soil organic matter and nutrient content in soils affected by wildfire as compared to unburned 318 soils (e.g., González-Pérez et al., 2004; García-Orenes et al., 2017), including nutrient 319 320 availability and water retention (Certini 2005), increases in pH (Mataix-Solera et al., 2002; Ulery et al., 1993), and reduction of the aggregate stability and soil structure decay (DeBano 2000). 321 322 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 and 323 Cerda, 2009). Our results corroborate this fact as our textures clearly differed between NB and 324 325 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 326 periods. We attribute the lack of difference between B+NL and B+L to the lightweight 327 machinery used during logging operations. For this research, logging operations were carried out 328 using a single pass of an agricultural tractor with pneumatic tires, resulting in low ground 329 pressure. Fernández et al. (2019) found similarly little impact of post fire salvage logging on 330 331 vegetaton recovery.

332

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. Literature shows that soil pH and EC tend to rise after fire (e.g., Pereira et al., 2018), and 336 these properties gradually return to the original pre-fire values due to the washout effect (Mataix-337 Solera et al. 2009; Muñoz-Rojas et al. 2016). In our study, the pH of soil did not respond to 338 burning or burning and logging, possibly due to the buffering capacity of our carbonated soils, 339 which slows or prevents the movement of the acid front and therefore the mobilization of soil 340 elements (Certini 2005; Mataix-Solera et al. 2009). Conversely, EC of the burned soils in our 341 342 study initially increased and then decreased relative to the unburned soils as predicted by the 343 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 344 345 other nutrients from burned forest fuel (Caon et al. 2014).

346

Some of the other physico-chemical properties of soils significantly changed immediately after 347 348 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 349 350 subjected to logging. Moreover, these changes persisted or further increased in the second sample period with a simultaneous increase of the C:N ratio, driven by the slight increase in OC. 351 Of all the physical and chemical soil properties, OM content is one of the most important quality 352 indicators, given its influence on plant growth-related functions such as water retention, nutrient 353 exchange, and soil structure (Mataix-Solera et al. 2011; Muñoz-Rojas et al. 2016). The increase 354 of soil organic matter may be due to accumulation of ash, which contains carbon and other 355 nutrients from burned forest fuel (Bodí et al., 2014; Caon et al., 2014; Harper et al., 2019). In 356 general, the variability of the C:N ratio was similar across the three treatments, indicating low 357 activity and disintegration speed for OM as well as a low degree of N mineralisation regardless 358

of burning and logging, which may be due to a more recalcitrant chemical composition of litterand low litter quality (Martín-Peinado et al. 2016).

361

The simultaneous measurement of several enzymatic activities might be useful as an indicator of 362 the bioactivity and biochemical fertility of a soil (Gil-Sotres et al. 1992). Enzymatic activity 363 plays an important role in catalysing biological reactions (Mataix-Solera et al. 2009). This study 364 365 has confirmed how wildfire can modify enzymatic activity and microbial biomass and how these 366 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 367 368 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 369 individual enzymes for particular substrates. To summarise, we measured significant decreases 370 371 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 372 wet period and autumn 2017 was drier than the reference period (Figure 2). As Merilä et al. 373 (2002) showed, low soil moisture is a major factor in controlling the activity of microbes. 374 Seasonal changes in soil moisture were frequently reported to affect enzymatic activities in forest 375 soils (Baldrian et al. 2010). As Criquet et al. (2004) demonstrated, some enzymatic activities 376 (e.g. urease, phosphatase and β -glucosidade) were substantially reduced in dry seasons. Sardans 377 and Peñuelas (2005) also concluded that forest soil contained less microbial biomass and 378 379 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 380 factor. In this regard, BSR and MC were significantly different between the NB and burned soils. 381

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 (Muñoz-Rojas et al. 2016) and their decomposition in the seven-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.

388

The lack of variation in DHA observed in the unburned, burned, and burned and logged soils, 389 and the absence of relationship between DHA and all of the physical characteristics and all of the 390 chemical parameters except a negative correlation with BSR, confirms the lack of sensitivity of 391 DHA to seasonality and site effects found in other studies in Mediterranean areas (Lucas-Borja et 392 al., 2011 and 2019). The lack of effect could be related to the fact that dehydrogenases are not 393 active as extracellular enzymes in soil, thus presenting a different pattern compared to 394 extracellular soil enzymes such as β-glucosidase, urease and acid-phosphatase (Blonska et al. 395 2017). Thus and according to our results, the usefulness of DHA as an indicator of soil quality in 396 burned areas is low. 397

398

Based on our correlation results, an increase of OM in the burned soils did not generate a parallel increase of 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 404 activity suggests a stress or disturbance of the soil microbial community (Lucas-Borja et al. 405 2011). Our study demonstrated that Glomalin-Related Soil Protein (GPRS) content in B+NL and 406 B+L soils in autumn, approximately one year post-fire, exceeded the spring burned 407 measurements and the autumn measurements in the unburned soil. Result also showed that 408 GPRS values were significantly correlated with OM content and the C/N ratio. Burnt plots 409 (either logged or not) favouring higher OM accumulation and C:N ratios would generate GPRS 410 411 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 412 413 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 four years after fire was due 414 to species' rapid root colonisation and associated arbuscular mycorrhizal fungi colonization. 415 416 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 417 factor. However, this is a short period to assess changes and the implications for mid or long-418 term responses should be corrently addresed. In addition, particular attention should be paid to 419 different types of forest logging machines and forestry equipment. 420

421

422 **5.** Conclusions

423

In order to evaluate whether and to what extent logging alters soil functionality in the shortperiod 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 427 physico-chemical and biochemical properties of soils under the three conditions showed some 428 discrimination between unburned and burned plots (logged or not) 8 months after wildfire and 429 again 15 months after the fire, but few difference 3 and 10 months after post-fire logging. 430 Specifically, the burned (either logged or not) soils had greater organic matter content, greater 431 nitrogen content, and higher basal soil respiration rate than the unburned controls, although the 432 basal soil respiration rate was not significantly higher in the autumn (15 months after fire) 433 434 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 435 436 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 437 hypothesis that logging negatively affects soil functionality immediately after fire in 438 439 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 440 suggest the important effects of wildfires on soil functionality. In our study, the seasonal 441 differences in some of the indicators of unburned soils were more significant than the differences 442 between the burned plots with and without logging. 443

444

445 Acknowledgements

This study was supported by funds provided to the VIS4FIRE Spanish R&D project (RTA201700042-C05-00) co-funded by the INIA and FEDER program. Spanish Ministry of Economy,
Industry and Competitiveness Research Projects, BIORESOC (CGL2017-88734-R) and FEDERJunta de Andalucía Research Project RESTAGRO (UAL18-RNM-A021-B) provided financial

support aid in this article. Isabel Miralles is grateful for funding received from the Ramón y
Cajal Research Grant (RYC-2016-21191) from the Spanish Ministry of Economy, Industry and
Competitiveness (MINECO). Raúl Ortega acknowledges the University of Almería Research
Plan postdoctoral contract Hipatia.

454

455 **References**

- 456 Anderson M, Gorley RN, Clarke RK (2008) Permanova+ for primer: guide to software and
- 457 statistical methods: primer-E limited
- Anderson MJ (2001) A new method for non-parametric multivariate analysis of variance. Austral
 Ecol 26:32–46
- 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
- 462 Bastida F, Zsolnay A, Hernández T, García C (2008) Past, present and future of soil quality
- 463 indices: a biological perspective. Geoderma 147:159–171
- Bento-Gonçalves A, Vieira A, Úbeda X, Martin D (2012) Fire and soils: key concepts and recent
 advances. Geoderma 191:3–13
- 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
- 468 Błońska A, Kompała-Bąba A, Sierka E, et al (2019) Impact of Selected Plant Species on
- 469 Enzymatic Activity of Soil Substratum on Post-Mining Heaps
- 470 Boucher D, Gauthier S, Noël J, et al (2014) Salvage logging affects early post-fire tree
- 471 composition in Canadian boreal forest. For Ecol Manage 325:118–127
- 472 Bremner JM, Mulvaney CS (1982) Nitrogen—Total 1. Methods soil Anal Part 2 Chem

473 Microbiol Prop 595–624

- Burgess D, Wetzel S (2000) Nutrient availability and regeneration response after partial cutting
 and site preparation in eastern white pine. For Ecol Manage 138:249–261
- 476 Caon L, Vallejo VR, Ritsema CJ, Geissen V (2014) Effects of wildfire on soil nutrients in
- 477 Mediterranean ecosystems. Earth-Science Rev 139:47–58
- 478 Certini G (2005) Effects of fire on properties of forest soils: a review. Oecologia 143:1–10
- 479 D'Ascoli R, Rutigliano FA, De Pascale RA, et al (2005) Functional diversity of the microbial
- 480 community in Mediterranean maquis soils as affected by fires. Int J Wildl Fire 14:355–363
- 481 DellaSala DA, Karr JR, Schoennagel T, Perry D, Noss RF, Lindenmayer D, Beschta R, Hutto
- 482 RL, Swanson ME, Evans J. (2006) Post-fire logging debate ignores many issues. Science,
- 483314, 51-52.DeBano LF (2000) The role of fire and soil heating on water repellency in
- 484 wildland environments: a review. J Hydrol 231:195–206
- 485 Donato DC, Fontaine JB, Campbell JL, et al (2006) Post-wildfire logging hinders regeneration
 486 and increases fire risk. Science (80-) 311:352
- Ebel BA, Moody JA (2017) Synthesis of soil-hydraulic properties and infiltration timescales in
 wildfire-affected soils. Hydrol Process 31:324–340
- 489 Eivazi F, Tabatabai MA (1977) Phosphatases in soils. Soil Biol Biochem 9:167–172
- 490 Fernández C, Vega JA (2016a) Effects of mulching and post-fire salvage logging on soil erosion
- and vegetative regrowth in NW Spain. For Ecol Manage 375:46–54.
- 492 https://doi.org/10.1016/j.foreco.2016.05.024
- 493 Fernández C, Vega JA (2016b) Modelling the effect of soil burn severity on soil erosion at
- 494 hillslope scale in the first year following wildfire in NW Spain. Earth Surf Process
- 495 Landforms 41:928–935

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

- 498 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. L
- 500 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
- 503 monitoring research. Sci Total Environ 586:1057–1065
- 504 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
- 506 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 Manage 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
- 511 Guitián-Ojea F, Carballas T (1976) Técnicas de Análisis de Suelos. Pico Sacro, Santiago de
 512 Compostela, Spain.
- 513 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
- 515 M.) forest stands. Solid Earth 6:243–252
- 516 Hessburg PF, Agee JK (2003) An environmental narrative of inland northwest United States
- 517 forests, 1800–2000. For Ecol Manage 178:23–59
- 518 Ice GG, Neary DG, Adams PW (2004) Effects of wildfire on soils and watershed processes. J

519 For 102:16–20

- 520 Imeson AC, Verstraten JM, Van Mulligen EJ, Sevink J (1992) The effects of fire and water
- 521 repellency on infiltration and runoff under Mediterranean type forest. Catena 19:345–361
- 522 James CE, Krumland B (2018) Immediate Post–Forest Fire Salvage Logging, Soil Erosion, and
- 523 Sediment Delivery. For Sci 64:246–267
- 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
- 528 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
- 533 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
- 537 López-Poma R, Bautista S (2014) Plant regeneration functional groups modulate the response to
- 538 fire of soil enzyme activities in a Mediterranean shrubland. Soil Biol Biochem 79:5–13
- 539 Lozano E, Chrenková K, Arcenegui V, et al (2016) Glomalin-related soil protein response to
- 540 heating temperature: A laboratory approach. L Degrad Dev 27:1432–1439.
- 541 https://doi.org/10.1002/ldr.2415

542	Lucas-Borja ME, Candel D, Jindo K, et al (2012) Soil microbial community structure and
543	activity in monospecific and mixed forest stands, under Mediterranean humid conditions.
544	Plant Soil 354:359-370
545	Lucas-Borja ME, González-Romero J, Plaza-Álvarez PA, et al (2019) The impact of straw
546	mulching and salvage logging on post-fire runoff and soil erosion generation under
547	Mediterranean climate conditions. Sci Total Environ 654:441–451
548	Lucas-Borja ME, Hedo J, Cerdá A, et al (2016) Unravelling the importance of forest age stand
549	and forest structure driving microbiological soil properties, enzymatic activities and soil
550	nutrients content in Mediterranean Spanish black pine (Pinus nigra Ar . ssp . salzmannii).
551	Sci Total Environ 562:145-154. https://doi.org/10.1016/j.scitotenv.2016.03.160
552	Lucas-Borja ME, Zema DA, Carrà BG, et al (2018) Short-term changes in infiltration between
553	straw mulched and non-mulched soils after wildfire in Mediterranean forest ecosystems.
554	Ecol Eng 122:. https://doi.org/10.1016/j.ecoleng.2018.07.018
555	Lucas-Borja ME, Bastida F, Moreno JL, et al (2011) The effects of human trampling on the
556	microbiological properties of soil and vegetation in Mediterranean mountain areas. L
557	Degrad Dev 22:383–394
558	Malvar MC, Silva FC, Prats SA, et al (2017) Short-term effects of post-fire salvage logging on
559	runoff and soil erosion. For Ecol Manage 400:555–567
560	Martín-Peinado FJ, Navarro FB, Jiménez MN, et al (2016) Long-term Effects of Pine Plantations
561	on Soil Quality in Southern Spain. L Degrad Dev 27:1709–1720
562	Mataix-Solera J, Cerdà A (2009) Los efectos de los incendios forestales en los suelos. Síntesis y
563	conclusiones. Nuevos retos en la investigación y en la gestión. Efectos los Incend For sobre
564	los suelos en España El estado la cuestión visto por los científicos españoles Cátedra Divulg

- 565 la Ciència Univ València, València 355–383
- 566 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
- 569 Mataix-Solera J, Guerrero C, García-Orenes F, et al (2009) Forest fire effects on soil
- 570 microbiology. Fire Eff soils Restor Strateg 5:133–175
- 571 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
- Nelson DW, Sommers LE (1996) Total carbon, organic carbon, and organic matter. Methods soil
 Anal part 3—chemical methods 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
- 578 Peinado M, Monje L, Martínez Parras JM (2008) El Paisaje Vegetal de Castilla-La Mancha.
- 579 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 Manage 326:133–141
- 584 Pourreza M, Hosseini SM, Sinegani AAS, et al (2014) Soil microbial activity in response to fire
- severity in Zagros oak (Quercus brantii Lindl.) forests, Iran, after one year. Geoderma
 213:95–102
- 587 Prats SA, Malvar MC, Coelho COA, Wagenbrenner JW (2019) Hydrologic and erosion

589

responses to compaction and added surface cover in post-fire logged areas: Isolating splash, interrill and rill erosion. J Hydrol 575:408–419

- 590 Rab MA (1996) Soil physical and hydrological properties following logging and slash burning in
- the Eucalyptus regnans forest of southeastern Australia. For Ecol Manage 84:159–176
- 592 Rincón A, Pueyo JJ (2010) Effect of fire severity and site slope on diversity and structure of the
- 593 ectomycorrhizal fungal community associated with post-fire regenerated Pinus pinaster Ait.
 594 seedlings. For Ecol Manage 260:361–369
- 595 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
- 597 bosques de Araucaria araucana del centro-sur de Chile. Bosque (Valdivia) 37:409–417
- Robichaud PR, Wagenbrenner JW, Pierson FB, et al (2016) Infiltration and interrill erosion rates
 after a wildfire in western Montana, USA. Catena 142:77–88
- 600 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

- 602 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 Manage 98:43–50
- Sansano Anaya MT (2016) Evaluación del uso de la glomalina como indicador del impacto del
 fuego y el manejo post-incendio
- Santa Regina I, Tarazona T (2001) Nutrient cycling in a natural beech forest and adjacent planted
 pine in northern Spain. Forestry 74:11–28
- 609 Sheridan GJ, Lane PNJ, Noske PJ (2007) Quantification of hillslope runoff and erosion
- 610 processes before and after wildfire in a wet Eucalyptus forest. J Hydrol 343:12–28

- 611 Smith NR, Kishchuk BE, Mohn WW (2008) Effects of wildfire and harvest disturbances on
- forest soil bacterial communities. Appl Environ Microbiol 74:216–224
- 613 Tabatabai MA (1994) Soil enzymes. Methods soil Anal part 2—microbiological Biochem Prop
- 614 775–833
- Tabatabai MA, Bremner JM (1969) Use of p-nitrophenyl phosphate for assay of soil phosphatase
 activity. Soil Biol Biochem 1:301–307
- 617 Thorn S, Bässler C, Brandl R, et al (2018) Impacts of salvage logging on biodiversity: A
- 618 meta-analysis. J Appl Ecol 55:279–289
- 619 Ulery AL, Graham RC, Amrhein C (1993) Wood-ash composition and soil pH following intense
- 620 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
- 623 Vega JA, Fontúrbel T, Merino A, et al (2013) Testing the ability of visual indicators of soil burn
- severity to reflect changes in soil chemical and microbial properties in pine forests and
 shrubland. Plant Soil 369:73–91
- 626 Verma S, Jayakumar S (2012) Impact of forest fire on physical, chemical and biological
- 627 properties of soil: A review. Proc Int Acad Ecol Environ Sci 2:168
- 628 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
- 631 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
- 633 western United States. For Ecol Manage 335:176–193.

- 634 https://doi.org/10.1016/j.foreco.2014.09.016
- 635 Wagenbrenner JW, Robichaud PR, Brown RE (2016) Rill erosion in burned and salvage logged
- 636 western montane forests: Effects of logging equipment type, traffic level, and slash
- 637 treatment. J Hydrol 541:889–901
- 638 Wu S, Chang J, Dai Y, et al (2013) Treatment performance and microorganism community
- 639 structure of integrated vertical-flow constructed wetland plots for domestic wastewater.
- 640 Environ Sci Pollut Res 20:3789–3798
- 641 Zavala LMM, de Celis Silvia R, López AJ (2014) How wildfires affect soil properties. A brief
- review. Cuad Investig geográfica/Geographical Res Lett 311–331

644 TABLES

645

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).

650

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				

651 Notes: df = degrees of freedom; SS = sum of squares; MS = mean squares; Pseudo-F = MS Burn condition: MS Residuals ratio;

652 P(perm) = threshold for significance in PERMANOVA; Unique perms = number of unique values of the test statistic obtained under

653 permutation.

655

Table 2. Main physical and chemical properties (mean \pm standard error) of soil samples collected in spring (S) and autumn(A) in nonburned (NB), burned and non-logged (B+NL) and burned and logged (B+L) plots (n = 3 per treatment/season) (Liétor, Castilla La Mancha, Spain). Different lowercase letters among treatments and seasons indicate statistically significant differences (p <0.05) based on the permanova analyses.

Treatment/	Clay	Silt	Sand	ОМ	OC	рН	EC	TN	C·N
season	(%)	(%)	(%)	(%)	(%)		(µS/cm)	(%)	CIN
NB/S	$32.6 \pm 0.34(a)$	$19.9 \pm 1.35(c)$	$47.4 \pm 2.23(a)$	$2.65 \pm 0.23(c)$	$1.54 \pm 0.09(c)$	$8.73\pm0.13(a)$	$124 \pm 16.2(a)$	$0.07\pm0.02(b)$	$22.1\pm0.23(a)$
NB/A	$32.1 \pm 0.52(a)$	$19.1 \pm 1.10(c)$	$48.2 \pm 1.02(a)$	$2.19\pm0.16(c)$	$1.27 \pm 0.09(c)$	$8.64\pm0.21(a)$	$103 \pm 17.7 (ab)$	$0.09\pm0.01(b)$	$13.9\pm0.73(c)$
B+NL/S	14.8 ± 1.65 (bc)	$32.9\pm0.74(ab)$	$52.1 \pm 2.40(a)$	$4.75\pm0.15(ab)$	$2.75\pm0.08(ab)$	$8.47\pm0.03(a)$	$90.9\pm7.2(b)$	$0.21\pm0.01(a)$	$12.6\pm0.33(d)$
B+NL/A	$7.71 \pm 1.03(b)$	$41.8 \pm 1.96(a)$	$50.3 \pm 3.21(a)$	$6.20\pm0.73(a)$	$3.60\pm0.42(a)$	$8.45\pm0.10(\text{a})$	$81.4\pm19.8(b)$	$0.24\pm0.03(a)$	$15.1\pm0.41(b)$
B+L/S	$6.99 \pm 1.45 (b)$	$42.2 \pm 0.37(a)$	$50.7\pm2.24(a)$	$6.45\pm0.38(a)$	$3.75\pm0.15(a)$	$8.60\pm0.12(\text{a})$	$93.3\pm7.54(b)$	$0.22\pm0.01(\text{a})$	$17.0 \pm 0.22(b)$
B+L/A	$6.68\pm0.34(b)$	$42.0\pm0.03(a)$	$51.2\pm1.04(ab)$	$7.12\pm0.09(a)$	$4.14\pm0.05(a)$	$8.47\pm0.07(a)$	$88.2\pm6.92(b)$	$0.25\pm0.02(a)$	$16.6\pm0.25(b)$
661 Notes:	OC = c	organic carbon;	OM =	organic matte	r; EC =	electrical co	onductivity; T	N = total	nitrogen

Table 3. Main biochemical properties (mean \pm 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). Different lowercase letters indicate statistically significant differences (p < 0.05) based on the permanova analyses and among treatments and seasons.

Treatment/ season	BGA (µmol p-NP hour ⁻¹ g ⁻¹)	UA (µmol N-NH4+ hour ⁻¹ g ⁻¹)	Acid-PA (µmol p-NP hour ⁻¹ g ⁻¹)	DHA (µg INTF hour ⁻¹ g ⁻¹)	BSR (μgCO ₂ hour ⁻¹ g ⁻¹)	GPRS (µ g ⁻¹ dry soil)	MC (mg C kg ⁻¹ dry soil)		
NB/S	$0.86\pm0.05(ab)$	$0.73 \pm 0.03(a)$	$1.16 \pm 0.04(a)$	$0.10\pm0.01(\text{a})$	$1.94\pm0.05(b)$	$1700 \pm 149(b)$	$56.3 \pm 0.52(c)$		
NB/A	$0.59\pm0.06(c)$	$0.50\pm0.11(a)$	$0.47\pm0.04(b)$	$0.11 \pm 0.02(a)$	$1.94\pm0.11(b)$	$1030 \pm 118(c)$	$369\pm20.4(a)$		
B+NL/S	$0.86\pm0.21(ab)$	$0.53\pm0.09(a)$	$0.77\pm0.06(ab)$	$0.12\pm0.02(a)$	$3.73\pm0.73(a)$	$1394 \pm 183(c)$	$191 \pm 9.63(b)$		
B+NL/A	$0.96\pm0.14(ab)$	$0.44\pm0.05(a)$	$0.93 \pm 0.03(a)$	$0.11\pm0.06(a)$	$4.47\pm0.57(a)$	$2845 \pm 289(a)$	$204\pm3.91(b)$		
B+L/S	$1.18\pm0.47(ab)$	$0.85\pm0.40(a)$	$1.22 \pm 0.51(a)$	$0.14\pm0.03(a)$	$2.10\pm0.24(b)$	$2278\pm635(ab)$	$224 \pm 108(b)$		
B+L/A	$1.28\pm0.01(\text{a})$	$0.66\pm0.09(a)$	$1.35\pm0.08(a)$	$0.08\pm0.01(a)$	$2.05\pm1.13(b)$	$2890 \pm 77(a)$	$195\pm5.00(b)$		

Notes: $BGA = \beta$ -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.

Table 4. Correlation matrix among physico-chemical and biochemical properties of soil samples collected in spring and autumnin non-burned, burned and non-logged and burned and logged plots (n = 18) (Liétor, Castilla La Mancha, Spain). Values in bold are statistically significant at p < 0.05 based on the canonical correlation analysis.

Soil property	%Silt	%Sand	рН	EC	ОМ	TN	C:N	BGA	UA	Acid- PA	DHA	GPRS	BSR	МС
%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
рН				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

Notes: EC = electrical conductivity; OC = organic carbon; OM = organic matter; TN = total nitrogen; $BGA = \beta$ -glucosidase activity; UA = urease activity; Acid-PA = acid phosphatase activity; DHA = dehydrogenase activity; GPRS = glomalin-related soil protein, BSR = basal soil respiration; and MC = microbial carbon.

FIGURES

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



Control plot

Burned and logged plot



Burned and non-logged plot







