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

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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

62 December 2016 using a lightweight agricultural tractor. The results showed significant
63 differences among three groups: unburned soils sampled in spring (i) and autumn (ii), and burned
64 soils (not subject or subject to logging) sampled in spring and autumn. In unburned plots,
65 seasonality had a significant effect, which disappeared in burned plots regardless of whether they
66 had been logged. The burned plots had higher content of organic matter and total nitrogen than
67 the unburned soils but they were not correlated to higher soil respiration or microbial biomass.
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
70 content than the unburned soil in the autumn measurement. Overall, the results suggest a short-
71 term wildfire impact of soil properties whereas logging using a lightweight tractor produced no
72 significant impacts in this sparse Mediterranean pine forest.

73

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

76

77 **1. Introduction**

78 Wildfires are a natural disturbance factor in Mediterranean forests, often enhanced by human
79 activities such as intentional or accidental ignitions (Ruiz-Mirazo et al., 2012; Balch et al., 2017)
80 and altered fire potential related to climate change (Jolly et al., 2015). Fires also alter the timing
81 of vegetation succession (Pausas et al., 2009) and can affect the chemical and biological
82 properties of soils (DeBano 2000, Ginzberg and Steinberger 2004, Certini 2005).

83

84 Postfire salvage logging is used primarily to recover timber values but may also be prescribed to
85 reduce possible insect and disease outbreaks and fire recurrence, reduce safety hazards, and for
86 watershed restoration (e.g., to create contour log dams) (Ice et al., 2004; Leverkus et al., 2018).
87 The pros (e.g., economic benefits, reduced fire susceptibility, increased worker safety and
88 access) and cons (e.g., increased soil compaction, increased hydrologic responses, long-term loss
89 of habitat and large downed wood) of salvage logging have been debated for years. The debate
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.
92 Post-fire salvage logging creates a secondary disturbance that can affect vegetation structure
93 (Donato et al., 2006; Boucher et al., 2014; Knapp and Ritchie 2016), macrofauna habitat and
94 populations (Thorn et al. 2018), and the physical properties of soils (Wagenbrenner et al. 2015,
95 2016, Prats et al. 2019), but little is known about the impacts of fire or post-fire salvage logging
96 on soil microbiological or chemical properties (Ginzburg and Steinberger, 2012; Kishchuk et al.,
97 2015, Leverkus et al., 2018), particularly in Mediterranean ecosystems (Lucas-Borja et al.,
98 2019).

99

100 In many cases salvage logging is carried out in the period immediately after a fire to provide
101 some economic benefit to the owner, since the wood value decreases with time (Akay et al.
102 2006). Given that a negative influence on the soil hydrological response after post-fire logging
103 has been well documented (e.g., Fernandez et al., 2007; Wagenbrenner et al. 2015; DellaSala et
104 al. 2016; Lucas-Borja et al. 2018), one might ask whether salvage logging after wildfire may
105 affect the short-term soil functionality of forest ecosystems. More research is needed to evaluate

106 the influence of logging on soil functionality, with particular attention to the Mediterranean
107 forests where soils are especially prone to degradation and the risk of fire is high.

108

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

119

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

129 glucosidase and arylsulfatase, respectively), and microbial biomass, such as dehydrogenase
130 activity (DHA) and soil respiration (Bastida et al., 2008; Lucas-Borja et al., 2011; Hedo et al.,
131 2015) can be used to assess soil functionality. Moreover, the variations in C:N ratio (Lucas-Borja
132 et al., 2012; Hedo et al., 2015), soil pH (Lucas-Borja et al., 2012), soil texture (Fterich et al.,
133 2014), nutrient status (Burgess and Wetzel 2000; Santa-Regina and Tarazona 2001) and
134 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
137 plant matter and bare soil were detected throughout the first year after the wildfire relative to the
138 unburned forest (Lucas-Borja et al., 2019). The added disturbance of post-fire salvage logging
139 led to increases in dry sediment deposition in the first year (Lucas-Borja et al., 2019). However,
140 little research has been done regarding the microbiotic impacts of logging on soil functionality
141 (e.g., Rab 1996; Garcia-Orenes et al. 2017; Pereira et al. 2018). We suspect that the changes in
142 soil vegetation cover and microclimatic conditions induced by the wildfire and salvage logging
143 may have altered the physico-chemical and biochemical soil properties in the short-term. This
144 study aims to determine whether and to what extent wildfire and post-fire logging altered short-
145 term soil functionality of a Mediterranean forest of *Pinus halepensis* M. To this aim, several
146 indicators of soil functionality were measured in the spring and autumn in forested areas with
147 and without wildfire and post-fire logging. We hypothesised that logging negatively affected the
148 short-term post-fire soil functionality because it increased soil compaction and reduced
149 vegetation cover and organic matter content, and these impacted the metabolic processes of
150 forest soils.

151

152 **2. Materials and methods**

153

154 *2.1. Study site*

155

156 The Sierra de las Quebradas forest (Liétor, Castilla-La Mancha region, province of Albacete,
157 Spain (W1°56'35.02'', N38°30'40.79''; Figure 1) ranges in elevation between 520 and 770 m,
158 and the study sites have west or southwest aspects. The semiarid climate is categorized as type
159 BSk according to the Köppen classification (Kottek et al. 2006) with a mean annual temperature
160 of 16.6°C and mean annual precipitation of 321 mm. Soils are classified as *Calcic Aridisols*
161 (USDA Soil Taxonomy, 1999) and have a sandy loam texture. The dominant overstory
162 vegetation consists of Aleppo pine (*Pinus halepensis* Mill.) and kermes oak (*Quercus cocciferae*)
163 (Peinado et al., 2008). Before the wildfire, the stand density ranged from 500–650 trees/ha and
164 the tree heights ranged from 7–14 m. Additional understory vegetation includes *Rosmarinus*
165 *officinalis* L., *Brachypodium retusum* (Pers.) Beauv., *Cistus clusii* Dunal, *Lavandula latifolia*
166 Medik., *Thymus vulgaris* L., *Helichrysum stoechas* L., *Stipa tenacissima* L., *Quercus coccifera*
167 L. and *Plantago albicans* L. The economic value of the understory species decreased in the mid-
168 1900s, which led to agricultural abandonment and reforestation by Aleppo pines of natural
169 origin.

170

171 In July 2016, a wildfire burned much of the forest. In September 2016, we selected a study
172 catchment (700 ha) which included unburned forest and burned forest where crown fire had
173 occurred and resulted in 100% tree mortality (Figure 1). A WatchDog 2000 model 2700 weather
174 station (Spectrum Technologies, Inc., Aurora, IL, USA), was installed in the study area and

175 measured precipitation depth and intensity and air temperature. We compared the air temperature
176 and precipitation during the study to climatic records (1978-2012) (AEMET, 2015) to assess the
177 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
183 and located at least 200 m from the nearest plot. Characteristics such as slope, aspect, pre-fire
184 vegetation, and soil type were relatively uniform among the plots. Three of the nine plots were in
185 unburned forest. The remaining six plots had burned at high severity, which was assessed
186 previous to logging in ten 20 cm x 20 cm quadrats placed at systematically identified points
187 along one placed on the centre of each plot using methods described by Fernández and Vega
188 (2016). Of the six burned plots, three received no additional treatment and three had been logged
189 in December 2016. Salvage logging was conducted using an agricultural adapted tractor with
190 herringbone-tyre pneumatic rubber agricultural wheels (tyre size 18.4R30) (Figure 1). The
191 tractor was a 4-cylinder model DT9880 (Landini), which can reach a rated power of 94/69.2
192 C.V. kW⁻¹. The working speed ranges from 6.0 to 8.0 km h⁻¹. The total tractor weight was 4,697
193 kg. Soils in each of the nine plots were sampled in March and October 2017. Hereafter, the
194 treatments are indicated with capital letters ("NB", non-burned, "B+NL", burned and non-logged,
195 and "B+L", burned and logged) and the sampling seasons are indicated by capital letters: "/S" for
196 spring (March 2017); and "/A" for autumn (October 2017). For example, "B+L/S" indicates a
197 burned and logged plot sampled in March 2017.

198

199 *2.3. Soil sampling*

200

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

208

209 *2.4. Physico-chemical soil analyses*

210

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

219

220 *2.5. Biochemical soil analyses*

221

222 Collected samples were dried one day after sampling during 48 at lab temperature for measuring
223 several biochemical properties. We used a fumigation-extraction method to determine microbial
224 carbon (MC, expressed as mg C kg⁻¹ dry soil) (Vance et al. 1987). Basal soil respiration (BSR,
225 expressed as the µg CO₂ hour⁻¹ g⁻¹ of dry soil), was measured with a respirometer (Micro-
226 Oxymax, Columbus Instruments, Inc., OH, USA). Soil dehydrogenase activity was determined
227 by the reduction of p-iodonitrotetrazolium chloride (INT) to p-iodonitrotetrazolium formazan
228 (INTF) following Von Mersi and Schinner (1991) and expressed as µg INTF hour⁻¹ g⁻¹ of dry
229 soil. Urease activity (UA, expressed as µmol N-NH₄⁺ hour⁻¹ g⁻¹ of dry soil) was measured using
230 urea as a substrate and a borate buffer at pH = 10 (Tabatabai 1994, Kandeler and Gerber 1988).
231 The activity of acid phosphatase (acid-PA) and β-glucosidase (BGA), both expressed as µmol
232 pNP hour⁻¹ g⁻¹ of dry soil, were determined using the methods of Tabatabai and Bremner (1969)
233 and Eivazi and Tabatabai (1977), respectively. glomalin-related soil protein content (GPRS,
234 expressed as g⁻¹ dry soil) was measured with the techniques of Lozano et al. (2016). GPRS was
235 extracted from 0.25 g subsamples with 2 ml citric acid buffer, pH 7.0, at 121 °C for 30 min in an
236 autoclave. After extractions, samples were centrifuged at 3000 revolutions per minute for 15
237 minutes to remove soil particles. Protein in the supernatant was determined by a Bradford assay
238 (Wright and Upadhyaya, 1996).

239

240 *2.6. Statistical analyses*

241

242 Statistical differences in physical, chemical and biochemical characteristics of non-burned,
243 burned and non-logged, and burned and logged soil samples obtained in autumn and spring were

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

252

253 **3. Results**

254 Air temperature was similar between the reference period (1978-2012) and the study period
255 (November 2016 to November 2017). In contrast, precipitation from November 2016 to January
256 2017 was greater than during the reference period (1978-2012), while the rest of the study year
257 was dry in comparison to the reference period (Figure 2). Moreover, The PERMANOVA
258 analysis on the suite of physico-chemical and biochemical properties showed significant
259 differences (Pseudo-F: 7.6; $p < 0.001$) between unburned soils and burned soils (subject to
260 logging or not) in both field sampling campaigns (Table 1).

261

262 *3.1. Differences among treatments and temporal changes in physical and chemical soil* 263 *properties*

264

265 The soil texture of the NB plots was a sandy clay loam, while both the burned soils (B+NL and
266 B+L) were sandy loams (Table 2). The different textures resulted from higher clay and lower silt

267 contents in the NB plots as compared to the B+NL and B+L plots. The soil pH ranged from 8.45
268 to 8.73, indicating slight alkalinity, and there was no significant difference in pH among any of
269 the plots or sample periods. In general, the NB plots showed the lowest contents of OC, OM and
270 TN and the highest for the C:N ratio (Table 2). The OC, OM, EC and TN significantly differed
271 between the NB plots and the burned (either logged or not) plots in spring 2017. More
272 specifically, as compared to the NB samples, the B+NL and B+L soils had higher OC and OM
273 (about +80% and +140%, respectively for both variables) and much higher TN (at least +200%
274 for both treatments), which resulted in lower C:N (-43% and -23%, respectively). The C:N ratio
275 was significantly different among the spring 2017 samples of the three treatments.

276

277 With regard to the seasons, none of the treatments had any differences in any of the physical or
278 chemical properties between the spring and autumn samples except for a significant decrease in
279 C:N ratio (-58%) in the NB plots and a significant increase in the C:N ratio (+20%) in the B+NL
280 plots between spring and autumn (Table 2). The soil properties in the B+NL samples from the
281 autumn field campaign were generally similar to those of the B+L samples in both seasons, and
282 combined, these burned samples had significantly higher OC, OM and TN contents than the NB
283 soils. Similarly, significant decreases in EC between the burned and unburned soils were
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

290 lower in the B+NL plots than the NL and B+L plots, and the MC in B+NL and B+L were higher
291 than the NB (Table 3). Comparing the autumn to spring results from the NB plots showed that
292 BGA, Acid-PA and GPRS decreased significantly, whereas MC increased significantly and there
293 was no change in UA, DHA, or BSR (Table 3). In the burned soils, the GPRS increased in the
294 B+NL plots and there were no significant differences in any of the indices in the B+L plots from
295 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 ($|r|$
300 > 0.56). As regards the physico-chemical soil properties, strong and significant correlations ($|r| >$
301 0.47) were identified among OM, TN and C:N. The pH was significantly correlated with the clay
302 and silt fractions of soils ($|r| \geq 0.60$) and negatively with the OM and TN contents ($r \leq -0.52$)
303 (Table 4). Concerning the biochemical soil properties, BGA, Acid-PA and GPRS were
304 significantly correlated with each other ($r \geq 0.74$) and with several physico-chemical soil
305 properties (particularly with OM and TN, $r \geq 0.51$). In more detail, BGA and GPRS each had a
306 large number of positive correlations ($r \geq 0.59$) with the physico-chemical soil properties, and
307 they both were negatively correlated with clay content ($r \leq -0.62$). UA showed significant and
308 positive correlations with BGA and Acid-PA ($r = 0.61$ and $r = 0.74$, respectively), while DHA
309 was only negatively correlated with BSR ($r = -0.46$). No significant correlation was found
310 between the EC or MC and any of the physico-chemical or biochemical soil properties (Table 4).

311

312 **4. Discussion**

313

314 The results of our PERMANOVA analysis showed that wildfire is a significant disturbance
315 factor of soil, as indicated by the remarkable differences between unburned and burned soils,
316 with or without logging at the end of the first post-fire wet season (spring 2017) and at the end of
317 the following dry season (autumn 2017) (Table 2). Others have detected significant changes in
318 soil organic matter and nutrient content in soils affected by wildfire as compared to unburned
319 soils (e.g., González-Pérez et al., 2004; García-Orenes et al., 2017), including nutrient
320 availability and water retention (Certini 2005), increases in pH (Mataix-Solera et al., 2002; Ulery
321 et al., 1993), and reduction of the aggregate stability and soil structure decay (DeBano 2000).
322 Changes in soil texture related to burning have also been identified in previous studies, and
323 attributed to aggregate breakdown with loss of soil organic matter (e.g. Certini 2005; Mataix and
324 Cerda, 2009). Our results corroborate this fact as our textures clearly differed between NB and
325 burned plots (B+NL and B+L). Moreover, there were no differences in textural properties
326 between the spring and autumn samples, and we attribute this to the short time between sample
327 periods. We attribute the lack of difference between B+NL and B+L to the lightweight
328 machinery used during logging operations. For this research, logging operations were carried out
329 using a single pass of an agricultural tractor with pneumatic tires, resulting in low ground
330 pressure. Fernández et al. (2019) found similarly little impact of post fire salvage logging on
331 vegetation recovery.

332

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

336 GPRS. Literature shows that soil pH and EC tend to rise after fire (e.g., Pereira et al., 2018), and
337 these properties gradually return to the original pre-fire values due to the washout effect (Mataix-
338 Solera et al. 2009; Muñoz-Rojas et al. 2016). In our study, the pH of soil did not respond to
339 burning or burning and logging, possibly due to the buffering capacity of our carbonated soils,
340 which slows or prevents the movement of the acid front and therefore the mobilization of soil
341 elements (Certini 2005; Mataix-Solera et al. 2009). Conversely, EC of the burned soils in our
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
344 plots. The difference in EC may be because of burning, which accumulates ash containing C and
345 other nutrients from burned forest fuel (Caon et al. 2014).

346

347 Some of the other physico-chemical properties of soils significantly changed immediately after
348 the wildfire. These changes indicated a shift of burned soils towards a higher content of organic
349 matter and nutrients, thus improving their fertility, and these increases were no different in soils
350 subjected to logging. Moreover, these changes persisted or further increased in the second
351 sample period with a simultaneous increase of the C:N ratio, driven by the slight increase in OC.
352 Of all the physical and chemical soil properties, OM content is one of the most important quality
353 indicators, given its influence on plant growth-related functions such as water retention, nutrient
354 exchange, and soil structure (Mataix-Solera et al. 2011; Muñoz-Rojas et al. 2016). The increase
355 of soil organic matter may be due to accumulation of ash, which contains carbon and other
356 nutrients from burned forest fuel (Bodí et al., 2014; Caon et al., 2014; Harper et al., 2019). In
357 general, the variability of the C:N ratio was similar across the three treatments, indicating low
358 activity and disintegration speed for OM as well as a low degree of N mineralisation regardless

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

361

362 The simultaneous measurement of several enzymatic activities might be useful as an indicator of
363 the bioactivity and biochemical fertility of a soil (Gil-Sotres et al. 1992). Enzymatic activity
364 plays an important role in catalysing biological reactions (Mataix-Solera et al. 2009). This study
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
367 influence both degradative processes in the soil and changes in organic matter (Ceccanti and
368 García 1994) but as Nannipieri et al. (1990) suggested, it would be difficult for one activity alone
369 to be taken as representative of the overall nutrient state of a soil due to the great specificity of
370 individual enzymes for particular substrates. To summarise, we measured significant decreases
371 in BGA, Acid-PA, and GPRS and a significant increase in MC between spring and autumn in the
372 non-burned plots. As indicated by the climatic records, spring 2017 was preceded by a relatively
373 wet period and autumn 2017 was drier than the reference period (Figure 2). As Merilä et al.
374 (2002) showed, low soil moisture is a major factor in controlling the activity of microbes.
375 Seasonal changes in soil moisture were frequently reported to affect enzymatic activities in forest
376 soils (Baldrian et al. 2010). As Criquet et al. (2004) demonstrated, some enzymatic activities
377 (e.g. urease, phosphatase and β -glucosidase) were substantially reduced in dry seasons. Sardans
378 and Peñuelas (2005) also concluded that forest soil contained less microbial biomass and
379 exhibited reduced enzyme activities in dry periods. However, when burned, either logged or not,
380 differences for soil enzyme activities were hard to find and seasonality was not as an important
381 factor. In this regard, BSR and MC were significantly different between the NB and burned soils.

382 These enzymatic effects detected in NB soils compared to B+NL plots (either logged or not) may
383 be due to the accumulation of organic matter and nitrogen coming from the burned plant material
384 (Rodríguez et al. 2017), which continued until these mineralised materials had been consumed
385 (Muñoz-Rojas et al. 2016) and their decomposition in the seven-month monitoring period. This
386 result was further confirmed by the positive correlations between the BGA and Acid-PA on one
387 hand and OM and TN on the other hand.

388

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

398

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

404 high microbial biomass. Moreover, the uncoupling of the soil microbial biomass and its general
405 activity suggests a stress or disturbance of the soil microbial community (Lucas-Borja et al.
406 2011). Our study demonstrated that Glomalin-Related Soil Protein (GPRS) content in B+NL and
407 B+L soils in autumn, approximately one year post-fire, exceeded the spring burned
408 measurements and the autumn measurements in the unburned soil. Result also showed that
409 GPRS values were significantly correlated with OM content and the C/N ratio. Burnt plots
410 (either logged or not) favouring higher OM accumulation and C:N ratios would generate GPRS
411 recovery even to higher values compared to unburned plots. The glomalin, which is a
412 glycoprotein produced by Arbuscular Mycorrhizal Fungi (AMF), is an indicator of C and N
413 storage, which in turn play key roles in aggregate stability or water repellence of soils (Lozano et
414 al. 2016). As Rivas et al. (2016) showed, the GPRS level recovery four years after fire was due
415 to species' rapid root colonisation and associated arbuscular mycorrhizal fungi colonization.
416 Overall, it can be said that logging after wildfire affect does not significantly alter soil
417 functionality in the short-term in *Pinus halepensis* M. forests whereas wildfire is an influential
418 factor. However, this is a short period to assess changes and the implications for mid or long-
419 term responses should be currently addressed. In addition, particular attention should be paid to
420 different types of forest logging machines and forestry equipment.

421

422 **5. Conclusions**

423

424 In order to evaluate whether and to what extent logging alters soil functionality in the short-
425 period after a wildfire in a Mediterranean forest of *Pinus halepensis* M., we sampled unburned
426 soils (control), and plots burned and subjected to no logging or logging in March and October

427 2017 following a severe wildfire in July 2016 and logging in December 2016. Differences in
428 physico-chemical and biochemical properties of soils under the three conditions showed some
429 discrimination between unburned and burned plots (logged or not) 8 months after wildfire and
430 again 15 months after the fire, but few difference 3 and 10 months after post-fire logging.
431 Specifically, the burned (either logged or not) soils had greater organic matter content, greater
432 nitrogen content, and higher basal soil respiration rate than the unburned controls, although the
433 basal soil respiration rate was not significantly higher in the autumn (15 months after fire)
434 measurement. The glomalin-related soil protein content was also greater in the burned plots than
435 the controls in the autumn (15 months after burning). There were no differences in soil pH, sand
436 fraction, urease activity, dehydrogenase activity, or microbial carbon among the unburned,
437 burned, and burned and logged soil conditions. These results led us to reject the initial working
438 hypothesis that logging negatively affects soil functionality immediately after fire in
439 Mediterranean forests. Logging operations using a lightweight tractor produced no significant
440 impacts on logged plots. Overall, the differences between non-burned and wildfire affected plots
441 suggest the important effects of wildfires on soil functionality. In our study, the seasonal
442 differences in some of the indicators of unburned soils were more significant than the differences
443 between the burned plots with and without logging.

444

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643

644 **TABLES**

645

646 **Table 1.** One-way permutational multivariate analysis of variance (PERMANOVA) for burn condition ("NB", non-burned soil,
 647 "B+NL", burned and non-logged soil, and "B+L", burned and logged soil in both spring (March 2017) and autumn (October 2017))
 648 and applied to physico-chemical and biochemical properties of soil samples collected in this study (n = 18) (Liétor, Castilla La
 649 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.

654

655

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

660

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

661 Notes: OC = organic carbon; OM = organic matter; EC = electrical conductivity; TN = 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 ($\mu\text{mol p-NP}$ $\text{hour}^{-1} \text{g}^{-1}$)	UA ($\mu\text{mol N-NH}_4^+$ $\text{hour}^{-1} \text{g}^{-1}$)	Acid-PA ($\mu\text{mol p-NP}$ $\text{hour}^{-1} \text{g}^{-1}$)	DHA ($\mu\text{g INTF hour}^{-1} \text{g}^{-1}$)	BSR ($\mu\text{gCO}_2 \text{ hour}^{-1} \text{g}^{-1}$)	GPRS ($\mu \text{g}^{-1} \text{ dry soil}$)	MC ($\text{mg C kg}^{-1} \text{ dry soil}$)
NB/S	0.86 \pm 0.05(ab)	0.73 \pm 0.03(a)	1.16 \pm 0.04(a)	0.10 \pm 0.01(a)	1.94 \pm 0.05(b)	1700 \pm 149(b)	56.3 \pm 0.52(c)
NB/A	0.59 \pm 0.06(c)	0.50 \pm 0.11(a)	0.47 \pm 0.04(b)	0.11 \pm 0.02(a)	1.94 \pm 0.11(b)	1030 \pm 118(c)	369 \pm 20.4(a)
B+NL/S	0.86 \pm 0.21(ab)	0.53 \pm 0.09(a)	0.77 \pm 0.06(ab)	0.12 \pm 0.02(a)	3.73 \pm 0.73(a)	1394 \pm 183(c)	191 \pm 9.63(b)
B+NL/A	0.96 \pm 0.14(ab)	0.44 \pm 0.05(a)	0.93 \pm 0.03(a)	0.11 \pm 0.06(a)	4.47 \pm 0.57(a)	2845 \pm 289(a)	204 \pm 3.91(b)
B+L/S	1.18 \pm 0.47(ab)	0.85 \pm 0.40(a)	1.22 \pm 0.51(a)	0.14 \pm 0.03(a)	2.10 \pm 0.24(b)	2278 \pm 635(ab)	224 \pm 108(b)
B+L/A	1.28 \pm 0.01(a)	0.66 \pm 0.09(a)	1.35 \pm 0.08(a)	0.08 \pm 0.01(a)	2.05 \pm 1.13(b)	2890 \pm 77(a)	195 \pm 5.00(b)

Notes: 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.

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

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

Notes: 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; 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 non-logged plot



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

