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Short-term impacts of wildfire and post-fire mulching on ecosystem multifunctionality in a semi-arid pine forest

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17 **Long-term evaluation of soil functionality in Mediterranean forests after a wildfire**
18 **and post-fire hillslope stabilisation**

19

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35

36 **Abstract**

37

38 The effects of hillslope stabilisation techniques on soil properties and vegetation cover
39 of Mediterranean forests affected by wildfires have been deeply explored in the short
40 term, while the long-term evaluations are scarce. Following previous investigations
41 carried out in a pine forest of Castilla-La Mancha (Spain) burned by a severe wildfire in
42 2012 and treated with log erosion barriers (LEBs) or contour felled log debris (CFD) as
43 post-fire management actions, this study evaluates the changes in soil physico-chemical
44 and biological properties, and vegetation cover eleven years after the fire and structure
45 construction in unburned, burned and untreated (with north or south aspect), and burned
46 and treated soils (with CFDs or LEBs). The results have shown that none of the
47 physico-chemical and biological properties of soil as well as the ground cover
48 significantly differs between sites treated with CFDs and LEBs. The latter structures
49 appear to be more effective in storing organic matter and water in the soil, which is
50 important for post-fire vegetation recovery. The aforementioned effectiveness of post-

51 fire treatments in limiting the changes in soil and vegetation due to wildfire was
52 particularly evident in the burned and untreated sites exposed to the south, which should
53 be prioritised for treatment, since these areas show long-term reductions in soil water
54 content and availability. This prioritisation helps to support a quicker restoration of
55 vegetation cover, which may find water shortage as a limiting factor compared to sites
56 with north aspect. Finally, since, in such a long term, the changes in several soil
57 properties (e.g., most of the enzymatic activities and basal respiration) between
58 unburned, and burned and treated sites disappeared, and vegetation cover was almost
59 fully restored up to the unburned level, it can be confirmed that the analysed hillslope
60 stabilisation techniques were successful in recovering the pre-fire conditions of soil and
61 vegetation conditions that are typical of unburned sites.

62

63 **Keywords:** soil properties; enzymatic activities; ground cover; log erosion barriers;
64 contour felled log debris.

65

66 **1. Introduction**

67

68 The effects of wildfires on forest ecosystem have been widely studied in the literature
69 under almost all climatic conditions (e.g., Caon et al., 2014; Girona-García et al., 2021;
70 Moody et al., 2013; Pausas et al., 2008; Zavala et al., 2014). As a result of this research,
71 the impacts of wildfire have been acknowledged on both soil and vegetation
72 (Almendros and González-Vila, 2014; Moody et al., 2013; Stavi, 2019). According to
73 the majority of studies, after high-severity, fires vegetation is almost totally removed,
74 and soil undergoes noticeable and long-lasting changes. These effects of wildfires on
75 vegetation and soil result in noticeable increases in surface runoff and erosion rates in
76 the short term (Nelson et al., 2022; Shakesby, 2011; Stavi, 2019), which may lead to
77 severe off-site hydrogeomorphological hazards, such as flooding, landslides, and burial
78 of infrastructures (Moody et al., 2013; Shakesby and Doerr, 2006). Therefore, post-fire
79 management actions are essential to properly control and mitigate these
80 hydrogeomorphological hazards (Garrido-Ruiz et al., 2022; MacDonald and Larsen,
81 2009; Zema, 2021), and to support the post-fire recovery of natural vegetation and
82 biodiversity for a quick restoration of burned forests (García Matallana et al., 2022;
83 Lucas-Borja, 2021; Maestre and Cortina, 2004).

84 Recently, Girona-García et al. (2021) published a systematic review and a meta-analysis
85 about the effectiveness of many post-fire management techniques on soil's hydrological
86 response in burned forests. According to this study, the application of post-fire
87 treatments should be advised against no action, especially when soil is exposed to high
88 natural erosion. The post-fire management actions can be implemented both on
89 hillslopes or in channels of burned catchments (Lucas-Borja, 2021; Robichaud, 1998;
90 Robichaud et al., 2010). Hillslope stabilisation treatments include grass seeding, log
91 erosion barriers (LEB), contour-felled log debris (CFD) and mulching (Garrido-Ruiz et
92 al., 2022; Girona-García et al., 2021; Vieira et al., 2018). Treatments using burned or
93 unburned wood materials are often preferred to other techniques, since these materials
94 accelerate the decomposition and incorporation of vegetal biomass into soil, and reduce
95 fuel load for future wildfires (Fernández et al., 2019; Robichaud et al., 2010, 2008). In
96 general, several studies have demonstrated the effectiveness of post-fire hillslope
97 treatments using wood materials for both soil conservation and vegetation recovery
98 purposes (Girona-García et al., 2021; Jourgholami et al., 2020; Robichaud et al., 2020).
99 Several studies have evaluated the effects of CFDs and LEBs on surface runoff and soil
100 erosion (e.g., Albert-Belda et al., 2019; Fernández et al., 2019; Jourgholami et al.,
101 2020). The studies about the effects of these treatments on soil chemical and
102 biochemical properties are much lower (Wittenberg et al., 2020), although their effects
103 may significantly affect the post-fire functionality of soils (Fernández et al., 2019;
104 Robichaud et al., 2008; Wagenbrenner et al., 2021). This scarce knowledge may hinder
105 the ability of forest managers to understand the effects of post-fire management
106 practices on soil functionality.

107 Moreover, the effectiveness of LEBs and CFDs has been evaluated in studies
108 throughout for a short time, due to their usual construction immediately after the
109 wildfire (when the hydrological risks are the highest) (Francos et al., 2018; Lucas-Borja
110 et al., 2021) and limited or even absent financial supports for long-term monitoring
111 (Girona-García et al., 2021; Zema and Lucas-Borja, 2023). The duration of the impacts
112 of wildfire is variable according to the ecosystem component under study (e.g., water,
113 soil, vegetation), and, furthermore, it depends on the ecosystem resilience to fire, which
114 changes site by site. (Prosser and Williams, 1998) termed the post-fire period with the
115 most evident effects of wildfire as “window of disturbance”. These authors reported that
116 world-wide its length more typically lies in the range of three to ten years, which refers
117 to the short- or mid-term duration. Long-term studies (i.e., more than ten years) are

118 scarce, and this scarcity hampers a full understanding of long-term effects of post-fire
119 management (Garrido-Ruiz et al., 2022; Granged et al., 2011; Spanos et al., 2005). In
120 other words, it is not clear which effects of LEBs and CFDs on soil properties and
121 ground covers (e.g., vegetation, dead wood material, bare soil) are durable, how these
122 effects evolve after the construction of structures, and when soil properties and
123 vegetation cover recover the pre-fire levels (García Matallana et al., 2022;
124 Wagenbrenner et al., 2021).

125 In three previous studies carried out in a Mediterranean pine forest in Central Eastern
126 Spain, the effects of CFD and LEB treatments on several physico-chemical and
127 biological soil properties and vegetation characteristics were investigated four, five and
128 eight years after a wildfire (Gómez-Sánchez et al., 2019; Lucas-Borja et al., 2022;
129 Martínez et al., 2021). A first research (four years after the fire) evaluated the changes
130 in vegetation cover and composition after wildfire among unburned, burned and
131 untreated, and burned and treated soils (using LEBs and CFDs) (Martínez et al., 2021).
132 A second study (five years after fire) showed that LEBs and, to a lesser extent, CFDs
133 improved post-fire soil quality, which improves edaphic conditions to help ecosystem
134 functions rapidly recover (Gómez-Sánchez et al., 2019). A third investigation (eight
135 years after fire) demonstrated that both LEBs and CFDs increased soil organic matter
136 and basal respiration, while the biological properties did not completely recover
137 compared to unburned areas (Lucas-Borja et al., 2022).

138 This study continues those investigations in the same areas eleven years after the
139 wildfire, monitoring the long-term changes in soil physico-chemical and biological
140 properties, and ground covers (rock, dead wood, vegetation, and bare soil) in hillslopes
141 treated with LEBs and CFDs compared to unburned and burned areas without post-fire
142 restoration actions, assumed as control. The analysis is carried out considering the
143 differences in the ensemble of soil properties and ground covers between soil conditions
144 rather than focussing on each individual parameter. This approach is adopted in order to
145 circumvent the natural variability in each soil property and ground cover, which may be
146 due to soil heterogeneity or intrinsic variations. The research questions supporting the
147 study are three: (i) did CFDs and LEBs affect soil properties and ground covers
148 differently? (ii) were the treatments effective at limiting the post-fire changes in soil and
149 vegetation compared to the burned and untreated sites? (iii) did these hillslope
150 stabilisation techniques restore the pre-fire soil and vegetation conditions that are
151 typical of unburned sites? The responses to these questions should indicate to forest

152 managers how long and to what extent soil functionality and vegetation cover are
153 affected by post-fire management treatments in the long term in comparison with both
154 unburned, and burned and untreated areas.

155

156

157 *1. Study area*

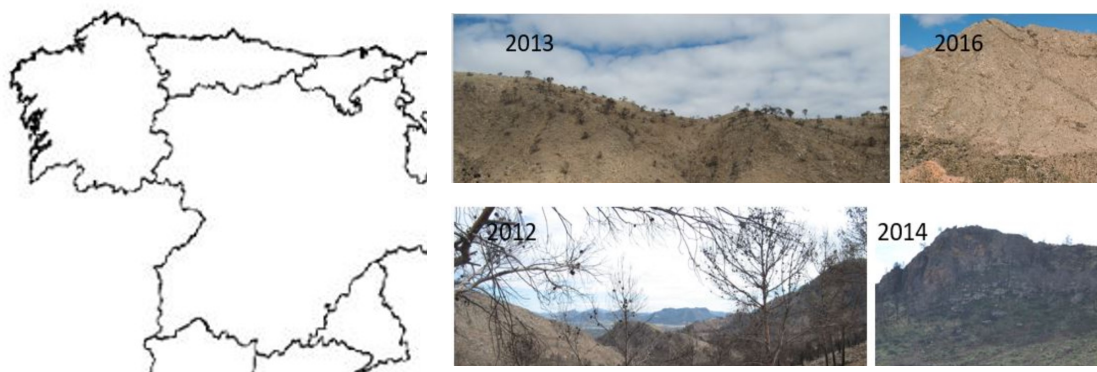
158

159 **2. Study area**

160

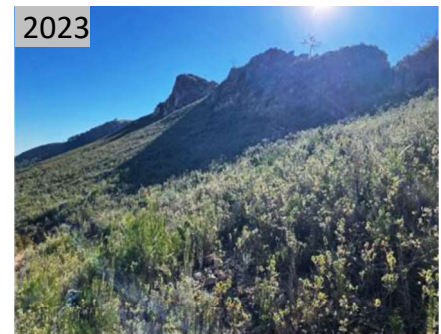
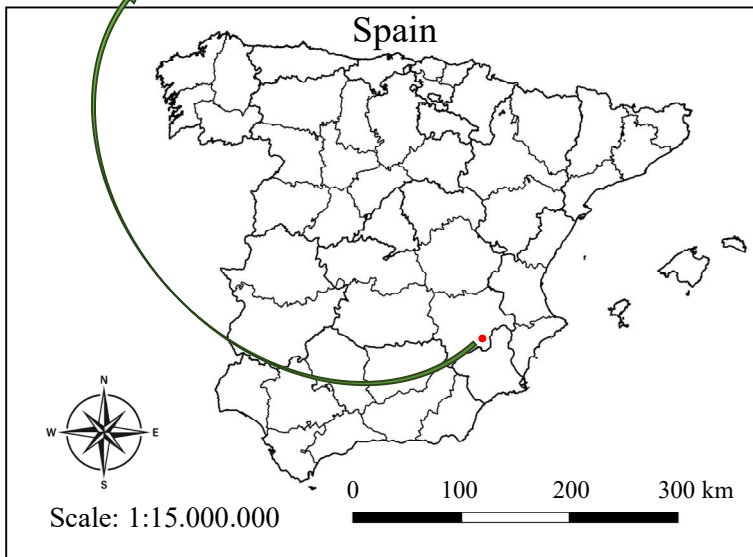
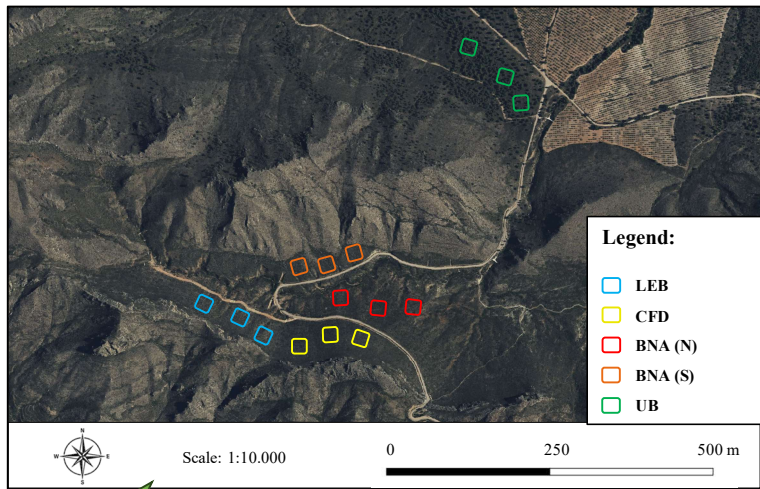
161 The study area is the Sierra de Los Donceles forest, located at an altitude between 304
162 m and 808 m a.s.l. close to Hellín (Castilla-La Mancha, Central Eastern Spain) (Figure
163 1). The climate of the area is semi-arid, Csa class according to the classification of
164 Koppen (Kottek et al., 2006). The mean annual temperature is 16.6°C, and annual
165 precipitation is on average 321 mm, with maximum monthly values of 44.5 mm
166 (October) and 39.6 mm (May) (data from 1990-2014, Spanish Meteorological Agency,
167 AEMET).

168



169

170



172 Figure 1 – Location of the study area in Spain (a) and evolution of some of experimental plots (BNA(S), upper figure, and LEB, lower figure) (b)
173 for long-term monitoring of soil properties and ground covers after a wildfire and post-fire hillslope stabilisation treatments (Sierra de Los
174 Donceles, Hellín, Castilla-La Mancha, Spain).

175

176 Before the wildfire of July 2012, which devastated about 6500 ha of Mediterranean
 177 maquis, the dominant vegetation in the area included mature trees of *Pinus halepensis* S.
 178 and a large shrub cover of *Quercus cocciferae* (Peinado Lorca et al., 2008). The latter
 179 formed an intricate mass of thorny nanophanerophyte, e.g., kermes oak (*Quercus*
 180 *coccifera* L.), black hawthorn (*Rhamnus lycioides* L.), esparto grass (*Macrochloa*
 181 *tenacissima* (L) Kunth), Italian buckthorn (*Rhamnus alaternus* L.), grey asparagus
 182 (*Asparagus horridu* L.s) and other inerns (*Pistacia lentiscus* L., *Genista spartioides*
 183 *subsp. Retamoides* (Spach) Rivas Godoy & Rivas Mart (Broom)). In the 1980s,
 184 accessible public lands were repopulated by Aleppo pine along with thermophile
 185 scrublands in sunny spots (spartals and rosemary scrublands) (Table 1).

186 Soils are rather homogenous and belong to the Calcic Aridisols type with a loamy to
 187 sandy loam texture (USDA Soil Taxonomy System, Nachtergaele, 2001; Soil Survey
 188 Staff, 2014) (Table 1).

189

190 Table 1 - Main soil and vegetation characteristics of the study area (Hellín, Castilla-La
 191 Mancha, Spain).

192

Characteristics		Soil condition				
		<i>UB</i>	<i>BNA(N)</i>	<i>BNA(S)</i>	<i>LEB</i>	<i>CFD</i>
Soil	Altitude (m a.s.l.)	405-500	500-550	450-500	450-500	500-550
	Average slope (%)	32	47	33	32	44
	Aspect	Variable	North	South	Variable	Variable
	Type	Calcic Aridisols				
	Texture (sand, silt, and clay contents, in %)	53 40 7				
Vegetation	Tree layer	<i>Pinus halepensis</i>				
	Shrub layer	<i>Pistacia lentiscus, Quercus coccifera, Quercus ilex,</i> <i>Juniperus oxycedrus, Rosmarinus officinalis,</i> <i>Macrochloa tenaccisima, Thymus vulgaris</i>				

193

194 After the July 2012 fire, in the immediate autumn, the regional forest service of
195 Castilla-La Mancha carried out stabilisation treatments on hillslopes consisting of log
196 erosion barriers (LEB) and contour-felled log debris (CFD).
197 Each LEB and CFD were built by felling burned trees that were placed on the ground
198 along the slope contour (Napper, 2006). Each log was 10 m-long, and was anchored in-
199 place, and the space between the lowest log and the soil surface was filled to store
200 sediments in the upstream basin. In contrast to LEB construction, logs of CFDs were
201 not anchored; each CFD was 50 m long. Occasionally, earth berms were also installed
202 to avoid water circumventing the log sides. The mean areal and linear densities of the
203 structures were 30 LEBs and 17 CFD per hectare, and 300 m (LEBs) and 850 m (CFDs)
204 of logs per hectare. The small diameter and low density of trees in the area, which made
205 suitable wood material scarce for building LEB construction, these densities were quite
206 limited compared to actual needs. Conversely, the less compacted and concentrated
207 material was more suitable for building CFDs.

208

209 **3. Material and methods**

210

211 *3.1. Experimental design*

212

213 In April 2023, fifteen 20 x 20 m plots were randomly set up in the burned sites of the
214 study area: (i) three plots in the areas with CFDs; (ii) three in the areas with LEBs; (iii)
215 six in the burned and untreated areas, of which three in sites with north aspect, and three
216 with south aspect (hereafter indicated “Burned and No Action(North)”, “BNA(N)”, and
217 “Burned and No Action(South)”, “BNA(S), respectively); and (iv) three plots in an
218 unburned area inside the forest (“UB” plots), very close to the burned area. The
219 reciprocal distance among plots was higher than approximately 300 meters (Figure 1) to
220 be considered spatially independent. All plots were located at a mean altitude of
221 approximately 500 m a.s.l., with a slope of 30 to 45% (Table 1). The experimental plots
222 were located in sites with very similar climatic and geomorphological conditions, and
223 burned at the same burn severity. Therefore, changes in soil properties and ground cover
224 can be ascribed to the effects of wildfire and hillslope stabilisation techniques.

225

226 *3.2. Soil sampling and analysis*

227

228 In each plot, three soil samples, each of 600 g, were randomly collected from the
229 surface layer (0-10 cm) after litter removal and mixed in a composite sample. After
230 sieving (2-mm diameter) and storing at 4 °C in the laboratory, the composite was
231 analysed after 15 days after sampling. The following soil physico-chemical and
232 biological properties were determined on the collected samples: (i) Available Water
233 (AW) for plants, by measuring the pFs at -1500 (wilting point, WP) and -33 (Field
234 Capacity, FC) kPa by Richards' method (Richards, 1947); (ii) Soil Water Content
235 (SWC), using a VG400 (Vegetronix, Utah, USA) device emplaced on the surface and
236 connected to a data logger (Onset HOBO, Massachusetts, USA); (iii) pH and electrical
237 conductivity (EC), in distilled water, at a soil:solution ratio of 1:2.5 and 1:5, using a
238 digital pHmeter, LAQUA PH1100, HORIBA, Tokio, Japan, and a conductivity meter,
239 Crison 522, Barcelona, Spain respectively; (iv) Total Organic Carbon (TOC, by
240 Walkley and Black, 1934), modified by Mingorance et al. (2007), and measured in a
241 spectrophotometer (Spectronic Helios Gamma UV-Vis, Thermo Fisher Scientific,
242 Massachusetts, USA); (v) daily and cumulative basal soil respiration (BSR, expressed
243 as mg of C-CO₂ per kg of dry soil and per day and mg of C-CO₂ per kg of dry soil,
244 respectively), using an infrared CO₂ analyzer (IRGA S151, Qubit Systems Inc.,
245 Canada); (vi) Dehydrogenase activity (DHA, expressed as µg of p-iodonitrotetrazolium
246 formazan (INTF) per hour and per g of dry soil), by reduction of p-iodonitrotetrazolium
247 chloride (INT) to INTF following García et al. (1997); (vii) Urease activity (UA,
248 expressed as µmol of N-NH₄⁺ per hour and per g of dry soil), using urea as a substrate
249 and a borate buffer at pH = 10 (Kandeler and Gerber, 1988; Tabatabai and Bremner,
250 1969); (viii) Alkaline phosphatase (PA) and β-glucosidase (BGA) activities (both
251 expressed as µmol of para-nitrophenol (pNP) per g of dry soil), using the methods of
252 Tabatabai and Bremner (1969) and Eivazi and Tabatabai (1988), respectively.

253

254 3.3. *Measurement of ground covers*

255

256 The following characteristics of soil surface (hereafter “ground covers”) were also
257 evaluated in each plot, where three longitudinal 10-m x 1-m transects were identified,
258 two in the plot side, and one in its middle. Vegetation cover, rock and dead wood, and
259 bare soil as a percent over the total transect area were measured on the same dates as
260 soil sampling. The grid method (Vogel and Masters, 2001) using a grid square of 0.50 x

261 0.50-m for vegetation cover, and the photographic method for the remaining variables
262 (rock and dead wood covers, and bare soil) were used.

263

264 3.4. *Statistical analysis*

265

266 Relationships among soil properties and covers, depending on different soil conditions,
267 were assessed using a combination of statistical techniques. First, the statistical
268 differences in soil physico-chemical and biological properties, and ground covers were
269 separately identified by the multivariate permutational analysis of variance
270 (PERMANOVA, based on the Euclidean and Bray Curtis distance as resemblance
271 measure, and permutation method, for a maximum of 999 permutations) (Anderson,
272 2005), using the soil condition (with five levels, BNA, BNA(S), LEB, CFD and UB) as
273 factor. Prior to using PERMANOVA, all variables were square root transformed.

274 Then, the analysis of similarities (ANOSIM), described by Clarke (1993), was
275 separately applied to the soil physico-chemical and biological properties. Finally,
276 Principal Component Analysis (PCA) was separately applied to the (i) physico-
277 chemical and (ii) biological properties of soil as well as to (iii) ground covers to analyse
278 the associations among those properties/covers (Rodgers and Nicewander, 1988). After
279 standardising the original variables (expressed by different measuring units) and
280 computing Pearson's correlation matrix, the first two first Principal Components (PCs),
281 explaining most of the original variance, were retained and the factor loadings of the
282 original variables on the two PCs were calculated.

283 For the statistical analyses, the software PRIMER V7[®] with PERMANOVA add-on
284 (Anderson, 2005) and Statgraphics Centurion XVI[®] (StatPoint Technologies, Inc.,
285 Warrenton, VA, USA) were used. A significance level (p-value) of 0.05, which is a
286 measure of the probability that the observed differences between groups are due to
287 chance, was used, unless otherwise indicated. In addition, the effect size (i.e., the
288 "pseudo-F" statistic values) was also considered, since it is a measure of the magnitude
289 of the differences between the groups.

290

291 4. **Results**

292

293 4.1. *Analysis of soil properties and ground covers*

294

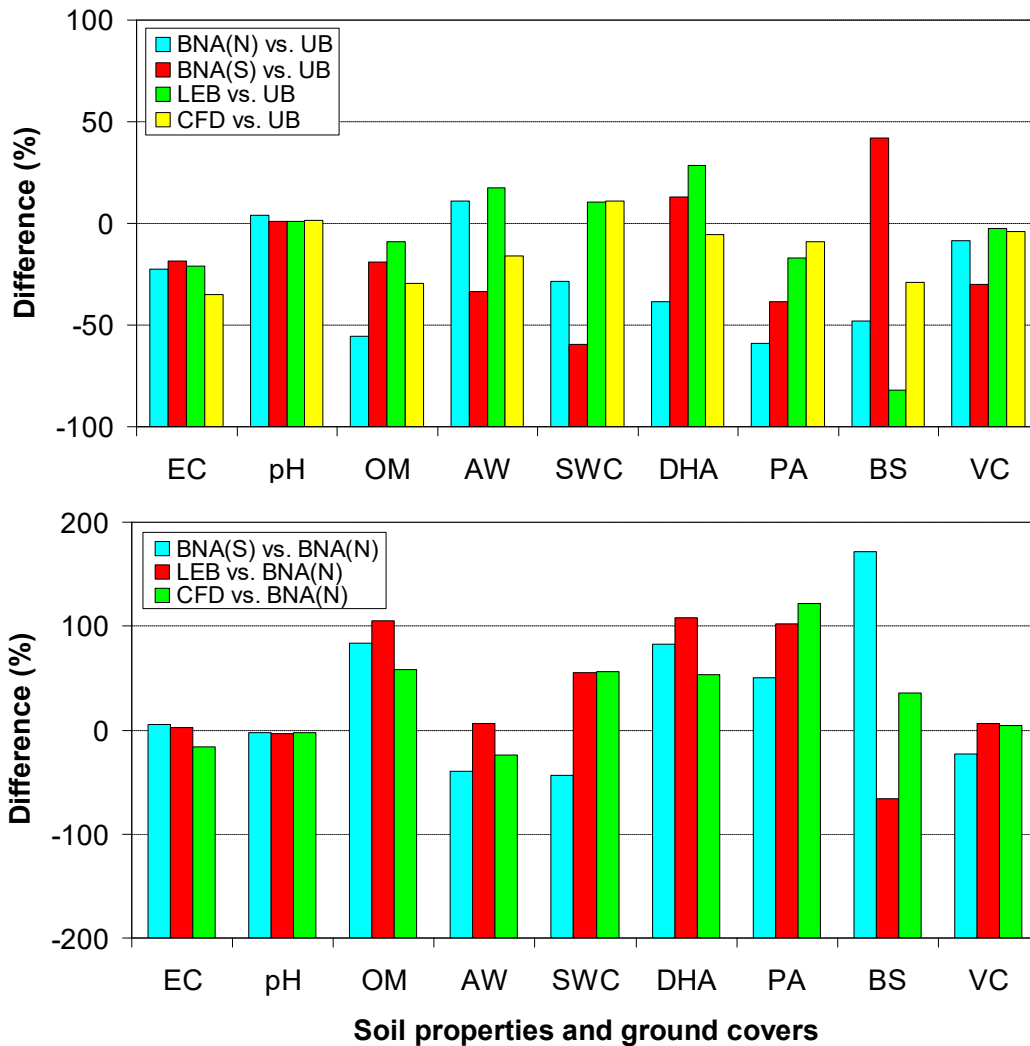
295 Table 1 reports the values of physico-chemical and biological properties of soil as well
296 as of ground covers, while Figure 2 depicts the differences in those variables among the
297 five soil conditions. In more detail, all soil properties and ground covers were
298 significantly different among soil conditions, except BGA, UA, d-BSR, c-BSR and
299 DWC. Among the significantly different variables, the following highest variations
300 were detected: (i) -59.7% in SWC between UB and BNA(S) soils, and -59% in PA
301 between UB and BNA(N); (ii) -82.2% in BS between LEB and UB, and -35% in EC
302 between CFD and UB; (iii) +172% in BS between BNA(N) and BNA(S); and (iv) 108%
303 in DHA between BNA(N) and LEB, and 121% between BNA(N) and CFD (Figure 2).
304

305 Table 2 – Mean \pm standard error (n = 3) of the main physico-chemical and biological properties of soils sampled in forests under five soil
 306 conditions (BNA(N) = burned and no action (north aspect); LEB = log erosion barriers; BNA(S) = burned and no action (south aspect); CFD =
 307 contour log felled debris; UB = unburned (Sierra de Los Donceles, Hellín, Castilla-La Mancha, Spain).
 308

Soil properties/ground covers	UB	BNA(N)	BNA(S)	LEB	CFD
EC	0.17 \pm 0.03 a	0.13 \pm 0.01 ab	0.14 \pm 0.00 ab	0.13 \pm 0.01 ab	0.11 \pm 0.01 a
pH	8.40 \pm 0.03 a	8.76 \pm 0.08 b	8.50 \pm 0.08 ab	8.46 \pm 0.06 a	8.54 \pm 0.13 ab
TOC	3.13 \pm 0.52 b	1.39 \pm 0.27 a	2.54 \pm 0.16 ab	2.85 \pm 0.17 b	2.20 \pm 0.72 ab
FC	31.4 \pm 2.28 b	26.5 \pm 0.26 ab	18.9 \pm 1.19 a	30.9 \pm 1.11 b	25.2 \pm 6.07 b
WP	18.6 \pm 1.52 c	12.3 \pm 0.26 ab	10.4 \pm 0.14 a	15.9 \pm 1.86 bc	14.4 \pm 3.61 abc
AW	12.8 \pm 1.04 ab	14.2 \pm 0.39 b	8.5 \pm 1.26 a	15.0 \pm 2.13 b	10.7 \pm 2.55 ab
SWC	5.65 \pm 0.40 b	4.03 \pm 0.33 ab	2.28 \pm 0.15 a	6.25 \pm 1.40 b	6.28 \pm 1.56 b
DHA	5.84 \pm 0.78 ab	3.61 \pm 1.07 a	6.60 \pm 0.49 b	7.51 \pm 0.69 b	5.52 \pm 0.59 b
BGA	0.77 \pm 0.22 a	0.54 \pm 0.11 a	0.46 \pm 0.21 a	0.71 \pm 0.38 a	0.49 \pm 0.08 a
PA	2.60 \pm 0.15 c	1.07 \pm 0.04 a	1.60 \pm 0.25 ab	2.16 \pm 0.16 bc	2.37 \pm 0.58 bc
UA	2.33 \pm 0.63 a	1.58 \pm 0.46 a	2.48 \pm 0.57 a	1.92 \pm 1.56 a	2.28 \pm 0.84 a
d-BSR	44.4 \pm 4.14 a	32.6 \pm 5.27 a	44.0 \pm 5.46 a	42.7 \pm 15.0 a	33.5 \pm 4.03 a
c-BSR	1269 \pm 119 a	944 \pm 149 a	1318 \pm 124 a	1275 \pm 427 a	1014 \pm 144 a

RC	3.62 ± 3.76 a	12.6 ± 1.82 abc	18.5 ± 3.03 c	15.7 ± 7.08 bc	6.47 ± 1.83 ab
DWC	0.08 ± 0.13 a	6.61 ± 3.94 a	0.21 ± 0.32 a	5.59 ± 2.97 a	6.03 ± 3.95 a
BS	19.1 ± 6.94 bc	9.96 ± 2.68 ab	27.1 ± 4.99 a	3.39 ± 1.11 b	13.5 ± 1.47 b
VC	77.2 ± 9.26 b	70.8 ± 1.98 ab	54.2 ± 6.41 a	75.4 ± 8.98 b	74.0 ± 6.65 b

309 Notes: AW = Available Water (AW) for plants; WP = Wilting Point; FC = Field Capacity; SWC = Soil Water Content; EC = Electrical Conductivity; TOC = Total Organic
310 Carbon; d-BSR, c-BSR = daily and cumulative Basal Soil Respiration; DHA = Dehydrogenase Activity; UA = Urease Activity; PA = Alkaline Phosphatase; BGA = β -
311 glucosidase. Different letters indicate significant differences among the soil conditions after pairwise comparisons (p-level < 0.05).



313

314 Figure 2 – Variations in soil properties and ground covers of soils sampled in forests
 315 under five conditions (BNA(N) = burned and no action (north aspect); LEB = log
 316 erosion barriers; BNA(S) = burned and no action (south aspect); CFD = contour log
 317 felled debris; UB = unburned (Sierra de Los Donceles, Hellín, Castilla La Mancha,
 318 Spain).

319

320 4.2. Changes in physico-chemical and biological properties among soil conditions

321

322 According to PERMANOVA, the soil treatments resulted in significant differences in
 323 several physico-chemical properties (pseudo-F = 6.902, p-value < 0.001). The
 324 treatments significantly influenced also the biological properties of soil (pseudo-F =
 325 2.063, p-value < 0.05).

326 For the physico-chemical properties of the soil, the physico-chemical properties of the
 327 soils in the BNA(N) plots were significantly different from LEB, BNA(S) and UB
 328 conditions, but not from CFD plots. In plots burned but not treated and exposed to the
 329 south, the physico-chemical properties of soil were different from LEB and UB plots,
 330 but not from CFD. However, it must be evidenced that the p-level of this difference was
 331 very close to 0.05 (Table 3). ANOSIM showed that, for the biological properties of the
 332 soil, BNA(N) plots was different only from UB soils, while no differences were
 333 detected in biological properties between these and the remaining soil conditions (Table
 334 3).

335

336 Table 3 – Analysis of similarities (ANOSIM) in physico-chemical and biological
 337 properties between pairs of soil sampled in forests under five conditions (BNA(N) =
 338 burned and no action (north aspect); LEB = log erosion barriers; BNA(S) = burned and
 339 no action (south aspect); CFD = contour log felled debris; UB = unburned (Sierra de
 340 Los Donceles, Hellín, Castilla-La Mancha, Spain).

341

Soil conditions	t	p-value	t	p-value
	<i>Physico-chemical properties</i>		<i>Biological properties</i>	
BNA(N) vs. LEB	2.994	0.019	1.517	0.175
BNA(N) vs. BNA(S)	3.973	0.004	1.989	0.089
BNA(N) vs. CFD	1.725	0.081	1.621	0.117
BNA(N) vs. UB	3.482	0.008	2.350	0.038
LEB vs. BNA(S)	4.609	0.002	0.770	0.604
LEB vs. CFD	1.486	0.177	1.003	0.442
LEB vs. UB	1.528	0.133	0.649	0.725
BNA(S) vs. CFD	2.17	0.051	1.753	0.08
BNA(S) vs. UB	4.111	0.004	1.812	0.069
CFB vs. UB	2.033	0.068	1.593	0.097

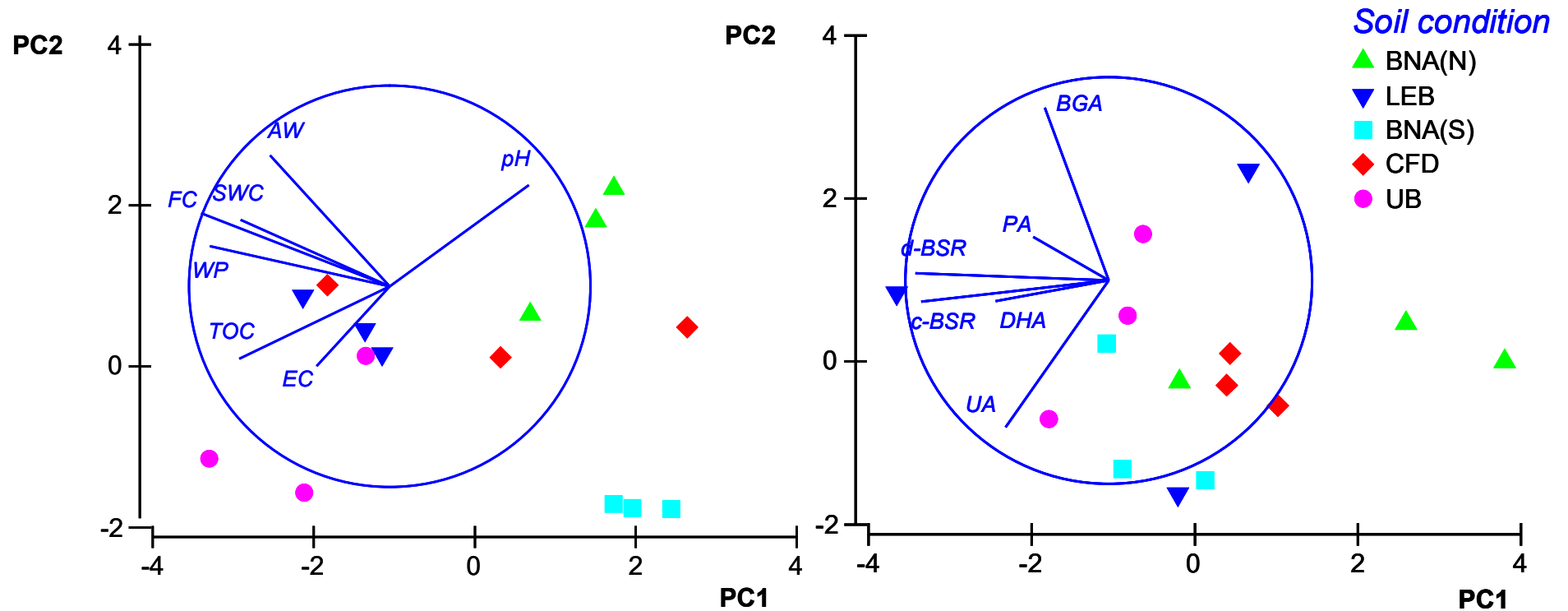
342 Note: bold characters indicate significant differences ($p < 0.05$); “t” is the value of the pairwise test.

343

344 The first two components of PCA explain 79.4% of the total variance of the original
 345 physico-chemical properties, and PC1 explains 55% of this variance. Soil pH (with

346 positive loadings), and SWC, FC, WP and TOC (with negative weights) noticeably
347 weigh on the first PC, while pH again and AW influence the second PC with positive
348 loadings (Figure 3). BNA(N) and BNA(S) plots are clustered in two different groups,
349 which are distinct from other clusters grouping soil samples under the other three soil
350 conditions (Figure 3).

351 The first two PCs calculated by PCA explained 70.7% of the variance in the biological
352 properties of the soil, of which 50.8%v is explained by PC1. All biological properties
353 (except BGA and UA) have high and negative loadings on the first PC, while PC2 is
354 noticeably influenced by the latter biological properties (Figure 3). The scatterplot does
355 not show any evident groups of soil samples according to the soil condition, except for
356 BNA(N) plots that may be grouped in one but large cluster (Figure 3).



358

359 Figure 3 - Principal Component Analysis biplot applied to physico-chemical (left) and biological (right) properties of soils sampled in forests
 360 under five conditions (BNA(N) = burned and no action (north aspect); LEB = log erosion barriers; BNA(S) = burned and no action (south
 361 aspect); CFD = contour log felled debris; UB = unburned (Sierra de Los Donceles, Hellín, Castilla-La Mancha, Spain).

362

363 4.3. Analysis of ground covers

364

365 PERMANOVA revealed that the soil condition significantly influenced ground covers
366 (pseudo-F = 8.902; p = 0.001). According to ANOSIM, significant differences in
367 ground covers were detected between all pairs of soil conditions, except the pair
368 ‘BNA(N) vs. LEB’ and ‘BNA(N) vs. CFD’ (Table 5).

369

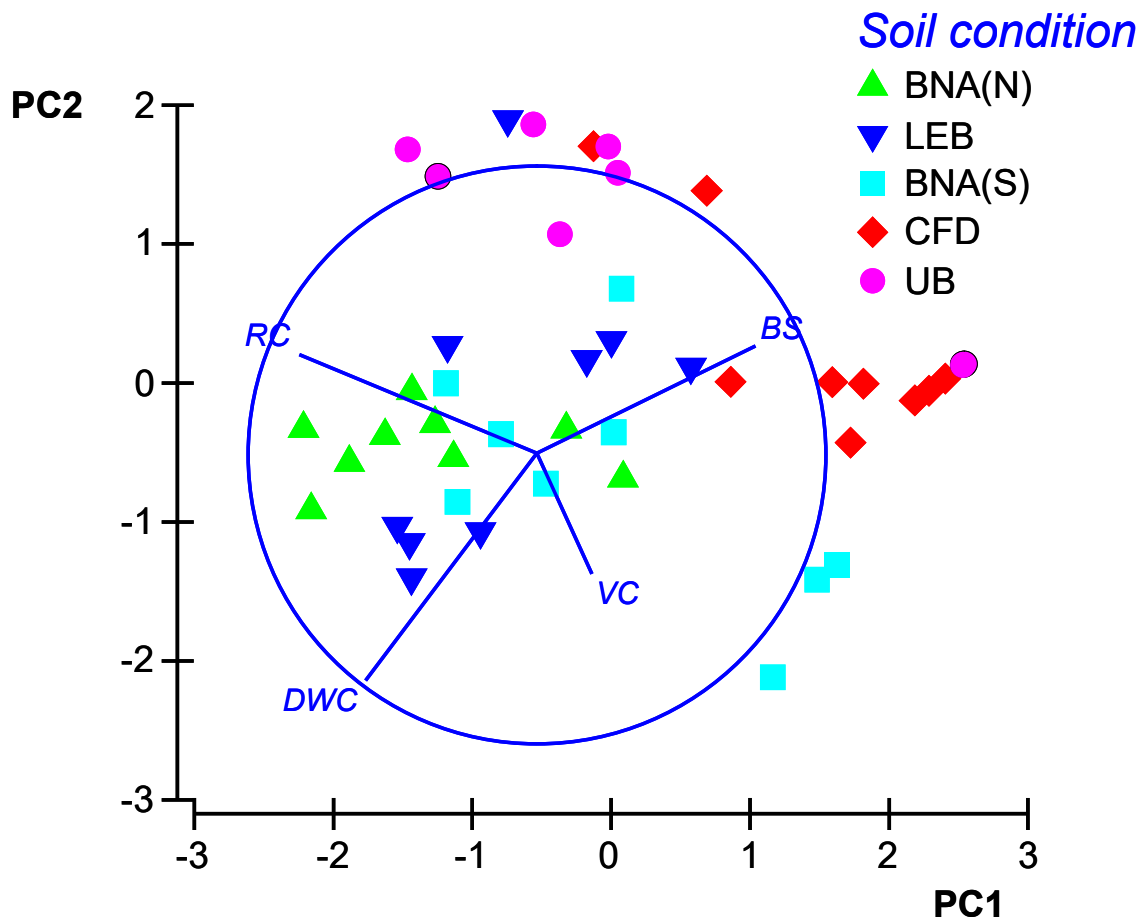
370 Table 5 – Analysis of similarities (ANOSIM) in ground covers between pairs of soil
371 sampled in forests under five conditions (BNA(N) = burned and no action (north
372 aspect); LEB = log erosion barriers; BNA(S) = burned and no action (south aspect);
373 CFD = contour log felled debris; UB = unburned (Sierra de Los Donceles, Hellín,
374 Castilla-La Mancha, Spain).

375

Soil conditions	t	p-value
BNA(N) vs. LEB	1.050	0.356
BNA(N) vs. BNA(S)	2.871	0.014
BNA(N) vs. CFB	4.804	0.003
BNA(N) vs. UB	5.068	0.001
LEB vs. BNA(S)	1.309	0.217
LEB vs. CFB	2.942	0.009
LEB vs. UB	2.491	0.022
BNA(S) vs. CFB	3.177	0.005
BNA(S) vs. UB	4.105	0.002
CFB vs. UB	2.864	0.017

376 Note: bold characters indicate significant differences (p-value < 0.05); “t” is the value of the pairwise test.

377



378
 379 Figure 5 - Biplot of Principal Component Analysis applied to ground covers of soils
 380 sampled in forests under five conditions (BNA(N) = burned and no action (north
 381 aspect); LEB = log erosion barriers; BNA(S) = burned and no action (south aspect);
 382 CFD = contour log felled debris; UB = unburned (Sierra de Los Donceles, Hellín,
 383 Castilla-La Mancha, Spain).

384

385

386 PCA selected two derivative PCs, which explain 60% and 30% of the original variance
 387 in ground covers (totalling 90% of this variance). RC and BS have high loadings
 388 (negative and positive, respectively) loadings on PC1, while DWC mostly influences
 389 the second PC (Figure 5). A clear gradient along DWC and BS direction is noticed
 390 among UB and CFD soils on one side, and the remaining soil conditions on the other
 391 side (Figure 5).

392

393 5. Discussion

394

395 The study of effects of post-fire management on soil and vegetation is essential but
396 complex due to very little relevant background. The combined but separate approach to
397 the analysis of three ensembles of variables that include the physico-chemical and
398 biological properties, as well as the ground cover as affected by wildfire and post-fire
399 hillslope stabilisation treatments, reveal the long-term soil functionality and vegetation
400 recovery, on which anthropogenic disturbances due to fire and structures impacted.

401

402 5.1. *Long-term effects of wildfire*

403

404 The severe changes in soil properties and ground cover in forests burned by wildfires
405 are well known (e.g., Agbeshie et al., 2022; Certini, 2005; Shakesby and Doerr, 2006;
406 Wagenbrenner et al., 2021; Zavala et al., 2014). For instance, the literature reveals
407 noticeable reductions in organic matter and nutrients (due to heating and mineralization)
408 as well as increases in EC (due to release of ions by ashes and charred residues,
409 (Mataix-Solera and Cerdà, 2009; Muñoz-Rojas et al., 2016) and changes in pH (which
410 generally have a short-lived impact, (Mataix-Solera et al., 2002; Ulery et al., 1993)
411 together with modifications in soil enzymatic activities and basal respiration (Lucas-
412 Borja et al., 2020; Mataix-Solera et al., 2009). When pre-fire values of soil properties
413 and vegetation cover and diversity recovered fully, this was observed many years after
414 the wildfire (Niemeyer et al., 2020; Wagenbrenner et al., 2021), and was due to leaching
415 caused by rainwater infiltration (Mataix-Solera and Cerdà, 2009; Muñoz-Rojas et al.,
416 2016) and regeneration of vegetation (Bodí et al., 2012; Granged et al., 2011).

417 In our study, the long-term (about 10-12 years elapsed from the fire) confirmed in
418 general these trends, while smoothing the expected changes in some parameters. In
419 more detail, significant differences between UB and BNA (regardless of aspect) were
420 detected in pH (+4.3% in BNA) and OM (-18.9%), while neither EC nor enzymatic
421 activities (except PA, -59%) underwent significant variations. After more than 10 years
422 after the wildfire, it can be noticed that the pre-fire enzymatic activity is almost fully
423 recovered, except for urease. The reduction in soil biological activity of soil is a clear
424 effect of wildfire, which destroys a large amount of enzymes due to the high soil
425 temperature (Barreiro et al., 2010). In previous investigations carried out five years after
426 the wildfire, no significant differences were noticed between the UB and BNA plots,
427 while, eight years after the fire, the differences in EC and pH, but not in OM, were
428 significant (Gómez-Sánchez et al., 2019; Lucas-Borja et al., 2022). Whereas, after five

429 years, only the differences in BGA and DHA were significant, at the later survey date,
430 all the enzymatic activities were significantly affected by the wildfire, while the
431 differences in BSR were not significant.

432 It is worth noting that in this study a significant change was detected in AW between
433 plots with different aspects (soils exposed to south showing a decrease by 40%
434 compared to north plots), and this may be a reason for the lower vegetation cover of
435 BNA(S) plots compared to UB soils (-30%). It is well known that water availability for
436 plants is a limiting factor for vegetation growth in semi-arid areas (Nunes et al., 2008;
437 Tangney et al., 2022), and the higher evaporation in soils exposed to south - shown by
438 the significantly lower SWC compared to UB plots (-59.7%) - may aggravate the
439 negative impact of fire on post-fire plant regeneration. This is supported by the fact that
440 vegetation cover was noticeably lower (54%) in BNA(S) compared to UB plots, while
441 no significant differences were noticed for post-fire regrowth of plants in BNA(N). This
442 is an important finding of our study and suggests prioritisation of sites with south aspect
443 for restoration actions targeted to the increase of post-fire regeneration of vegetation.
444 Post-fire plant recovery after wildfires depends on temperature and moisture of soil
445 (Tangney et al., 2022). Therefore, since post-fire management strategies can change
446 microclimate, this effect may result in delayed or failed emergence and survival of
447 plants (Gómez-Sánchez et al., 2023).

448

449 5.2. *Long-term effects of treatments compared to untreated soils*

450

451 The effectiveness of hillslope stabilization treatments in restoring soil functionality has
452 been demonstrated in many studies (e.g., Girona-García et al., 2021; Lucas-Borja, 2021;
453 Robichaud, 1998; Robichaud et al., 2010; Vieira et al., 2018; Zema, 2021). In our study,
454 after more than ten years from their construction, noticeable differences in some of the
455 physico-chemical and biological properties as well as ground covers were evident in
456 treated sites compared to untreated soils. These differences were more noticeable for
457 LEBs than for CFDs. In more detail, OM content of soil and some important enzymatic
458 activities (namely DHA and PA) were much higher in LEB sites (more than 100%)
459 compared to BNA(N) sites, although these changes were significant only for the plots
460 exposed to north. Also, the previous study carried out five years after the wildfire
461 showed, compared to BNA plots, no significant differences in EC (for both LEBs and
462 CFDs) and pH (in CFDs), while the difference in OM content were significant for both

463 treated soils (Gómez-Sánchez et al., 2019). The increase on soil OM content in sites
464 treated with LEBs may be due to the “barrier effect” (Robichaud et al., 2008;
465 Wohlgemuth et al., 2009), which accumulates, carbon and other nutrients from burned
466 vegetation and litter (Caon et al., 2014; Gómez-Sánchez et al., 2019) - providing
467 sources of OM due to its decomposition (Lucas-Borja et al., 2021; Robichaud et al.,
468 2000) - as well as from sediments trapped and retained by transverse structures,
469 particularly in areas with little rainfall (Fernández et al., 2011). Differences in OM
470 content between sites with LEBs or CFDs may be due to the fact that LEBs are less
471 pervious to water and sediment, and therefore can store more soil material (vegetal
472 residues and sediments carrying OM and nutrients) (Pérez-Cabello et al., 2011;
473 Robichaud et al., 2008; Wohlgemuth et al., 2009). This means that the long-term effects
474 on soil OM content are more pronounced in the case of LEBs, which seem to be more
475 effective at limiting the short-term depletion of OM due to wildfire (Caon et al., 2014).
476 This is an essential effect of post-fire stabilisation techniques, since a higher OM in soil
477 support beneficial ecosystem functions, such as plant growth in semi-arid soils that
478 generally show low fertility (Caon et al., 2014) thanks to enhanced carbon storage
479 (Lucas-Borja et al., 2022; Pereira et al., 2023).

480 In the previous studies by Gómez-Sánchez et al. (2019) and Lucas-Borja et al. (2022),
481 the enzymatic activities were not noticeably variable between CFD and BNA plots,
482 while, at LEB sites, only UA and BSR were significantly different. Eight years after the
483 wildfire, the differences in EC and OM (but not in pH) were significant for LEB plots,
484 while the reverse findings were detected for CFD (non-significant differences in EC and
485 OM, and significant difference in pH). In this period, almost all enzymatic activities in
486 CFD sites (except BSR) were similar as BNA plots, while only the differences in DHA
487 and UA were significant for the LEB sites. In this study, significant variations in the
488 enzymatic activities were detected only for PA (increased at both CFD and LEB sites by
489 over 100%) and DHA (only in LEB sites, +108%), but only compared to BNA(N) plots.
490 This means that the increase in the activity of soil microorganisms lasted for a few years
491 after fire (Gómez-Sánchez et al., 2019; Lucas-Borja et al., 2022), since presumably all
492 mineralised materials have been consumed (Muñoz-Rojas et al., 2016). Furthermore
493 (Badía et al., 2015) reported that post-fire management is active some years after a
494 wildfire on soils without plant cover, while other authors working in Mediterranean
495 areas reported that several enzymatic activities are less sensitive to management
496 practices compared to season and site effects (Quilchano and Marañón, 2002). As noted

497 by Lucas-Borja et al. (2022), simultaneous increases in the observed enzymatic
498 activities are not proportional to those recorded for soil OM, and this explains the
499 different dynamics between the biological and chemical variables. This leads to the
500 supposition that the soil functionality does not depend only on the quantity of the OM of
501 the soil, but rather on the quality of organic compounds supplied with the restoration
502 techniques (Ortega et al., 2023).

503 Moreover, the construction of LEBs and CFDs were also effective at smoothing the
504 aforementioned reduction in SWC (+175% in CFD and LEB plots) and AW (+76% for
505 LEBs) of BNA plots exposed to south, and this should have led to a significantly higher
506 vegetation cover (+35-40%) in treated soils, thus limiting the negative impact of
507 wildfire, especially in the drier sites.

508

509 5.3. *Long-term effects of treatments compared to unburned soils*

510

511 About ten years after the wildfire and stabilisation treatments, it is also worth noting
512 that, compared to UB sites, the only significant differences measured between burned
513 and treated, and unburned soils was the reduction in EC in CFD plots (-35%). Almost
514 all the other physico-chemical properties (i.e., pH and OM), enzymatic activities, and
515 ground covers (e.g., vegetation regrowth) restored to the pre-fire values. In contrast, in
516 the previous investigation five years after the wildfire, EC, pH and OM were
517 significantly different between LEB and UB sites, while only the difference in OM was
518 significant between CFD and UB plots. Enzymatic activities were very similar between
519 CFD and UB soils (except BGA), while only BSR and PA were significantly different
520 between LEB and UB plots (Gómez-Sánchez et al., 2019). Eight years after the fire, no
521 significant differences were detected in OM between treated and unburned soils, while
522 the differences in EC and pH remained noticeable in both LEB and CFD plots.
523 Enzymatic activities were in general more intense in CFD (except for BSR and DHA)
524 and LEB (except for DHA) sites compared to UB soils. Vegetation cover was more
525 developed at LEB sites compared to CFD plots, and close to the UB values at both dates
526 (Lucas-Borja et al., 2022). In general, these authors noted that the observed post-fire
527 recovery of soil functionality due to the presence of LEBs and CFDs did not reach the
528 level of the undisturbed (unburned) forest soils. This means that the implementation of
529 post-fire management actions may have beneficial effects in the short-term on essential
530 soil properties (such as OM and enzymatic activities), but these effects vanish over

531 time, presumably due to the fact that the structures cease their effectiveness on soil
532 functionality and ecosystem quality.

533

534 **6. Conclusions**

535

536 The combined analysis of the three ensembles of soil properties and ground covers in a
537 pine forest burned by a wildfire and treated with LEBs or CFDs shows that, about ten
538 years after disturbance, the long-term discrimination between burned and untreated on
539 one side, and unburned soils on the other side is due to few physico-chemical properties
540 (i.e., pH and TOC) and ground covers (vegetation, but only for hillslopes exposed to
541 south) rather than to biological properties. These changes also govern the long-term
542 evolution between burned and untreated soils on one side, and burned and treated sites
543 on the other side, but only in the case of LEB presence. In contrast, a clear
544 discrimination can be noticed for ground covers between burned and untreated soil
545 exposed to south, and sites burned and treated with LEB and CFD, the latter showing a
546 high similarity to burned and untreated sites with north aspect. This means that, in the
547 long-term, the effects in vegetation regeneration played by hillslope stabilisation
548 techniques progressively lose importance in almost all soil properties and ground
549 covers, but these post-fire management actions are important to support long-lasting
550 vegetation restoration, especially in sites affected by chronic water shortages.

551 Overall, these results help to reply to the three research questions supporting the study.
552 In reply to the first question, it has been demonstrated that, ten years after the wildfire,
553 none of the physico-chemical and biological properties of the soil as well as the ground
554 cover significantly differ between sites treated with CFDs and LEBs. The latter
555 structures seem to be more effective at storing organic matter and water in soil, which is
556 important for post-fire vegetation recovery. The aforementioned effectiveness of post-
557 fire treatments at limiting the changes in soil and vegetation due to wildfire was
558 particularly evident in burned and untreated sites exposed to south, and this finding
559 responds to the second research question. Therefore, these sites should be prioritised for
560 post-fire treatments, as these areas show long-term reductions in soil water content and
561 availability. This prioritisation helps to support a quicker restoration of vegetation
562 cover, which may find water shortage as limiting factor compared to sites with north
563 aspect. Finally, since, in such long term, the changes in several soil properties (e.g.,
564 most of the enzymatic activities and basal respiration) between unburned, and burned

565 and treated sites disappeared, and vegetation cover was almost fully restored up to the
566 unburned level, it can be confirmed that the analysed hillslope stabilisation techniques
567 were successful in recovering the pre-fire conditions of soil and vegetation conditions
568 that are typical of unburned sites, which replies to the third research question.

569

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571

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582

583 **Author contribution statement**

584

585 Manuel Esteban Lucas-Borja, Conceptualization, Formal analysis, Data Curation,
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594 Original Draft, Writing - Review & Editing.

595

596 **Data availability statement**

597

598 Data will be shared upon reasonable request to the authors.

599

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