

Science of the Total Environment

Limited contribution of post-fire eco-engineering techniques to support post-fire plant diversity

--Manuscript Draft--

Manuscript Number:	STOTEN-D-21-27504R1
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Keywords:	Wildfire; species richness; species diversity; log erosion barriers; contour felled log debris; mulching.
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First Author:	Manuel Esteban Lucas-Borja, Ph.D.
Order of Authors:	Manuel Esteban Lucas-Borja, Ph.D. Demetrio Antonio Zema Cristina Fernandez, Dr. Rocio Soria Isabel Miralles, Dr. Victor Santana, Dr. Javier Pérez-Romero Antonio Del Campo, Dr. Manuel Delgado-Baquerizo
Abstract:	Eco-engineering techniques are generally effective at reducing soil erosion and restore vegetal cover after wildfire. However, less evidence exists on the effects of the post-fire eco-engineering techniques to restore plant diversity. To fill this knowledge gap, a standardized regional-scale analysis of the influence of post-fire eco-engineering techniques (log erosion barriers, contour felled log debris, mulching, chipping and felling, in some cases with burning) on species richness and diversity is proposed, adopting the Iberian Peninsula as case study. In general, no significant differences in species richness and diversity (Shannon) were found between the forest treated with different post-fire eco-engineering techniques, and the burned and non-treated soils. Only small significant differences were found for some sites treated with log erosion barriers or mulching. The latter technique increased species richness and diversity in some pine species and shrublands. Contour felled log debris with burning slightly increased vegetation diversity, while log erosion barriers, chipping and felling were not successful in supporting plant diversity. This research will help forest managers and agents in Mediterranean forest to decide the best postfire management option for wildfire affected forest, and in the development of more effective post-fire strategies.
Response to Reviewers:	Response to Reviewers Ms. Ref. No.: STOTEN-D-21-27504 Title: Limited contribution of post-fire eco-engineering techniques to support post-fire plant diversity Journal: Science of the Total Environment Response: Dear Editor in Chief, Prof.. Damiá Barcelo, Thank you very much for the opportunity to revise our manuscript. We have addressed all your and reviewer's comments and we hope the manuscript is now ready for acceptance. Thank you very much for your suggestions, which have improved a lot the initially submitted version. Sincerely The authors Reviewer #1: The paper deals with the assessment of positive effects on plant diversity (richness and diversity) of various eco-engineering techniques applied in the aftermath

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COVER LETTER

Albacete (Spain), 16 November 2021

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Kind regards.

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SHORT COMMUNICATION

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Manuel Esteban Lucas-Borja^{1,*}, Demetrio Antonio Zema², Cristina Fernández,³ Rocío Soria⁴, Isabel Miralles⁴, Victor M. Santana^{5,6}, Javier Pérez-Romero⁷, Antonio D. del Campo⁷, Manuel Delgado-Baquerizo⁸

¹ Department of Agroforestry Technology, Science and Genetics, School of Advanced Agricultural and Forestry Engineering, Campus Universitario s/n, Castilla La Mancha University, E-02071 Albacete, Spain

² AGRARIA Department, Mediterranean University of Reggio Calabria, Località Feo di Vito, I-89122 Reggio Calabria, Italy

³ Centro de Investigación Forestal de Lourizán. Consellería do Medio Rural. Carretera de Marín, km 4. 36153. Pontevedra. Spain.

⁴ Department of Agronomy & Center for Intensive Mediterranean Agrosystems and Agri-food Biotechnology (CIAIMBITAL), University of Almeria, E-04120, Almería, Spain

⁵ Fundación Centro de Estudios Medioambientales del Mediterráneo (CEAM). Parque Tecnológico. C/Charles R. Darwin, 14. 46980. Paterna (Valencia), Spain

⁶ Departamento de Ecología. Facultad de Ciencias V. Universidad de Alicante. 03080. San Vicente del Raspeig (Alicante), Spain

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⁸ Instituto de Recursos Naturales y Agrobiología de Sevilla (IRNAS), CSIC, Av. Reina Mercedes 10, E-41012, Sevilla, Spain.

* manuelesteban.lucas@uclm.es

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5

6 **Abstract**

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8 vegetal cover after wildfire. However, less evidence exists on the effects of the post-fire
9 eco-engineering techniques to restore plant diversity. To fill this knowledge gap, a
10 standardized regional-scale analysis of the influence of post-fire eco-engineering
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22 development of more effective post-fire strategies.

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24 **Keywords:** wildfire; species richness; species diversity; log erosion barriers; contour
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27 **1. Introduction**

28 Forest ecosystems that are affected by wildfires undergo noticeable changes in soil
29 properties, and vegetation cover and biodiversity. Due to these changes, post-fire high-
30 intensity storms expose forest soil to erosion and consequent degradation (Pereira et al.,
31 2018; Fernández and Vega, 2016; Morán-Ordóñez et al., 2020). To contrast these
32 degradation factors, millions of euros are currently being spent in short-term post-fire
33 management actions (Lucas-Borja, 2021). Many of these actions are eco-engineering
34 techniques designed to support economic sustainability and environmental compatibility

35 including mulching, and the construction of log erosion barriers or contour felled log
36 debris (Lucas-Borja, 2021; Zema, 2021). Post-fire eco-engineering techniques are
37 conducted within one year of a fire to stabilize the burned soil, protect public health and
38 infrastructures, and reduce the risk of additional damage to valued forest ecosystems
39 (Robichaud et al., 2010; Vega et al., 2018). These techniques control the soil's
40 hydrological response and, at the same time, enhance recovery of soil properties and
41 restoration of plant cover and biomass to the pre-fire levels. Much less is known, however,
42 on the capacity of post-fire eco-engineering techniques to support the restoration of plant
43 diversity. For example, by trapping seeds or generating higher soil moisture nearby eco-
44 engineering techniques, postfire management structures may change seeder-to-resprouter
45 and woody-to-nonwoody species ratios, which alters forest structure after wildfires
46 (Gómez-Sánchez et al., 2019). Moreover, current knowledge, based on local surveys, on
47 the effectiveness of post-fire eco-engineering techniques is highly variable, and depends
48 on the wildfire severity and characteristics of forest ecosystems (topography, rainfall
49 characteristics and plant composition) (Badía et al., 2015; Robichaud, 1998; Girona-
50 García et al. 2021).

51

52 Although several studies have evaluated the effects of several post-fire eco-engineering
53 techniques on soil hydrology and vegetation cover (Morgan et al., 2014; Gómez-Sánchez
54 et al., 2019; Fernández et al., 2019), less information is available on how vegetation
55 diversity responds after the installation of eco-engineering materials and structures. In
56 other words, while the increase in vegetation cover is expected after post-fire management
57 actions, the knowledge on how and to what extent the eco-engineering techniques drive
58 richness and plant diversity is very limited. This is an essential concern in the
59 Mediterranean forest ecosystems, which are considered a global hotspot of biodiversity
60 and are threatened by a severe risk of wildfire and often affected by high erosion rates
61 (Moody et al., 2013; Shakesby, 2011). In these environmental contexts, these risks may
62 be aggravated by the expected scenarios of climate change (Collins et al., 2013), which
63 forecast a directional loss in water-limited climates of plant community diversity at
64 multiple levels of organization (Harrison et al., 2020). Learning more about how post-fire
65 eco-engineering techniques influence plant diversity is further essential to support the
66 myriad of ecosystem functions and services supported by biodiversity.

67

68 To fill this gap of knowledge, a standardized regional-scale database about the influence
69 of post-fire eco-engineering techniques on plant diversity was collected. The effects of a
70 set of five techniques (log erosion barriers, contour felled log debris, mulching, chipping
71 and felling, in some cases with burning) on species richness and diversity are evaluated
72 in nine forest sites that were affected by wildfire in Spain. This country together with
73 Greece, France, Italy, and Portugal constitute over 85% of the most vulnerable areas to
74 fire in Europe, and belong to the Mediterranean Basin that is largely threatened by
75 extreme wildfires (Moreira et al., 2020) (San-Miguel-Ayanz et al., 2017). To the authors'
76 best knowledge, this is the first comprehensive study that has analyzed the effect of a
77 broad set of post-fire management techniques on vegetation diversity of a wildfire-prone
78 forest area, such as the Iberian Peninsula. We hypothesize that all the analyzed eco-
79 engineering techniques modify plant diversity in wildfire-affected areas in comparison to
80 non-treated areas under the Mediterranean climate. However, the influence of each
81 technique on plant diversity might be site-dependent, that is, it should be influenced by
82 the forest type and ecosystem properties. This study aims to advance our knowledge on
83 how plant diversity responds to the most common post-fire management strategies,
84 considering the variability of climate, soil, and forest species.

85

86 **2. Material and methods**

87

88 *2.1. Study areas and experimental sites*

89 This study has been carried out in nine wildfire-affected forest sites of six Spanish
90 provinces, both in the North-western (under oceanic temperate climate) and South-
91 Eastern (under dry sub-humid and semi-arid climates) zones of this country (Fig. 1). Table
92 1 reports the main climatic, morphological and plant characteristics of these forest sites.
93 Different eco-engineering techniques have been immediately applied in the subsequent
94 months after fire at each experimental site (Table 1). **The experimental areas used in this
95 work are representative of forest areas that have burned and are actively managed in Spain. Some
96 of the most frequent restoration strategies at the hillslope scale include log erosion barriers (LEB),
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109

110 2.2. Evaluation of richness and plant diversity

111 In each site and for each combination of post-fire eco-engineering techniques and main
112 forest species depicted in Table 1, the species richness (hereafter indicated as “SR”) and
113 diversity (“SD”) were evaluated five years (Hellín), three years (El Tranco, Calderona and
114 Porto do Son), and two years (Arbo, Entrimo, Cualedro and Liétor and Llutxent) after the
115 wildfires. In more detail, SR was the number of species identified in each plot, while SD
116 was calculated using the well-known Shannon index. The species richness and relative
117 abundance have been quantified by the α -diversity index (H_α) proposed by Hill (1973),
118 which utilizes Rényi’s function (Li and Reynolds, 1993; O’Neill et al., 1988):

$$119 \quad SD = -\sum_{i=1}^S p_i \ln p_i . \quad (1)$$

120 where:

121 - $p_i = \frac{n_i}{N}$ = frequency of “ n_i ” plants belonging to the species “ i ” with respect to the total

122 number of plants “ N ” in the plot;

123 - S = number of species in each plot.

124

125 The sampling design in each site was replicated between control and treatment plots and
126 was performed to keep balanced and representative measures across studied sites. We
127 have simply used the burned and non-action areas as the baseline of the natural plant
128 diversity since the area was not disturbed by postfire management. For each site, an effect
129 size for the contrast between each eco-engineering technique and the burned site without
130 any post-fire action was calculated for both SR and SD. This effect size was estimated as
131 the natural logarithm (\ln) of the response ratio (RR, (Curtis and Wang, 1998; Hedges et
132 al., 1999)) - hereafter “log response ratio” or “lnRR” - using the following equation:

$$\ln RR = \frac{x_T}{x_{BNA}} \quad (2)$$

where x_T is the mean value of the response variable measured in the plot subjected to the eco-engineering technique “T” and x_{BNA} is the corresponding value measured in the burned plot without any post-fire action (burned and no action, BNA). Therefore, in our study, two lnRRs were calculated, namely “lnRR(SR)”, which is the log response ratio of the species richness, and the “lnRR(SD)”, which is the log response ratio of the species diversity.

A negative lnRR of a technique T is a SR or SD that is lower compared to the SR or SD of a burned and non-treated area, while, if lnRR is positive, the SR or SD is higher than in the BNA plot (Eldridge and Delgado-Baquerizo, 2017). This approach allowed a standardized analysis of data from different sites and after sampling by different methods (Lajeunesse, 2015). Moreover, the 95%-confidence interval (CI_{95}) of both lnRR was calculated, in order to evaluate the significance of the effect of a technique. If the extremes of the CI_{95} are both positive and negative, the lnRR is significant, otherwise (that is, if both these extremes are positive or negative), it is not significant. Finally, in order to quantify the increase or decrease in SR and SD due to the eco-engineering technique compared to the BNA area, the percent variation of each effect evaluated in the treated plot was evaluated.

2.3. Statistical analyses

First, linear correlations between LnRR(SR) and LnRR(SD) on one side and some key factors of the nine sites on the other side (total annual precipitation, mean annual temperature, Aridity Index (mean annual precipitation / potential evapotranspiration), and soil slope and altitude) were investigated. To this aim, the values of the LnRR indexes were averaged among the different post-fire management strategies. Then, a one-way ANOVA was applied to the SR and SD (response variables) separately for each site (except El Tranco site), assuming as factor the soil condition (the different technique and the burned and non-treated area), the latter considered as independent factors. In El Tranco site, where different forest species and eco-engineering techniques were investigated and considered as independent factors, a 2-way ANOVA was applied. The pairwise comparison by Tukey’s test (at $p < 0.05$) was also used to evaluate the statistical significance of the differences in the response variables. In order to satisfy the

166 assumptions of the statistical tests (equality of variance and normal distribution), the data
167 were subjected to normality test or were square root-transformed whenever necessary.
168 All the statistical tests were carried out by with the XLSTAT software.

169

170 **3. Results**

171 In general, we did not find a significant effect of post-fire eco-engineering techniques on
172 plant diversity (Fig. 1). According to ANOVA, the differences in SR and SD among the
173 investigated post-fire techniques and the BNA soils were never significant ($p < 0.05$) with
174 some exceptions. These differences were significant ($p < 0.05$) only for SR in the forest
175 of *P. halepensis* subjected to LEBs (Hellin), and for both SR and SD in the forest of *P.*
176 *halepensis* (Liétor) and in *P. pinaster* stands (Entrimo), both subjected to soil mulching.
177 Moreover, low and non-significant linear correlations ($r^2 < 0.05$) were found between the
178 mean values of LnRR(SR) and LnRR(SD), considered as dependent variables, and total
179 annual precipitation, mean annual temperature, Aridity Index, and soil slope and altitude,
180 as independent variables (data not shown).

181

182 Only the influence of soil mulching on plant diversity after wildfire was evident (Table
183 1SM). This evidence is shown by the positive LnRRs of both SR and SD in three (Arbo,
184 Liétor and Entrimo) of the four burned forests treated with mulching, although the
185 differences compared to BNA sites were significant in two sites (Liétor and Entrimo)
186 (Figures 2a and 2b). In these three sites, LnRRs(SR) and LnRR(SD) were in the range
187 0.10 (shrubland of Arbo) to 0.41 (forest of *P. halepensis* in Liétor) and 0.04 (shrubland
188 of Arbo) to 0.24 (forest of *P. pinaster* in Entrimo), respectively. In contrast, both LnRRs
189 were negative (-0.18, LnRR(SR), and -0.14, LnRR(SD) in the shrubland of Porto do Son
190 (Figures 2a and 2b). Mulching increased SR by 10.3% (shrubland of Arbo) to 51.3% in
191 the forest of *P. halepensis* in Liétor, and SD by 4.3% (shrubland of Arbo) to 26.9% (*P.*
192 *pinaster* in Entrimo). In contrast, these characteristics decreased by 16.2% (SR) and
193 13.1% (SD) in shrubland of Arbo (Figures 3a and 3b).

194

195 CFD treatments played positive effects on vegetation diversity in the forest of *P. pinaster*
196 of El Tranco and on the shrubland in Llutxent. In more detail, CFD with burning gave
197 LnRR(SR) and LnRR(SD) over 0.18 in *P. pinaster* of El Tranco, while only LnRR(SR)
198 was positive (0.10) after CFD without burning in the same site; in the shrubland of
199 Llutxent, LnRR(SR) was 0.20 and LnRR(SD) was 0.10. In contrast, both LnRR(SR)

200 (equal to -0.06) and LnRR(SD) (-0.22) were negative, when CFD was combined with
201 LEB (*P. pinaster* in El Tranco). Overall, the CFD treatment increased SR and SD up to
202 26.1%, both estimated in the forest of *P. pinaster* in El Tranco under CFD + B treatment
203 (Figures 3a and 3b).

204

205 Positive effects on vegetation diversity - LnRR(SR) or LnRR(SD) > 0 - were also
206 estimated for chipping treatment in Arbo (0.05 and 0.04, respectively) and felling and
207 burning in El Tranco (the latter only for LnRR (SR)) (Figures 2a and 2b). In these sites,
208 maximum increases in SR and SD by 5.4% (SR) and 3.8% (SD) were estimated
209 (shrubland of Arbo subjected to chipping), while the increase in SR measured under the
210 treatment of felling and burning was 0.4% (Figures 3a and 3b).

211

212 Conversely, all the other post-fire eco-engineering techniques played negative effects on
213 vegetal diversity, as showed by the negative values of LnRR(SR) and LnRR(SD). In the
214 case of LEB, both these indexes were negative (with a minimum of -0.14 detected for
215 LnRR(SR) in shrubland of Lutxent) in all sites, also when this post-fire action was
216 implemented in combination with other eco-engineering techniques (Figures 2a and 2b).
217 The maximum decreases in SR and SD were detected under CFD treatment (-17.6%,
218 forest of *P. halepensis* in Hellin) and under combined treatments of LEB and CFD (-
219 20.1%, forest of *P. pinaster* in El Tranco) (Figures 3a and 3b).

220

221 **4. Discussion and conclusion**

222

223 This standardized field study, carried out at the regional scale in the Iberian Peninsula,
224 provides evidence that the analyzed post-fire eco-engineering techniques have a very
225 limited influence on plant diversity. Thus, no significant differences in species richness
226 and diversity were, in general, found between the forest soils treated with each post-fire
227 eco-engineering technique, and the burned and non-treated sites. These differences were
228 only noticeable and thus significant in some sites treated with log erosion barriers or
229 mulching. The latter technique increased species richness and diversity in forests of *P.*
230 *halepensis* and *P. pinaster*, and shrublands. These results are in partial accordance with
231 Morgan et al. (2014) and Jonas et al. (2019), who observed higher species richness as we
232 did, but did not find any differences in species diversity in response to the mulching
233 treatments. Contour felled log debris with burning slightly increased vegetal diversity,

234 while log erosion barriers, chipping and felling were not successful for this effect. Our
235 findings suggest that the current post-fire eco-engineering techniques on plant diversity
236 are not efficient, and that new strategies might be needed.

237

238 Direct and indirect effects of fire on soils and plants can be critical for the functioning of
239 forest ecosystems and alter the capacity of biodiversity to support multiple ecosystem
240 functions from carbon sequestration to fibre production. Thus, promoting post-fire
241 recovery of forests is fundamental for an adequate management and planning of these
242 ecosystems (Lucas-Borja, 2021). In this case, scientific literature has widely
243 demonstrated that some Mediterranean species are able to regenerate through different
244 post-fire strategies, including resprouting, serotiny, soil seed banks or wind seed
245 dispersion into a fire- affected site (Valladares et al., 2014, Resco 2021). The short-term
246 period evaluated in this research and the good adaptation of the surveyed vegetation to
247 fire indicate that a post-fire emergence treatment should not be targeted to biodiversity
248 recovery in wildfire-affected areas, since no influence was found on plant diversity. Even
249 so, longer-term monitoring is needed to provide further evidence on the importance of
250 post-fire eco-engineering techniques, in order to support plant diversity in a context of
251 climate change and land use intensification.

252

253 The only significant strategy was related to straw mulching in semi-arid locations. **As**
254 **Wright and Rocca (2017) have indicated, mulch-retained moisture may benefit natural**
255 **pine regeneration in water-stressed environments, whereas deep mulch applications may**
256 **inhibit the establishment of natural regeneration by acting as a physical barrier to seed**
257 **emergence.** This suggests that mulch acts as a retainer for soil nutrients and moisture
258 which may act as limiting factors for seedling growth in water-stressed environments. In
259 fact, Bontrager et al. (2019) found that increased mulch suppressed pine recovery at
260 higher altitudes and in northern aspects than in southern aspects with less precipitation
261 and higher temperature. In contrast, Lucas-Borja et al. (2020) demonstrated that mulching
262 had no detrimental effects on the short-term initial vegetation recovery in sub-humid sites.
263 In addition, the same authors found that leaving the burned trees standing seemed not to
264 be a feasible management option for enhancing vegetation recovery in northern Spain.
265 Mulching seemed to influence neither the natural availability of nutrients nor moisture.

266

267 Overall, this research has demonstrated that, on a broad scale, soil mulching is generally
268 able to restore post-fire vegetal diversity regardless of the specific site conditions.
269 Conversely, other eco-engineering techniques must be implemented with caution since
270 these post-fire actions may even decrease the vegetation diversity of severely burned
271 forest ecosystems. These measures play beneficial effects in reducing the runoff and
272 erosion rates, in contrasting the soil degradation and supporting vegetation recovery, but
273 no result is seen in the recovery of diversity or species richness. **The effects of plant and
274 soil restoration strategies on burned forests need to be effectively outlined with the aim
275 to generate a scientific basis for post-fire management guidelines and properly restore
276 wildfire affected forest ecosystems.**

277

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284

285 **List of symbols/nomenclature**

Post-fire eco-engineering techniques

BNA	Burned and No Action
CFD	Contour Felled Log Debris
LEB	Log Erosion Barriers
M	Mulching
C	Chipping
CFD + B	Contour Felled Log Debris + Burning
LEB + CFD	Log Erosion Barriers + Contour Felled Log Debris
LEB + B	Log Erosion Barriers + Burning
F + B	Felling + Burning

Investigated sites

Cu	Cualedro
Ca	Calderona
He	Hellín
Li	Liétor
Ja	Jaén
Ll	Llutxent
Ar	Arbo
Ps	Porto do Son
En	Entrimo

Main forest species

Ps	<i>P. sylvestris</i>
Ph	<i>P. halepensis</i>
Pn	<i>P. nigra</i>
Pp	<i>P. pinaster</i>
S	<i>Shrubland</i>

286

287 **Supplementary material**

288 List of plant species at each site.

289

290 **References**

291 Badía, D., Sánchez, C., Aznar, J.M., Martí, C., 2015. Post-fire hillslope log debris dams for runoff
292 and erosion mitigation in the semiarid Ebro Basin. *Geoderma* 237, 298–307.
293 <https://doi.org/10.1016/j.geoderma.2014.09.004>

294 Bontrager, J.D., Morgan, P., Hudak, A.T., Robichaud, P.R., 2019. Long-term vegetation response
295 following post-fire straw mulching. *Fire Ecol.* <https://doi.org/10.1186/s42408-019-0037-9>

296 Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X.,
297 Gutowski, W.J., Johns, T., Krinner, G., 2013. Long-term climate change: projections,
298 commitments and irreversibility, in: *Climate Change 2013-The Physical Science Basis:*
299 *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel*
300 *on Climate Change.* Cambridge University Press, pp. 1029–1136.

301 Curtis, P.S., Wang, X., 1998. A meta-analysis of elevated CO₂ effects on woody plant mass, form,
302 and physiology. *Oecologia* 113, 299–313. <https://doi.org/10.1007/s004420050381>

303 Eldridge, D.J., Delgado-Baquerizo, M., 2017. Continental-scale Impacts of Livestock Grazing on
304 Ecosystem Supporting and Regulating Services. *Land Degradation and Development* 28, 1473–
305 1481. <https://doi.org/10.1002/ldr.2668>

306 Harrison, S., Spasojevic, M.J., Li, D., 2020. Climate and plant community diversity in space and
307 time. *Proceedings of the National Academy of Sciences*, 117 (9) 4464-4470; DOI:
308 10.1073/pnas.1921724117

309 Hedges, L.V., Gurevitch, J., Curtis, P.S., 1999. The meta-analysis of response ratios in
310 experimental ecology. *Ecology* 80, 1150–1156. [https://doi.org/10.1890/0012-9658\(1999\)080\[1150:TMAORR\]2.0.CO;2](https://doi.org/10.1890/0012-9658(1999)080[1150:TMAORR]2.0.CO;2)

312 Lajeunesse, M.J., 2015. Bias and correction for the log response ratio in ecological meta-analysis.
313 *Ecology* 96, 2056–2063. <https://doi.org/10.1890/14-2402.1>

314 Li, H., Reynolds, J.F., 1993. A new contagion index to quantify spatial patterns of landscapes.
315 *Landscape Ecology* 8, 155–162. <https://doi.org/10.1007/BF00125347>

316 Lucas-Borja, M.E., 2021. Efficiency of postfire hillslope management strategies: Gaps of
317 knowledge. *Current Opinion in Environmental Science & Health* 21, 100247.
318 <https://doi.org/10.1016/j.coesh.2021.100247>

319 Lucas-Borja, M.E., Plaza-Álvarez, P.A., González-Romero, J., Miralles, I., Sagra, J., Molina-
320 Peña, E., Moya, D., de las Heras, J., Fernández, C., 2020. Post-wildfire straw mulching and
321 salvage logging affects initial pine seedling density and growth in two Mediterranean contrasting
322 climatic areas in Spain, *Forest Ecology and Management*, doi.org/10.1016/j.foreco.2020.118363.

323 Moody, J.A., Shakesby, R.A., Robichaud, P.R., Cannon, S.H., Martin, D.A., 2013. Current
324 research issues related to post-wildfire runoff and erosion processes. *Earth-Science Reviews* 122,
325 10–37.

326 Moreira, F., Ascoli, D., Safford, H., Adams, M.A., Moreno, J.M., Pereira, J.M., Catry, F.X.,
327 Armesto, J., Bond, W., González, M.E., 2020. Wildfire management in Mediterranean-type
328 regions: paradigm change needed. *Environmental Research Letters* 15, 011001.

329 O'Neill, R.V., Krummel, J.R., Gardner, R.H., Sugihara, G., Jackson, B., DeAngelis, D.L., Milne,
330 B.T., Turner, M.G., Zygmunt, B., Christensen, S.W., Dale, V.H., Graham, R.L., 1988. Indices of
331 landscape pattern. *Landscape Ecology* 1, 153–162. <https://doi.org/10.1007/BF00162741>

332 Pereira, P., Francos, M., Brevik, E.C., Ubeda, X., Bogunovic, I., 2018. Post-fire soil management.
333 *Current Opinion in Environmental Science & Health* 5, 26–32.
334 <https://doi.org/10.1016/j.coesh.2018.04.002>

335 Resco de Dios, V. 2020. Plant-Fire Interactions. In *Applying Ecophysiology to Wildfire*
336 *Management*; Springer: Cham, Switzerland.

337 Robichaud, P.R., 1998. Post-fire treatment effectiveness for hillslope stabilization. US
338 Department of Agriculture, Forest Service, Rocky Mountain Research Station.

339 San-Miguel-Ayanz, J., Durrant, T., Boca, R., Libertà, G., Branco, A., De Rigo, D., Ferrari, D.,
340 Maianti, P., Vivancos, T.A., Costa, H., 2017. Forest fires in Europe. *Middle East and North Africa*
341 10, 2017.

342 Shakesby, R.A., 2011. Post-wildfire soil erosion in the Mediterranean: review and future research
343 directions. *Earth-Science Reviews* 105, 71–100.

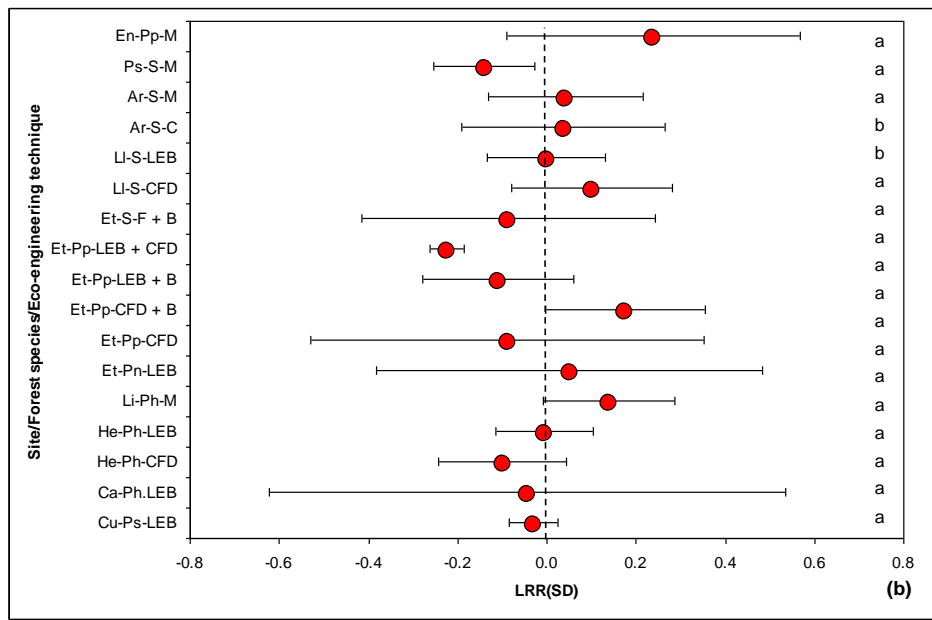
344 Valladares F, Rabasa SG, Benavides R, Díaz M, Pausas JG, Paula S, Simonson WD 2014.
345 Global change and Mediterranean forests: current impacts and potential responses. In: Coomes
346 DA, Burslem DFRP, Simonson WD (eds). *Forests and Global Change*. pp. 47-75. Cambridge
347 University Press

348 Zema, D.A., 2021. Postfire management impacts on soil hydrology. *Current Opinion in*
349 *Environmental Science & Health* 21, 100252. <https://doi.org/10.1016/j.coesh.2021.100252>

Graphical Abstract



Limited contribution of post-fire eco-engineering techniques to support post-fire plant diversity



(b)

Highlights

- Effects of post-fire management actions on vegetation diversity should be experimented
- Mulching is able to restore post-fire specific site vegetal diversity
- Log erosion barriers, chipping and felling were not successful in supporting plant diversity

1 **SHORT COMMUNICATION**

2

3 **Limited contribution of post-fire eco-engineering techniques to support post-fire** 4 **plant diversity**

5

6 **Abstract**

7 Eco-engineering techniques are generally effective at reducing soil erosion and restore
8 vegetal cover after wildfire. However, less evidence exists on the effects of the post-fire
9 eco-engineering techniques to restore plant diversity. To fill this knowledge gap, a
10 standardized regional-scale analysis of the influence of post-fire eco-engineering
11 techniques (log erosion barriers, contour felled log debris, mulching, chipping and felling,
12 in some cases with burning) on species richness and diversity is proposed, adopting the
13 Iberian Peninsula as case study. In general, no significant differences in species richness
14 and diversity (Shannon) were found between the forest treated with different post-fire
15 eco-engineering techniques, and the burned and non-treated soils. Only small significant
16 differences were found for some sites treated with log erosion barriers or mulching. The
17 latter technique increased species richness and diversity in some pine species and
18 shrublands. Contour felled log debris with burning slightly increased vegetation diversity,
19 while log erosion barriers, chipping and felling were not successful in supporting plant
20 diversity. This research will help forest managers and agents in Mediterranean forest to
21 decide the best postfire management option for wildfire affected forest, and in the
22 development of more effective post-fire strategies.

23

24 **Keywords:** wildfire; species richness; species diversity; log erosion barriers; contour
25 felled log debris; mulching.

26

27 **1. Introduction**

28 Forest ecosystems that are affected by wildfires undergo noticeable changes in soil
29 properties, and vegetation cover and biodiversity. Due to these changes, post-fire high-
30 intensity storms expose forest soil to erosion and consequent degradation (Pereira et al.,
31 2018; Fernández and Vega, 2016; Morán-Ordóñez et al., 2020). To contrast these
32 degradation factors, millions of euros are currently being spent in short-term post-fire
33 management actions (Lucas-Borja, 2021). Many of these actions are eco-engineering
34 techniques designed to support economic sustainability and environmental compatibility

35 including mulching, and the construction of log erosion barriers or contour felled log
36 debris (Lucas-Borja, 2021; Zema, 2021). Post-fire eco-engineering techniques are
37 conducted within one year of a fire to stabilize the burned soil, protect public health and
38 infrastructures, and reduce the risk of additional damage to valued forest ecosystems
39 (Robichaud et al., 2010; Vega et al., 2018). These techniques control the soil's
40 hydrological response and, at the same time, enhance recovery of soil properties and
41 restoration of plant cover and biomass to the pre-fire levels. Much less is known, however,
42 on the capacity of post-fire eco-engineering techniques to support the restoration of plant
43 diversity. For example, by trapping seeds or generating higher soil moisture nearby eco-
44 engineering techniques, postfire management structures may change seeder-to-resprouter
45 and woody-to-nonwoody species ratios, which alters forest structure after wildfires
46 (Gómez-Sánchez et al., 2019). Moreover, current knowledge, based on local surveys, on
47 the effectiveness of post-fire eco-engineering techniques is highly variable, and depends
48 on the wildfire severity and characteristics of forest ecosystems (topography, rainfall
49 characteristics and plant composition) (Badía et al., 2015; Robichaud, 1998; Girona-
50 García et al. 2021).

51

52 Although several studies have evaluated the effects of several post-fire eco-engineering
53 techniques on soil hydrology and vegetation cover (Morgan et al., 2014; Gómez-Sánchez
54 et al., 2019; Fernández et al., 2019), less information is available on how vegetation
55 diversity responds after the installation of eco-engineering materials and structures. In
56 other words, while the increase in vegetation cover is expected after post-fire management
57 actions, the knowledge on how and to what extent the eco-engineering techniques drive
58 richness and plant diversity is very limited. This is an essential concern in the
59 Mediterranean forest ecosystems, which are considered a global hotspot of biodiversity
60 and are threatened by a severe risk of wildfire and often affected by high erosion rates
61 (Moody et al., 2013; Shakesby, 2011). In these environmental contexts, these risks may
62 be aggravated by the expected scenarios of climate change (Collins et al., 2013), which
63 forecast a directional loss in water-limited climates of plant community diversity at
64 multiple levels of organization (Harrison et al., 2020). Learning more about how post-fire
65 eco-engineering techniques influence plant diversity is further essential to support the
66 myriad of ecosystem functions and services supported by biodiversity.

67

68 To fill this gap of knowledge, a standardized regional-scale database about the influence
69 of post-fire eco-engineering techniques on plant diversity was collected. The effects of a
70 set of five techniques (log erosion barriers, contour felled log debris, mulching, chipping
71 and felling, in some cases with burning) on species richness and diversity are evaluated
72 in nine forest sites that were affected by wildfire in Spain. This country together with
73 Greece, France, Italy, and Portugal constitute over 85% of the most vulnerable areas to
74 fire in Europe, and belong to the Mediterranean Basin that is largely threatened by
75 extreme wildfires (Moreira et al., 2020) (San-Miguel-Ayanz et al., 2017). To the authors'
76 best knowledge, this is the first comprehensive study that has analyzed the effect of a
77 broad set of post-fire management techniques on vegetation diversity of a wildfire-prone
78 forest area, such as the Iberian Peninsula. We hypothesize that all the analyzed eco-
79 engineering techniques modify plant diversity in wildfire-affected areas in comparison to
80 non-treated areas under the Mediterranean climate. However, the influence of each
81 technique on plant diversity might be site-dependent, that is, it should be influenced by
82 the forest type and ecosystem properties. This study aims to advance our knowledge on
83 how plant diversity responds to the most common post-fire management strategies,
84 considering the variability of climate, soil, and forest species.

85

86 **2. Material and methods**

87

88 *2.1. Study areas and experimental sites*

89 This study has been carried out in nine wildfire-affected forest sites of six Spanish
90 provinces, both in the North-western (under oceanic temperate climate) and South-
91 Eastern (under dry sub-humid and semi-arid climates) zones of this country (Fig. 1). Table
92 1 reports the main climatic, morphological and plant characteristics of these forest sites.
93 Different eco-engineering techniques have been immediately applied in the subsequent
94 months after fire at each experimental site (Table 1). The experimental areas used in this
95 work are representative of forest areas that have burned and are actively managed in Spain. Some
96 of the most frequent restoration strategies at the hillslope scale include log erosion barriers (LEB),
97 contour-felled log debris (CFD) and mulching (MG). A LEB consists of felling and laying burned
98 trees on the ground along the slope contour to stop the overland flow and sediment delivery. With
99 the same objective as that of a LEB, CFD entails felling and laying branches and burned canopy
100 trees along the slope contour. Both LEB and CFD are designed to slow runoff; store eroded
101 sediment; and increase water infiltration, all of which may favor plant cover and diversity

102 recovery after fire. Mulching consists of dispersing on the soil surface organic and inorganic
103 materials as an alternative surface cover, such as agricultural straw, plant leaves, plastic film,
104 logging slash, shredded barks, wood strands, chips, and shreds, as well as gravel and loose soil.
105 Among the different mulch materials, vegetal residues are considered the most effective at
106 reducing the soil hydrological responses. In general, organic residues, such as straw and wood
107 residues, are preferred to other mulch materials, due to its wide availability, high soil covering
108 capacity, low cost and ease-of-handling.

109

110 *2.2. Evaluation of richness and plant diversity*

111 In each site and for each combination of post-fire eco-engineering techniques and main
112 forest species depicted in Table 1, the species richness (hereafter indicated as “SR”) and
113 diversity (“SD”) were evaluated five years (Hellín), three years (El Tranco, Calderona and
114 Porto do Son), and two years (Arbo, Entrimo, Cualedro and Liétor and Llutxent) after the
115 wildfires. In more detail, SR was the number of species identified in each plot, while SD
116 was calculated using the well-known Shannon index. The species richness and relative
117 abundance have been quantified by the α -diversity index (H_α) proposed by Hill (1973),
118 which utilizes Rényi’s function (Li and Reynolds, 1993; O’Neill et al., 1988):

$$119 \quad SD = -\sum_{i=1}^S p_i \ln p_i . \quad (1)$$

120 where:

121 - $p_i = \frac{n_i}{N}$ = frequency of “ n_i ” plants belonging to the species “ i ” with respect to the total

122 number of plants “ N ” in the plot;

123 - S = number of species in each plot.

124

125 The sampling design in each site was replicated between control and treatment plots and
126 was performed to keep balanced and representative measures across studied sites. We
127 have simply used the burned and non-action areas as the baseline of the natural plant
128 diversity since the area was not disturbed by postfire management. For each site, an effect
129 size for the contrast between each eco-engineering technique and the burned site without
130 any post-fire action was calculated for both SR and SD. This effect size was estimated as
131 the natural logarithm (\ln) of the response ratio (RR, (Curtis and Wang, 1998; Hedges et
132 al., 1999)) - hereafter “log response ratio” or “ $\ln RR$ ” - using the following equation:

$$\ln RR = \frac{x_T}{x_{BNA}} \quad (2)$$

where x_T is the mean value of the response variable measured in the plot subjected to the eco-engineering technique “T” and x_{BNA} is the corresponding value measured in the burned plot without any post-fire action (burned and no action, BNA). Therefore, in our study, two lnRRs were calculated, namely “lnRR(SR)”, which is the log response ratio of the species richness, and the “lnRR(SD)”, which is the log response ratio of the species diversity.

A negative lnRR of a technique T is a SR or SD that is lower compared to the SR or SD of a burned and non-treated area, while, if lnRR is positive, the SR or SD is higher than in the BNA plot (Eldridge and Delgado-Baquerizo, 2017). This approach allowed a standardized analysis of data from different sites and after sampling by different methods (Lajeunesse, 2015). Moreover, the 95%-confidence interval (CI_{95}) of both lnRR was calculated, in order to evaluate the significance of the effect of a technique. If the extremes of the CI_{95} are both positive and negative, the lnRR is significant, otherwise (that is, if both these extremes are positive or negative), it is not significant. Finally, in order to quantify the increase or decrease in SR and SD due to the eco-engineering technique compared to the BNA area, the percent variation of each effect evaluated in the treated plot was evaluated.

2.3. Statistical analyses

First, linear correlations between LnRR(SR) and LnRR(SD) on one side and some key factors of the nine sites on the other side (total annual precipitation, mean annual temperature, Aridity Index (mean annual precipitation / potential evapotranspiration), and soil slope and altitude) were investigated. To this aim, the values of the LnRR indexes were averaged among the different post-fire management strategies. Then, a one-way ANOVA was applied to the SR and SD (response variables) separately for each site (except El Tranco site), assuming as factor the soil condition (the different technique and the burned and non-treated area), the latter considered as independent factors. In El Tranco site, where different forest species and eco-engineering techniques were investigated and considered as independent factors, a 2-way ANOVA was applied. The pairwise comparison by Tukey’s test (at $p < 0.05$) was also used to evaluate the statistical significance of the differences in the response variables. In order to satisfy the

166 assumptions of the statistical tests (equality of variance and normal distribution), the data
167 were subjected to normality test or were square root-transformed whenever necessary.
168 All the statistical tests were carried out by with the XLSTAT software.

169

170 **3. Results**

171 In general, we did not find a significant effect of post-fire eco-engineering techniques on
172 plant diversity (Fig. 1). According to ANOVA, the differences in SR and SD among the
173 investigated post-fire techniques and the BNA soils were never significant ($p < 0.05$) with
174 some exceptions. These differences were significant ($p < 0.05$) only for SR in the forest
175 of *P. halepensis* subjected to LEBs (Hellin), and for both SR and SD in the forest of *P.*
176 *halepensis* (Liétor) and in *P. pinaster* stands (Entrimo), both subjected to soil mulching.
177 Moreover, low and non-significant linear correlations ($r^2 < 0.05$) were found between the
178 mean values of LnRR(SR) and LnRR(SD), considered as dependent variables, and total
179 annual precipitation, mean annual temperature, Aridity Index, and soil slope and altitude,
180 as independent variables (data not shown).

181

182 Only the influence of soil mulching on plant diversity after wildfire was evident (Table
183 1SM). This evidence is shown by the positive LnRRs of both SR and SD in three (Arbo,
184 Liétor and Entrimo) of the four burned forests treated with mulching, although the
185 differences compared to BNA sites were significant in two sites (Liétor and Entrimo)
186 (Figures 2a and 2b). In these three sites, LnRRs(SR) and LnRR(SD) were in the range
187 0.10 (shrubland of Arbo) to 0.41 (forest of *P. halepensis* in Liétor) and 0.04 (shrubland
188 of Arbo) to 0.24 (forest of *P. pinaster* in Entrimo), respectively. In contrast, both LnRRs
189 were negative (-0.18, LnRR(SR), and -0.14, LnRR(SD) in the shrubland of Porto do Son
190 (Figures 2a and 2b). Mulching increased SR by 10.3% (shrubland of Arbo) to 51.3% in
191 the forest of *P. halepensis* in Liétor, and SD by 4.3% (shrubland of Arbo) to 26.9% (*P.*
192 *pinaster* in Entrimo). In contrast, these characteristics decreased by 16.2% (SR) and
193 13.1% (SD) in shrubland of Arbo (Figures 3a and 3b).

194

195 CFD treatments played positive effects on vegetation diversity in the forest of *P. pinaster*
196 of El Tranco and on the shrubland in Llutxent. In more detail, CFD with burning gave
197 LnRR(SR) and LnRR(SD) over 0.18 in *P. pinaster* of El Tranco, while only LnRR(SR)
198 was positive (0.10) after CFD without burning in the same site; in the shrubland of
199 Llutxent, LnRR(SR) was 0.20 and LnRR(SD) was 0.10. In contrast, both LnRR(SR)

200 (equal to -0.06) and LnRR(SD) (-0.22) were negative, when CFD was combined with
201 LEB (*P. pinaster* in El Tranco). Overall, the CFD treatment increased SR and SD up to
202 26.1%, both estimated in the forest of *P. pinaster* in El Tranco under CFD + B treatment
203 (Figures 3a and 3b).

204

205 Positive effects on vegetation diversity - LnRR(SR) or LnRR(SD) > 0 - were also
206 estimated for chipping treatment in Arbo (0.05 and 0.04, respectively) and felling and
207 burning in El Tranco (the latter only for LnRR (SR)) (Figures 2a and 2b). In these sites,
208 maximum increases in SR and SD by 5.4% (SR) and 3.8% (SD) were estimated
209 (shrubland of Arbo subjected to chipping), while the increase in SR measured under the
210 treatment of felling and burning was 0.4% (Figures 3a and 3b).

211

212 Conversely, all the other post-fire eco-engineering techniques played negative effects on
213 vegetal diversity, as showed by the negative values of LnRR(SR) and LnRR(SD). In the
214 case of LEB, both these indexes were negative (with a minimum of -0.14 detected for
215 LnRR(SR) in shrubland of Lutxent) in all sites, also when this post-fire action was
216 implemented in combination with other eco-engineering techniques (Figures 2a and 2b).
217 The maximum decreases in SR and SD were detected under CFD treatment (-17.6%,
218 forest of *P. halepensis* in Hellin) and under combined treatments of LEB and CFD (-
219 20.1%, forest of *P. pinaster* in El Tranco) (Figures 3a and 3b).

220

221 **4. Discussion and conclusion**

222

223 This standardized field study, carried out at the regional scale in the Iberian Peninsula,
224 provides evidence that the analyzed post-fire eco-engineering techniques have a very
225 limited influence on plant diversity. Thus, no significant differences in species richness
226 and diversity were, in general, found between the forest soils treated with each post-fire
227 eco-engineering technique, and the burned and non-treated sites. These differences were
228 only noticeable and thus significant in some sites treated with log erosion barriers or
229 mulching. The latter technique increased species richness and diversity in forests of *P.*
230 *halepensis* and *P. pinaster*, and shrublands. These results are in partial accordance with
231 Morgan et al. (2014) and Jonas et al. (2019), who observed higher species richness as we
232 did, but did not find any differences in species diversity in response to the mulching
233 treatments. Contour felled log debris with burning slightly increased vegetal diversity,

234 while log erosion barriers, chipping and felling were not successful for this effect. Our
235 findings suggest that the current post-fire eco-engineering techniques on plant diversity
236 are not efficient, and that new strategies might be needed.

237

238 Direct and indirect effects of fire on soils and plants can be critical for the functioning of
239 forest ecosystems and alter the capacity of biodiversity to support multiple ecosystem
240 functions from carbon sequestration to fibre production. Thus, promoting post-fire
241 recovery of forests is fundamental for an adequate management and planning of these
242 ecosystems (Lucas-Borja, 2021). In this case, scientific literature has widely
243 demonstrated that some Mediterranean species are able to regenerate through different
244 post-fire strategies, including resprouting, serotiny, soil seed banks or wind seed
245 dispersion into a fire- affected site (Valladares et al., 2014, Resco 2021). The short-term
246 period evaluated in this research and the good adaptation of the surveyed vegetation to
247 fire indicate that a post-fire emergence treatment should not be targeted to biodiversity
248 recovery in wildfire-affected areas, since no influence was found on plant diversity. Even
249 so, longer-term monitoring is needed to provide further evidence on the importance of
250 post-fire eco-engineering techniques, in order to support plant diversity in a context of
251 climate change and land use intensification.

252

253 The only significant strategy was related to straw mulching in semi-arid locations. As
254 Wright and Rocca (2017) have indicated, mulch-retained moisture may benefit natural
255 pine regeneration in water-stressed environments, whereas deep mulch applications may
256 inhibit the establishment of natural regeneration by acting as a physical barrier to seed
257 emergence. This suggests that mulch acts as a retainer for soil nutrients and moisture
258 which may act as limiting factors for seedling growth in water-stressed environments. In
259 fact, Bontrager et al. (2019) found that increased mulch suppressed pine recovery at
260 higher altitudes and in northern aspects than in southern aspects with less precipitation
261 and higher temperature. In contrast, Lucas-Borja et al. (2020) demonstrated that mulching
262 had no detrimental effects on the short-term initial vegetation recovery in sub-humid sites.
263 In addition, the same authors found that leaving the burned trees standing seemed not to
264 be a feasible management option for enhancing vegetation recovery in northern Spain.
265 Mulching seemed to influence neither the natural availability of nutrients nor moisture.

266

267 Overall, this research has demonstrated that, on a broad scale, soil mulching is generally
268 able to restore post-fire vegetal diversity regardless of the specific site conditions.
269 Conversely, other eco-engineering techniques must be implemented with caution since
270 these post-fire actions may even decrease the vegetation diversity of severely burned
271 forest ecosystems.. These measures play beneficial effects in reducing the runoff and
272 erosion rates, in contrasting the soil degradation and supporting vegetation recovery, but
273 no result is seen in the recovery of diversity or species richness. The effects of plant and
274 soil restoration strategies on burned forests need to be effectively outlined with the aim
275 to generate a scientific basis for post-fire management guidelines and properly restore
276 wildfire affected forest ecosystems.

277

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284

285 **List of symbols/nomenclature**

Post-fire eco-engineering techniques

BNA	Burned and No Action
CFD	Contour Felled Log Debris
LEB	Log Erosion Barriers
M	Mulching
C	Chipping
CFD + B	Contour Felled Log Debris + Burning
LEB + CFD	Log Erosion Barriers + Contour Felled Log Debris
LEB + B	Log Erosion Barriers + Burning
F + B	Felling + Burning

Investigated sites

Cu	Cualedro
Ca	Calderona
He	Hellín
Li	Liétor
Ja	Jaén
Ll	Llutxent
Ar	Arbo
Ps	Porto do Son
En	Entrimo

Main forest species

Ps	<i>P. sylvestris</i>
Ph	<i>P. halepensis</i>
Pn	<i>P. nigra</i>
Pp	<i>P. pinaster</i>
S	<i>Shrubland</i>

286

287 **Supplementary material**

288 List of plant species at each site.

289

290 **References**

291 Badía, D., Sánchez, C., Aznar, J.M., Martí, C., 2015. Post-fire hillslope log debris dams for runoff
292 and erosion mitigation in the semiarid Ebro Basin. *Geoderma* 237, 298–307.
293 <https://doi.org/10.1016/j.geoderma.2014.09.004>

294 Bontrager, J.D., Morgan, P., Hudak, A.T., Robichaud, P.R., 2019. Long-term vegetation response
295 following post-fire straw mulching. *Fire Ecol.* <https://doi.org/10.1186/s42408-019-0037-9>

296 Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X.,
297 Gutowski, W.J., Johns, T., Krinner, G., 2013. Long-term climate change: projections,
298 commitments and irreversibility, in: *Climate Change 2013-The Physical Science Basis:*
299 *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel*
300 *on Climate Change.* Cambridge University Press, pp. 1029–1136.

301 Curtis, P.S., Wang, X., 1998. A meta-analysis of elevated CO₂ effects on woody plant mass, form,
302 and physiology. *Oecologia* 113, 299–313. <https://doi.org/10.1007/s004420050381>

303 Eldridge, D.J., Delgado-Baquerizo, M., 2017. Continental-scale Impacts of Livestock Grazing on
304 Ecosystem Supporting and Regulating Services. *Land Degradation and Development* 28, 1473–
305 1481. <https://doi.org/10.1002/ldr.2668>

306 Harrison, S., Spasojevic, M.J., Li, D., 2020. Climate and plant community diversity in space and
307 time. *Proceedings of the National Academy of Sciences*, 117 (9) 4464-4470; DOI:
308 10.1073/pnas.1921724117

309 Hedges, L.V., Gurevitch, J., Curtis, P.S., 1999. The meta-analysis of response ratios in
310 experimental ecology. *Ecology* 80, 1150–1156. [https://doi.org/10.1890/0012-9658\(1999\)080\[1150:TMAORR\]2.0.CO;2](https://doi.org/10.1890/0012-9658(1999)080[1150:TMAORR]2.0.CO;2)

312 Lajeunesse, M.J., 2015. Bias and correction for the log response ratio in ecological meta-analysis.
313 *Ecology* 96, 2056–2063. <https://doi.org/10.1890/14-2402.1>

314 Li, H., Reynolds, J.F., 1993. A new contagion index to quantify spatial patterns of landscapes.
315 *Landscape Ecology* 8, 155–162. <https://doi.org/10.1007/BF00125347>

316 Lucas-Borja, M.E., 2021. Efficiency of postfire hillslope management strategies: Gaps of
317 knowledge. *Current Opinion in Environmental Science & Health* 21, 100247.
318 <https://doi.org/10.1016/j.coesh.2021.100247>

319 Lucas-Borja, M.E., Plaza-Álvarez, P.A., González-Romero, J., Miralles, I., Sagra, J., Molina-
320 Peña, E., Moya, D., de las Heras, J., Fernández, C., 2020. Post-wildfire straw mulching and
321 salvage logging affects initial pine seedling density and growth in two Mediterranean contrasting
322 climatic areas in Spain, *Forest Ecology and Management*, doi.org/10.1016/j.foreco.2020.118363.

323 Moody, J.A., Shakesby, R.A., Robichaud, P.R., Cannon, S.H., Martin, D.A., 2013. Current
324 research issues related to post-wildfire runoff and erosion processes. *Earth-Science Reviews* 122,
325 10–37.

326 Moreira, F., Ascoli, D., Safford, H., Adams, M.A., Moreno, J.M., Pereira, J.M., Catry, F.X.,
327 Armesto, J., Bond, W., González, M.E., 2020. Wildfire management in Mediterranean-type
328 regions: paradigm change needed. *Environmental Research Letters* 15, 011001.

329 O'Neill, R.V., Krummel, J.R., Gardner, R.H., Sugihara, G., Jackson, B., DeAngelis, D.L., Milne,
330 B.T., Turner, M.G., Zygmunt, B., Christensen, S.W., Dale, V.H., Graham, R.L., 1988. Indices of
331 landscape pattern. *Landscape Ecology* 1, 153–162. <https://doi.org/10.1007/BF00162741>

332 Pereira, P., Francos, M., Brevik, E.C., Ubeda, X., Bogunovic, I., 2018. Post-fire soil management.
333 *Current Opinion in Environmental Science & Health* 5, 26–32.
334 <https://doi.org/10.1016/j.coesh.2018.04.002>

335 Resco de Dios, V. 2020. Plant-Fire Interactions. In *Applying Ecophysiology to Wildfire*
336 *Management*; Springer: Cham, Switzerland.

337 Robichaud, P.R., 1998. Post-fire treatment effectiveness for hillslope stabilization. US
338 Department of Agriculture, Forest Service, Rocky Mountain Research Station.

339 San-Miguel-Ayanz, J., Durrant, T., Boca, R., Libertà, G., Branco, A., De Rigo, D., Ferrari, D.,
340 Maianti, P., Vivancos, T.A., Costa, H., 2017. Forest fires in Europe. *Middle East and North Africa*
341 10, 2017.

342 Shakesby, R.A., 2011. Post-wildfire soil erosion in the Mediterranean: review and future research
343 directions. *Earth-Science Reviews* 105, 71–100.

344 Valladares F, Rabasa SG, Benavides R, Díaz M, Pausas JG, Paula S, Simonson WD 2014.
345 Global change and Mediterranean forests: current impacts and potential responses. In: Coomes
346 DA, Burslem DFRP, Simonson WD (eds). *Forests and Global Change*. pp. 47-75. Cambridge
347 University Press

348 Zema, D.A., 2021. Postfire management impacts on soil hydrology. *Current Opinion in*
349 *Environmental Science & Health* 21, 100252. <https://doi.org/10.1016/j.coesh.2021.100252>

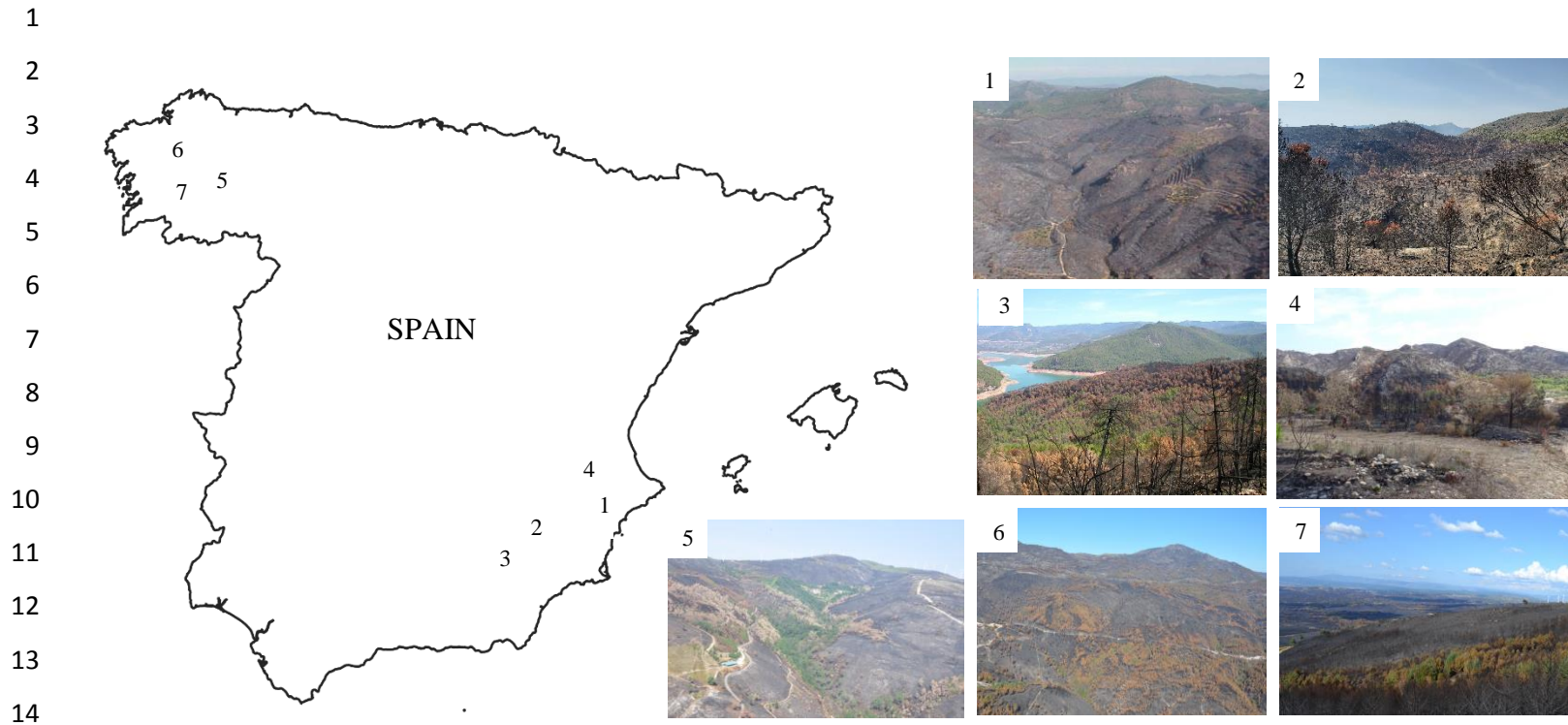
1 SUPPLEMENTARY MATERIAL

2 Table 1 - Characteristics of the experimental sites surveyed on this research.

Study area	Forest site	Number of plots	Climate type ⁽¹⁾	Mean annual temperature (°C)	Mean annual precipitation (mm)	Elevation (m a.s.l.)	Slope (%)	Soil type	Main forest species	Fire severity - date	Post-fire eco-engineering technique
(1) Valencia	Calderona	24	BSk	16.6	400	250 - 332	15-30	Acidic sandstones	<i>Pinus halepensis</i>	High - August 2004	CFD
(2) Albacete	Hellín	36	BSk	16.6	321	520 - 770	15-30	Calcic Aridisols	<i>Pinus halepensis</i>	High - July 2012	CFD LEB
	Liétor	18					15-30		<i>Pinus halepensis</i>	High - July 2016	M ⁽⁶⁾
(3) Jaén	El Tranco	7	Csa	10.6	882	796 - 1532	15-40	Limestones and dolomites	<i>Pinus nigra</i>	High - August 2005	LEB
		32							<i>Pinus pinaster</i>		CFD + B LEB + B LEB + CFD
		19							Shrubland ⁽²⁾		F + B
(4) Valencia	Llutxent	16	Csa	16.6	660	650	5-50	Limestones	<i>Quercus suber</i> , <i>Pinus pinaster</i> and shrubland ⁽³⁾	High - August 2018	CFD LEB
(5) Pontevedra	Arbo	30	Csb	14.6	1600	550	30-50	Umbric Regosols	Shrubland ⁽⁴⁾	High - August 2016	C M ⁽⁷⁾
(6) A Coruña	Porto do Son	19	Csb	14.6	1300	200	30-50	Humic Regosols	Shrubland ⁽⁵⁾	High - August 2016	M ⁽⁸⁾
(7) Ourense	Entrimo	8	Csb	13	1400	550	30-50	Humic Regosols	<i>P. pinaster</i>	High - September 2016	M ⁽⁹⁾
	Cualedro	8		10.6	860	800	30-50		<i>P. sylvestris</i>	High - August 2015	LEB

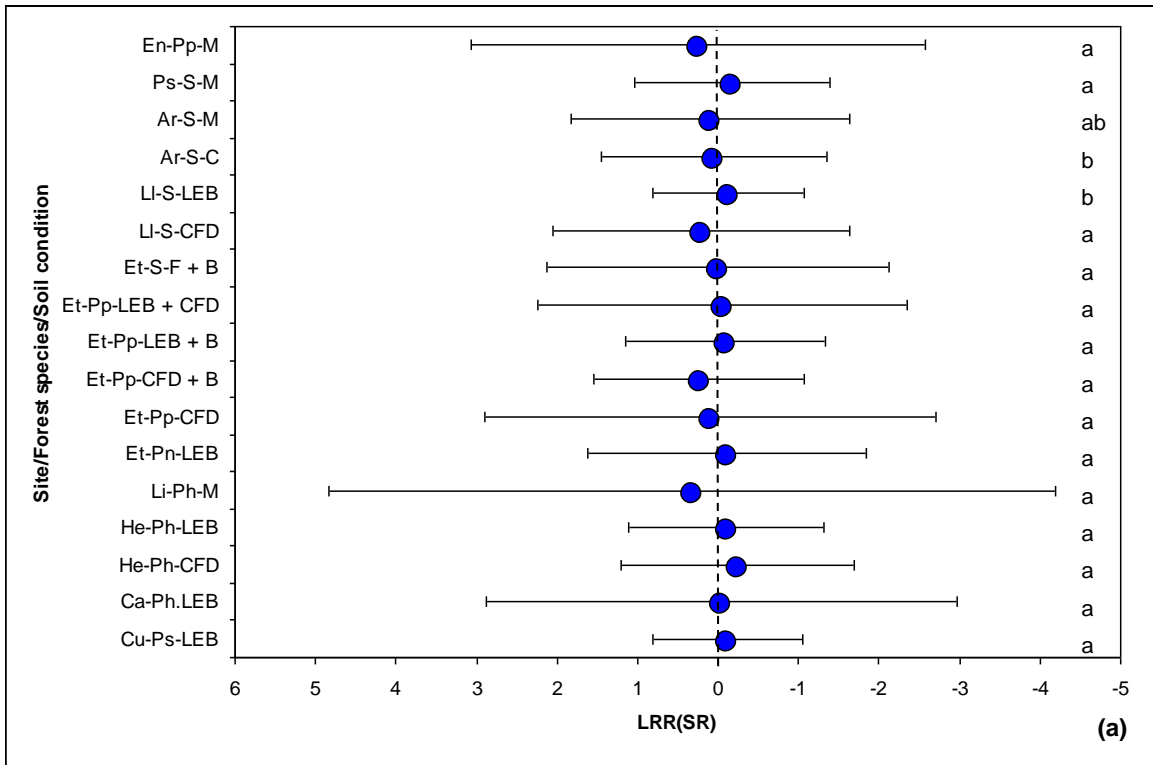
3 Notes: (1) according to Köppen classification (Kottek et al., 2006); (2) *Quercus coccifera*, *Pistacia lentiscus*, *Pistacia terebinthus*, *Juniperus oxycedrus*, *Daphne gnidium*, *Ulex*
4 *parviflorus*, *Berberis hispanica*, and *Rosmarinus officinalis*; (3) *Pistacia lentiscus*, *Anthyllis cytisoides*, *Erica multiflora*, *Chamaerops humilis*, *Ulex parviflorus*, *Arbutus unedo*,
5 *Quercus coccifera*, and *Cistus* sp.; (4) *Ulex europaeus* L., *Erica cinerea* L., and *Pterospartum tridentatum* (L.) Willk; (5) *Ulex europaeus* L. and *Erica cinerea* L.; (6) 0.2 kg

6 m² of wheat straw, dry weight, applied by hand; (7) 3.0-3.5 Mg ha⁻¹ of wheat straw applied by helicopter, and 11.5 Mg ha⁻¹ of wood strands applied by hand; (8) 3.5-4.0 Mg ha⁻¹
7 of wheat straw applied by helicopter; (9) 3.0 Mg ha⁻¹ of wheat straw applied by helicopter. LEB: log erosion barriers, CFD: contour felled log debris, M: mulching, F: chipping
8 and felling, B: burning.



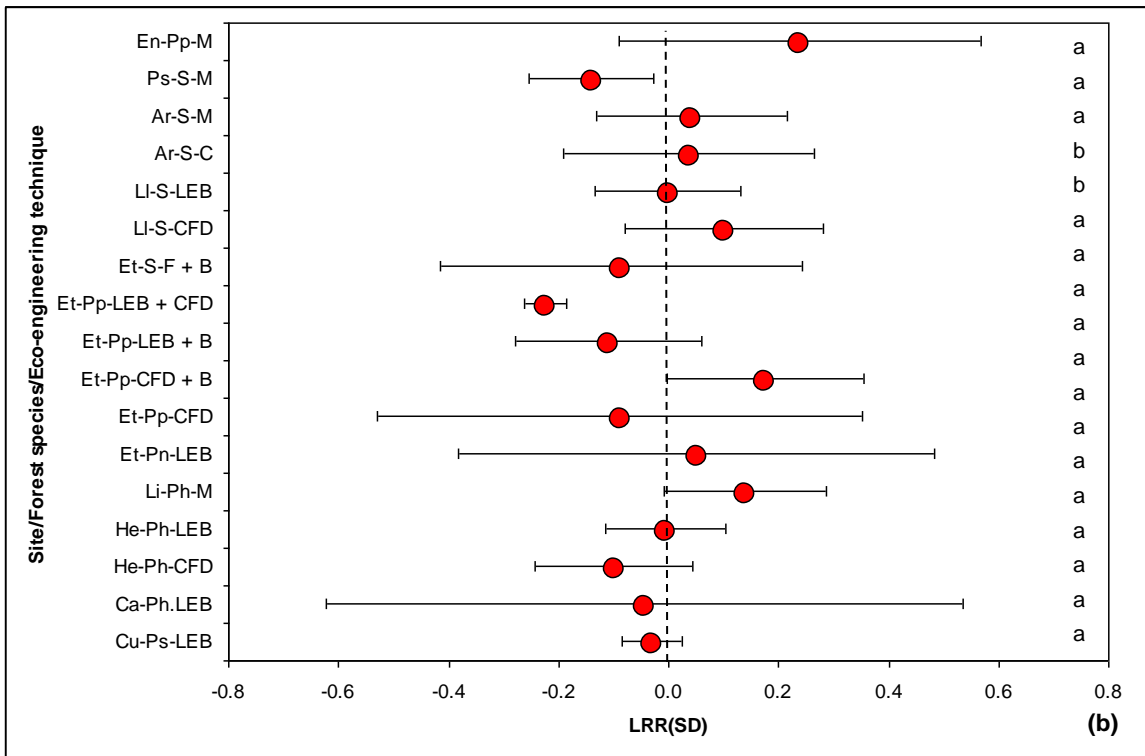
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Figure 1 - Geographical location of the experimental sites: 1: Valencia (Calderona), 2: Albacete, 3: Jaén, 4: Valencia (Llutxent), 5: Pontevedra. 6: A Coruña, 7: Ourense.



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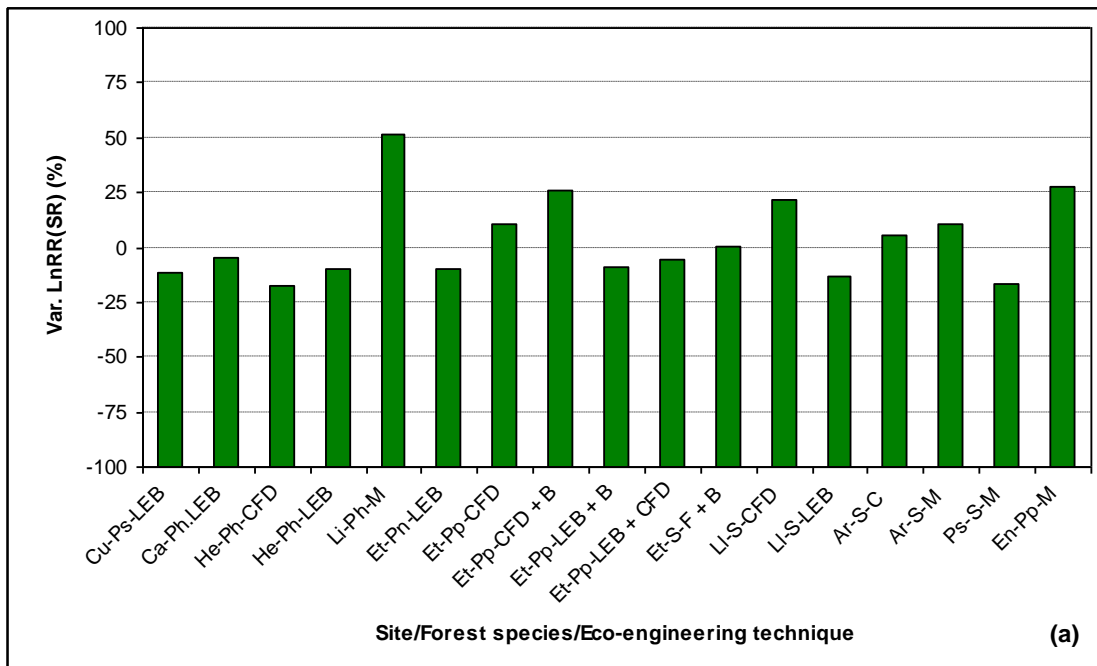
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Figure 2 - Log Response Ratio (LRR, mean and confidence interval) of species richness (SR, a) and species diversity (SD, b) evaluated in nine forest sites of South-Eastern and North-Western Spain under different post-fire eco-engineering techniques. *The first group of two letters indicates the site, the second group the forest species, and the third*

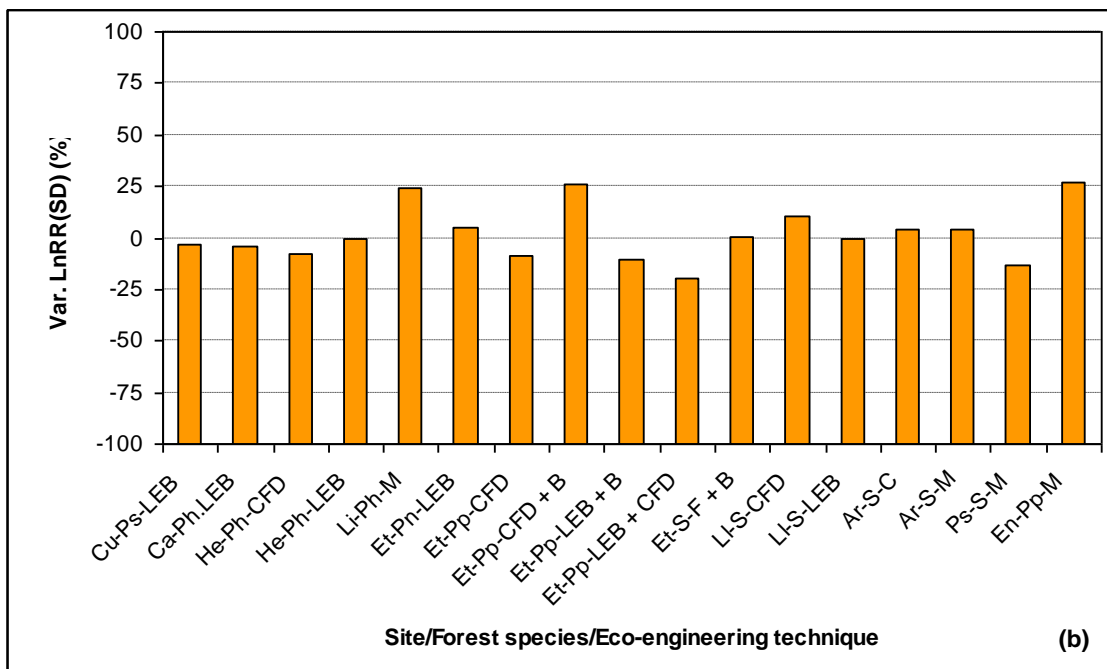
27 group the eco-engineering technique (for instance, Cu-Ps-LEB indicates the Cualedro
28 site (Cu) - Pinus sylvestris (Ps) - Log Erosion Barriers (LEB)). See the nomenclature
29 for the symbol meaning. The letters on the right side of the charts indicate significant
30 differences between the unburned, and the burned and treated sites.

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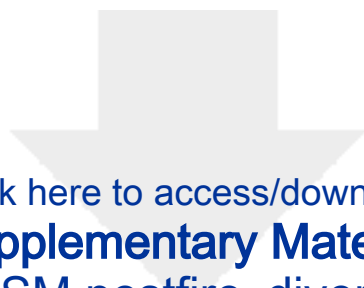
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35 Figure 3 - Variability of Log Response Ratio (LnRR, in comparison to the unburned
 36 forest) of species richness (SR, a) and species diversity (SD, b) evaluated in nine forest
 37 sites of South-Eastern and North-Western Spain under different post-fire eco-
 38 engineering techniques. *The first group of two letters indicates the site, the second*
 39 *group the forest species, and the third group the eco-engineering technique (for*
 40 *instance, Cu-Ps-LEB indicates the Cualedro site (Cu) - Pinus sylvestris (Ps) - Log*
 41 *Erosion Barriers (LEB)). See the nomenclature for the symbol meaning. The letters on*

- 42 *the right side of the charts indicate significant differences between the unburned, and*
43 *the burned and treated sites.*



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Supplementary Material

[Lucas Borja et al SM postfire_diversity_Final_R1.doc](#)



Declaration of interest statement

No conflict of interest exists in the submission of this manuscript, and manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part.

Yours sincerely

Manuel Esteban Lucas-Borja

(On behalf of co-authors)

Author contribution statements

Manuel Esteban Lucas-Borja, Rocío Soria, Isabel Miralles, Victor M. Santana, Javier Pérez-Romero, Cristina Fernandez, Antonio D. del Campo: Data collection.

Manuel Esteban Lucas-Borja, Manuel Delgado-Baquerizo, Demetrio A. Zema: Data processing, and article writing

Manuel Esteban Lucas-Borja, Cristina Fernandez, Rocío Soria, Isabel Miralles, Victor M. Santana, Javier Pérez-Romero, Antonio D. del Campo, Isabel Miralles, Manuel Delgado-Baquerizo, Demetrio A. Zema: Article review