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Short Communication

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

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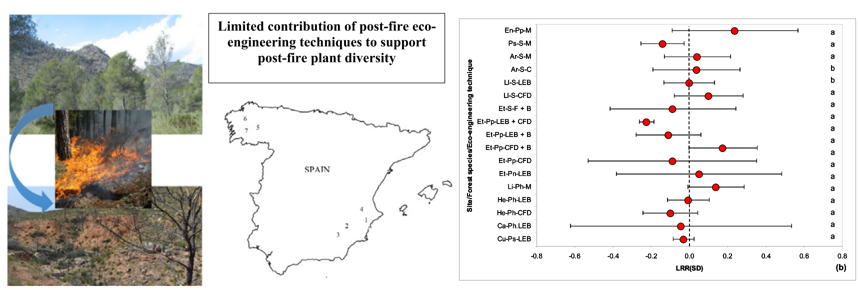
HIGHLIGHTS

- 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.

GRAPHICAL ABSTRACT



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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.

1. Introduction

Forest ecosystems that are affected by wildfires undergo noticeable changes in soil properties, and vegetation cover and biodiversity. Due to these changes, post-fire high-intensity storms expose forest soil to erosion

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and consequent degradation (Pereira et al., 2018; Fernández and Vega, 2016; Morán-Ordóñez et al., 2020). To contrast these degradation factors, millions of euros are currently being spent in short-term post-fire management actions (Lucas-Borja, 2021). Many of these actions are eco-engineering techniques designed to support economic sustainability and environmental compatibility including mulching, and the construction of log erosion barriers or contour felled log debris (Lucas-Borja, 2021; Zema, 2021). Post-fire eco-engineering techniques are conducted within one year of a fire to stabilize the burned soil, protect public health and infrastructures, and reduce the risk of additional damage to valued forest ecosystems (Robichaud et al., 2010; Vega et al., 2015). These techniques control the soil's hydrological response and, at the same time, enhance recovery of soil properties and restoration of plant cover and biomass to the pre-fire levels. Much less is known, however, on the capacity of post-fire eco-engineering techniques to support the restoration of plant diversity. For example, by trapping seeds or generating higher soil moisture nearby eco-engineering techniques, postfire management structures may change seeder-to-resprouter and woody-to-nonwoody species ratios, which alters forest structure after wildfires (Gómez-Sánchez et al., 2019). Moreover, current knowledge, based on local surveys, on the effectiveness of post-fire eco-engineering techniques is highly variable, and depends on the wildfire severity and characteristics of forest ecosystems (topography, rainfall characteristics and plant composition) (Badía et al., 2015; Robichaud, 1998; Girona-García et al., 2021).

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

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

2. Material and methods

2.1. Study areas and experimental sites

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

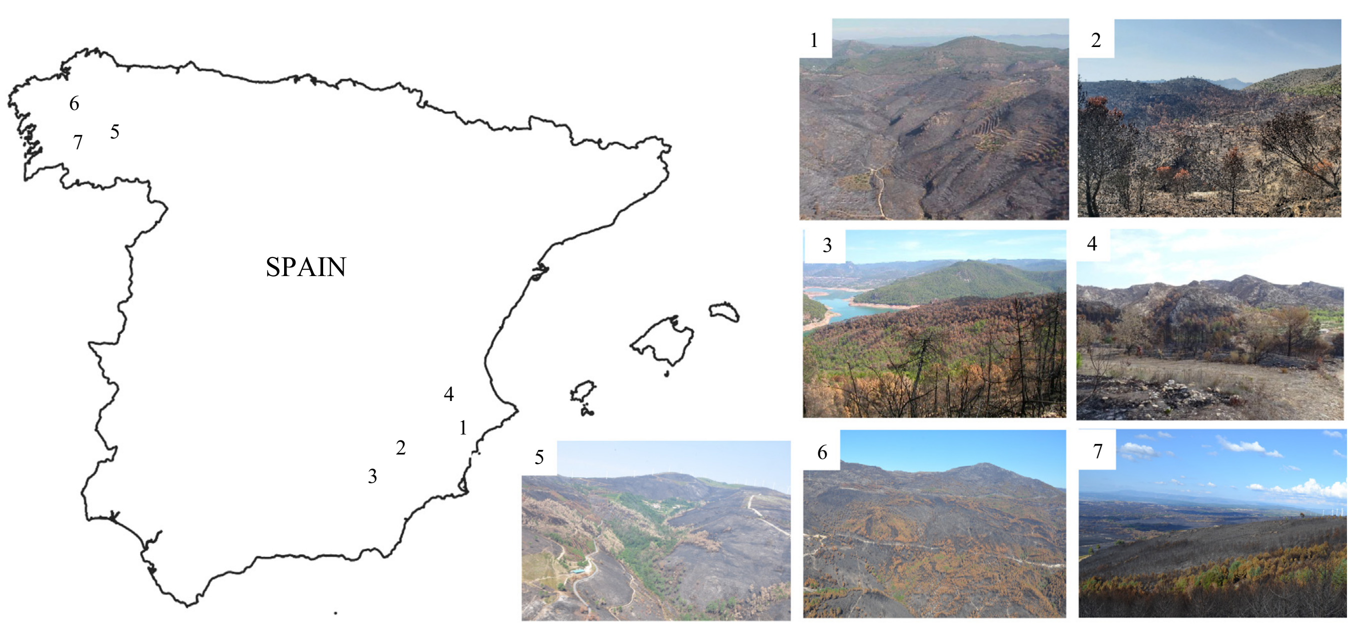


Fig. 1. Geographical location of the experimental sites: 1: Valencia (Calderona), 2: Albacete, 3: Jaén, 4: Valencia (Llutxent), 5: Pontevedra. 6: A Coruña, 7: Ourense.

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

Study area	Forest site	Number of plots	Climate type[a]	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	*Pinus halepensis*	High - August 2004	CFD
(2) Albacete	Hellín	36	BSk	16.6	321	520–770	15–30	Calcic Aridisols	*Pinus halepensis*	High - July 2012	CFD
											LEB
	Liétor	18					15–30		*Pinus halepensis*	High - July 2016	M[f]
(3) Jaén	El Tranco	7	Csa	10.6	882	796–1532	15–40	Limestones and	*Pinus nigra*	High - August 2005	LEB
		32						dolomites	*Pinus pinaster*		CFD + B
											LEB + B
											LEB + CFD
		19							Shrubland[b]		F + B
(4) Valencia	Llutxent	16	Csa	16.6	660	650	5–50	Limestones	*Quercus suber*,	High - August 2018	CFD
									Pinus pinaster		LEB
									and shrubland[c]		
(5) Pontevedra	Arbo	30	Csb	14.6	1600	550	30–50	Umbric Regosols	Shrubland[d]	High - August 2016	C
											M[g]
(6) A Coruña	Porto do Son	19	Csb	14.6	1300	200	30–50	Humic Regosols	Shrubland[e]	High - August 2016	M[h]
(7) Ourense	Entrimo	8	Csb	13	1400	550	30–50	Humic Regosols	*P. pinaster*	High - September 2016	M[i]
	Cualedro	8		10.6	860	800	30–50		*P. sylvestris*	High - August 2015	LEB

Notes: LEB: log erosion barriers, CFD: contour felled log debris, M: mulching, F: chipping and felling, B: burning.
[a] According to Köppen classification (Kottek et al., 2006).
[b] *Quercus coccifera*, *Pistacia lentiscus*, *Pistacia terebinthus*, *Juniperus oxycedrus*, *Daphne gnidium*, *Ulex parviflorus*, *Berberis hispanica*, and *Rosmarinus officinalis*.
[c] *Pistacia lentiscus*, *Anthyllis cytisoides*, *Erica multiflora*, *Chamaerops humilis*, *Ulex parviflorus*, *Arbutus unedo*, *Quercus coccifera*, and *Cistus* sp.
[d] *Ulex europaeus* L., *Erica cinerea* L., and *Pterospartum trdidentatum* (L.) Willk.
[e] *Ulex europaeus* L. and *Erica cinerea* L.
[f] 0.2 kg m^{-2} of wheat straw, dry weight, applied by hand.
[g] 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.
[h] 3.5–4.0 Mg ha^{-1} of wheat straw applied by helicopter.
[i] 3.0 Mg ha^{-1} of wheat straw applied by helicopter.

trees on the ground along the slope contour to stop the overland flow and sediment delivery. With the same objective as that of a LEB, CFD entails felling and laying branches and burned canopy trees along the slope contour. Both LEB and CFD are designed to slow runoff; store eroded sediment; and increase water infiltration, all of which may favor plant cover and diversity recovery after fire. Mulching consists of dispersing on the soil surface organic and inorganic materials as an alternative surface cover, such as agricultural straw, plant leaves, plastic film, logging slash, shredded barks, wood strands, chips, and shreds, as well as gravel and loose soil. Among the different mulch materials, vegetal residues are considered the most effective at reducing the soil hydrological responses. In general, organic residues, such as straw and wood residues, are preferred to other mulch materials, due to its wide availability, high soil covering capacity, low cost and ease-of-handling.

2.2. Evaluation of richness and plant diversity

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

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

where:

- $p_i = \frac{n_i}{N}$ = frequency of "n_i" plants belonging to the species "i" with respect to the total number of plants "N" in the plot;
- S = number of species in each plot.

The sampling design in each site was replicated between control and treatment plots and was performed to keep balanced and representative measures across studied sites. We have simply used the burned and non-action areas as the baseline of the natural plant diversity since the area was not disturbed by postfire management. For each site, an effect size for the contrast between each eco-engineering technique and the burned site without any post-fire action was calculated for both SR and SD. This effect size was estimated as the natural logarithm (ln) of the response ratio (RR (Curtis and Wang, 1998; Hedges et 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 assumptions of the statistical tests (equality of variance and normal distribution), the data were subjected to normality test or were square root-transformed whenever necessary. All the statistical tests were carried out by with the XLSTAT software.

3. Results

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

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

CFD treatments played positive effects on vegetation diversity in the forest of *P. pinaster* of El Tranco and on the shrubland in Llutxent. In more detail, CFD with burning gave LnRR(SR) and LnRR(SD) over 0.18 in *P. pinaster* of El Tranco, while only LnRR(SR) was positive (0.10) after CFD without burning in the same site; in the shrubland of Llutxent, LnRR(SR) was 0.20 and LnRR(SD) was 0.10. In contrast, both LnRR(SR) (equal to −0.06) and LnRR(SD) (−0.22) were negative, when CFD was combined with LEB (*P. pinaster* in El Tranco). Overall, the CFD treatment increased SR and SD up to 26.1%, both estimated in the forest of *P. pinaster* in El Tranco under CFD + B treatment (Fig. 3a and b).

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

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

4. Discussion and conclusion

This standardized field study, carried out at the regional scale in the Iberian Peninsula, provides evidence that the analyzed post-fire eco-engineering techniques have a very limited influence on plant diversity. Thus, no significant differences in species richness and diversity were, in general, found between the forest soils treated with each post-fire eco-engineering technique, and the burned and non-treated sites. These differences were only noticeable and thus significant in some sites treated with log erosion barriers or mulching. The latter technique increased species richness and diversity in forests of *P. halepensis* and *P. pinaster*, and shrublands. These results are in partial accordance with Morgan et al. (2014) and Jonas et al. (2019), who observed higher species richness as we did, but did not find any differences in species diversity in response to the mulching treatments. Contour felled log debris with burning slightly increased vegetal diversity, while log erosion barriers, chipping and felling were not successful for this effect. Our findings suggest that the current post-fire eco-engineering techniques on plant diversity are not efficient, and that new strategies might be needed.

Direct and indirect effects of fire on soils and plants can be critical for the functioning of forest ecosystems and alter the capacity of biodiversity to support multiple ecosystem functions from carbon sequestration to fibre production. Thus, promoting post-fire recovery of forests is fundamental for an adequate management and planning of these ecosystems (Lucas-Borja, 2021). In this case, scientific literature has widely demonstrated that some Mediterranean species are able to regenerate through different post-fire strategies, including resprouting, serotiny, soil seed banks or wind seed dispersion into a fire- affected site (Valladares et al., 2014; Resco de Dios, 2020). The short-term period evaluated in this research and the good adaptation of the surveyed vegetation to fire indicate that a post-fire emergence treatment should not be targeted to biodiversity recovery in wildfire-affected areas, since no influence was found on plant diversity. Even so, longer-term monitoring is needed to provide further evidence on the importance of post-fire eco-engineering techniques, in order to support plant diversity in a context of climate change and land use intensification.

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

Overall, this research has demonstrated that, on a broad scale, soil mulching is generally able to restore post-fire vegetal diversity regardless of the specific site conditions. Conversely, other eco-engineering techniques must be implemented with caution since these post-fire actions

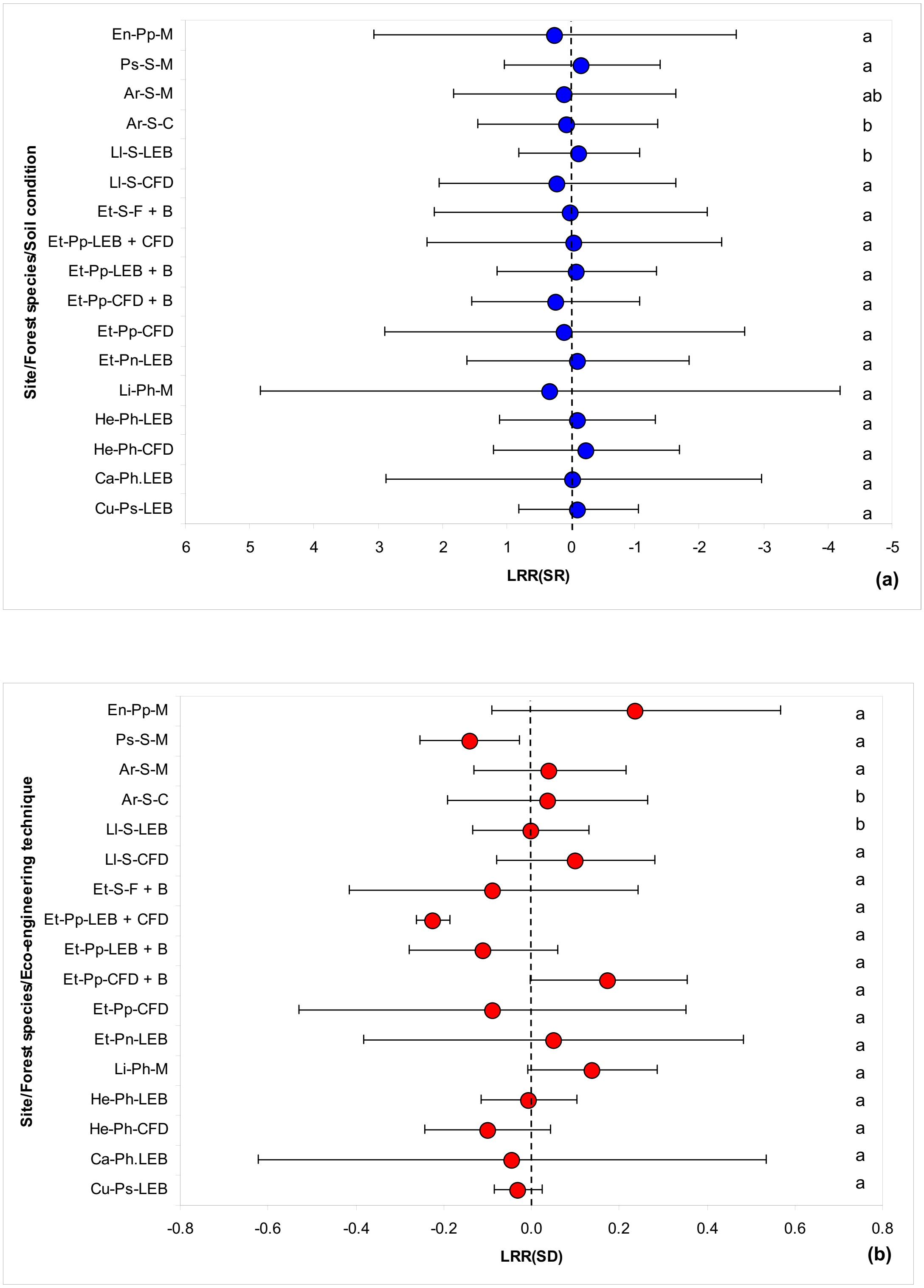
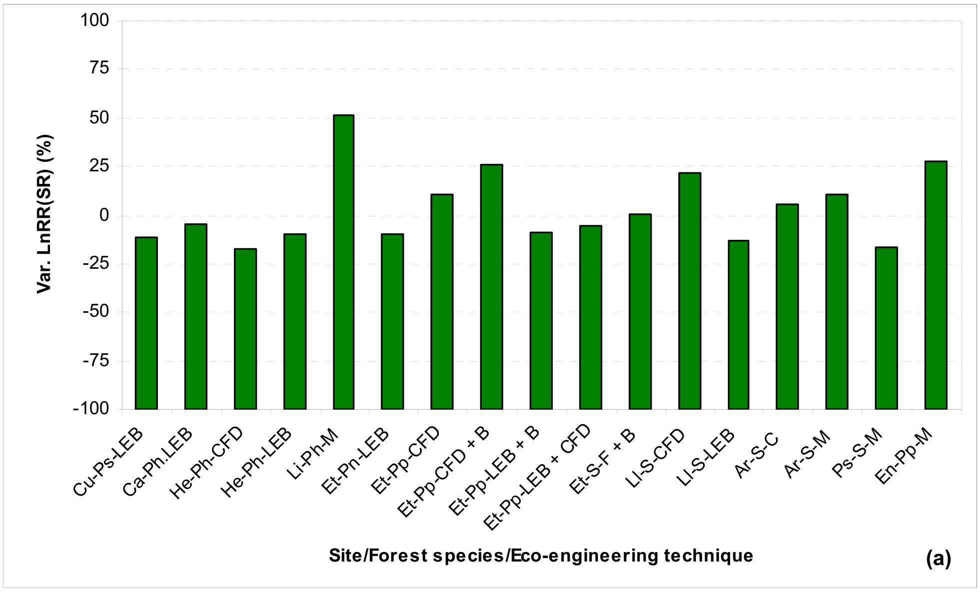


Fig. 2. Log response ratio (LRR, mean and confidence interval) of species richness (SR, a) and species diversity (SD, b) evaluated in nine forest sites of South-Eastern and North-Western Spain under different post-fire eco-engineering techniques. The first group of two letters indicates the site, the second group the forest species, and the third group the eco-engineering technique (for instance, Cu-Ps-LEB indicates the Cualedro site (Cu) - *Pinus sylvestris* (Ps) - Log erosion barriers (LEB)). See the nomenclature for the symbol meaning. The letters on the right side of the charts indicate significant differences between the unburned, and the burned and treated sites.

may even decrease the vegetation diversity of severely burned forest ecosystems. These measures play beneficial effects in reducing the runoff and erosion rates, in contrasting the soil degradation and supporting vegetation recovery, but no result is seen in the recovery of diversity or species richness. The effects of plant and soil restoration strategies on burned forests need to be effectively outlined with the aim to generate a scientific basis for post-fire management guidelines and properly restore wildfire affected forest ecosystems.



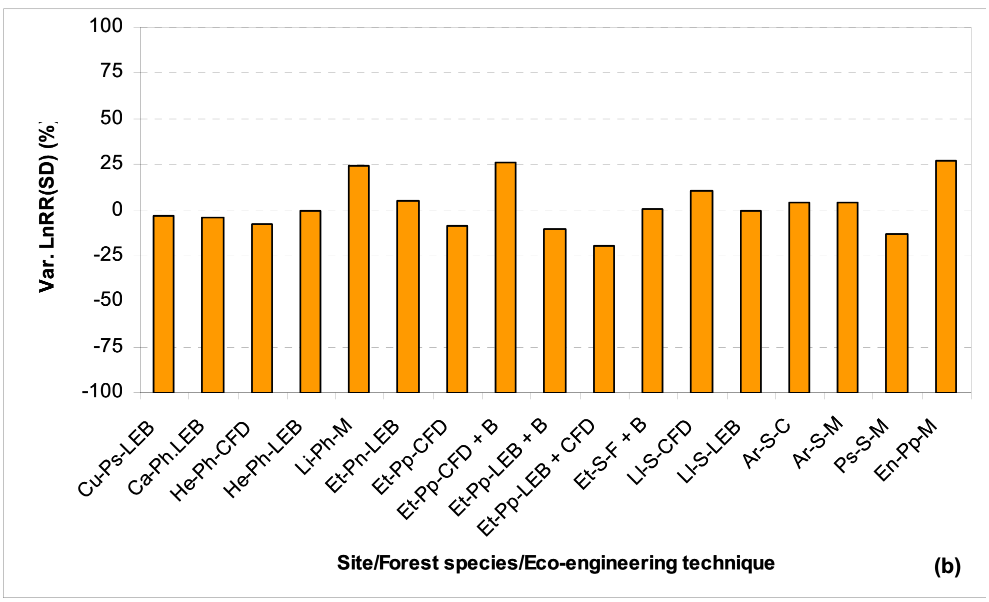


Fig. 3. Variability of log response ratio (LnRR, in comparison to the unburned forest) of species richness (SR, a) and species diversity (SD, b) evaluated in nine forest sites of South-Eastern and North-Western Spain under different post-fire eco-engineering techniques. The first group of two letters indicates the site, the second group the forest species, and the third group the eco-engineering technique (for instance, Cu-Ps-LEB indicates the Cualedro site (Cu) - *Pinus sylvestris* (Ps) - Log erosion barriers (LEB)). See the nomenclature for the symbol meaning. The letters on the right side of the charts indicate significant differences between the unburned, and the burned and treated sites.

List of plant species at each site. Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.152894.

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	*P. sylvestris*
Ph	*P. halepensis*
Pn	*P. nigra*
Pp	*P. pinaster*
S	Shrubland

CRediT authorship contribution statement

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.

Declaration of competing interest

No conflict of interest exits in the submission of this manuscript, and manuscript is approved by all authors for publication. The authors declare 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.

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