SHORT COMMUNICATION

Influence of post-fire eco-engineering techniques on plant diversity under Mediterranean climates

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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 on plant diversity. To fill this gap of knowledge, a 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 were found between the forest treated with each post-fire eco-engineering technique, and the burned and non-treated soils. These differences were noticeable and thus significant only in 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 for this effect. This research will help forest managers and agents in Mediterranean forest to decide the best postfire management option for wildfire affected forest.

Keywords: wildfire; species richness; species diversity; log erosion barriers; contour felled log debris; mulching; chipping; felling.

1. Introduction

Forest ecosystems that are affected by wildfires undergo noticeable changes in soil properties and vegetation cover. Due to these changes, post-fire high-intensity storms expose forest soil to erosion 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 that show economic sustainability and environmental compatibility; mulching, and the construction of log erosion barriers or contour felled log debris are examples of the post-fire eco-engineering techniques (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., 2018). These techniques control the soil's hydrological response and, at the same time, enhance recovery of soil properties and restoration of plant cover and diversity to the pre-fire levels. According to the scientific literature, the effectiveness of post-fire eco-engineering techniques is highly variable, depending 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 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 further reductions in vegetation cover and losses of vegetation diversity in forestlands.

Due to this lack of knowledge, the effectiveness of many techniques on plant diversity is in some cases debatable and in other local contexts even unknown. This implies that these strategies are applied by forest managers all over the Mediterranean area without precise plans, which should be based on evaluations of the effects of previous actions. To fill this gap of knowledge, a regional-scale database about the influence of post-fire eco-engineering techniques on plant diversity is proposed. 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 is. 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 (Figure 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).

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 and 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):

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

where:

- $p_i = \dfrac{n_i}{N}$ = 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.

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_T 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). Therefore, the lnRR is an easy and meaningful index to summarize the comparative value and direction of an ecological effect (Lajeunesse, 2015) in meta-analysis. This approach allowed a standardized analysis of data from different sites and after sampling by different methods. 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, 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

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). 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.

Only the influence of soil mulching on plant diversity after wildfire was evident (Table 1 sup mat). 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) (Figures 2a and 2b). 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 (Figures 2a and 2b). 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 (Figures 3a and 3b).

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 (Figures 3a and 3b).

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 Ln(RR)) (Figures 2a and 2b). 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% (Figures 3a and 3b).

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 (Figures 2a and 2b). 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) (Figures 3a and 3b).

4. Discussion and conclusions

This 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, partially confirming the working hypothesis that all the analyzed eco-engineering techniques modify plant diversity in wildfire-affected areas. In general, no significant differences in species richness and diversity were found between the forest treated with each post-fire eco-engineering technique, and the burned and non-treated soils. These differences were noticeable and thus significant only 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 found no differences in species diversity in response 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.

Direct and indirect effects of fire on soils and plants can be critical for the functioning of forest ecosystems. 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 2021). The short-term period evaluated here on this research and the fact that surveyed vegetation is well adapted to fire would indicate that postfire emergence treatment should not aim biodiversity recovery in wildfire affected areas as not influence on plant diversity was found. The only significant strategy was related to straw mulching in semi-arid locations. 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. Contrary to this, Lucas-Borja et al (2020) demonstrated that mulching had no detrimental effects on the short-term initial vegetation recovery in subhumid 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 may even decrease the vegetation diversity of severely burned forest ecosystems.

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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*

Supplementary material

List of plant species at each site.

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