Medium-term associations of soil properties and plant diversity in a semi-arid pine forest after post-wildfire management

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ABSTRACT

The medium- and long-term studies about the effectiveness of post-fire management techniques on soil and plant ecology are scarce, although the effects of wildfire and subsequent management can be long lasting. This study has evaluated the changes in the main physico-chemical properties of soil and plant diversity six years after a wildfire and post-fire treatments using contour felled log debris (CFD) and log erosion barriers (LEB) in a Mediterranean pine forest in comparison to unburnt (UB), and burnt but untreated (BNA) sites. Soil texture and pH did not generally change after wildfire and treatments, while organic matter and nutrients were significantly different between the treated soils and the other sites. Herbaceous plants were found only in UB and LEB sites, the latter showing the lowest number of tree species. Shrubs were equally distributed among the four soil conditions. Resprouting and germinating plants increased in the treated sites compared to BNA area, which however showed a higher number of facultative resprouters. The analysis of relationships between soil properties and plant diversity showed that, when organic matter (CFD plots) and nitrogen (LEB plots) contents are noticeably higher compared to BNA soils, more resprouting species are detected. Moreover, significant increases in pH (UB and BNA plots) and organic matter (CFD plots) are associated to more abundant tree and herbaceous species. The study

also indicates to forest managers the most resilient plant species after post-fire restoration several years after a wildfire under Mediterranean conditions.

Keywords: wildfire; Mediterranean forest; climate change; post-fire management; plant diversity.

1. INTRODUCTION

Fire is a natural and anthropogenic agent, strongly affecting many parts of ecosystem (Calderon-Aguilera et al., 2012; Shakesby, 2000). In forest ecosystems, fire, regardless of its severity, burns understorey and overstorey vegetation, and litter. Forest burning can change land surface properties and cross-scale hydrologic connectivities, directly altering patterns of runoff and erosion (Allen, 2007). In the case of wildfires with high severity, the soil is completely bare and thus becomes prone to surface runoff-induced soil erosion, which result in possible flooding and hydrogeological risks (debris flow, landslides, etc.) (Moody et al., 2013; Shakesby and Doerr, 2006). Moreover, fires can change several soil properties, such as aggregate stability, electrical conductivity, organic matter and nutrient contents, and can induce soil repellency (Certini, 2005; DeBano, 1981; Zavala et al., 2014). When the fire severity is high, these changes can increase the risk of soil degradation (Nelson et al., 2022; Stavi, 2019). From an ecological perspective, fire removes vegetation cover, and part of plant species, often causing a severe loss of biodiversity in the case of high-severity wildfires (Lucas-Borja et al., 2022d; Stinca et al., 2020). However, many vegetal species show fire-adaptive traits in post-fire environments (Buhk et al., 2007). The main mechanisms for post-fire vegetation regeneration are the capacity to resprout (resprouting species) and the stimulation of the recruitment by fire (seeders or germinating species). Resprouting is based on the plant revegetation thanks to some alive parts belowground, while the recovery of non-resprouting species strictly depends on seed germination that is associated to the fire recurrence interval and the seed resistance to the fire (Bodí et al., 2012).

To reduce the adverse hydrogeological and ecological impacts of wildfires on forest ecosystems, forest managers commonly implement post-fire management actions, both on hillslopes and in channels of burnt catchments (Lucas-Borja, 2021; Robichaud, 1998; Robichaud et al., 2010). Generally these actions are able to control the fire-related hydrological and erosive responses of forest soils, which so-called “window of disturbance” (Prosser and Williams, 1998). These controlling actions can limit the increases in surface runoff and soil erosion over a short-term (Garrido-Ruiz et al., 2022; MacDonald and Larsen, 2009; Zema, 2021). Moreover, these actions enhance a quick restoration of the original plant diversity in burnt forests, since biodiversity supports the forest resilience to possible disturbances (García Matallana et al., 2022; Maestre and Cortina, 2004). However, the performance of post-fire management techniques is generally site-specific, since the impacts on soil hydrology and ecology depend on the environmental characteristics of the areas to be treated (Lucas-Borja et al., 2022a; Moody et al., 2013; Vieira et al., 2018). This performance is evaluated in many environmental contexts with several soil conservation techniques (Fernández and Vega, 2016; Garrido-Ruiz et al., 2022; Jonas et al., 2019; Lopes et al., 2020; Robichaud et al., 2008), especially in Mediterranean forests (Fernández et al., 2012, 2008; Keizer et al., 2018; Prats et al., 2012; Vega et al., 2014). In this regard, Girona-García et al. (2021) presented an interesting systematic review with a meta-analysis about the effects of many post-fire management techniques on soil hydrology. The authors demonstrated that, in general, the application of post-fire treatments is a better choice compared to no action, especially in highly erodible sites. Wagenbrenner et al. (2021) have studied the hydrological post-fire recovery of burnt forests with or without post-fire conservation actions, showing inconsistent recovery times across sites due to the different locations, response variables and study design. Lucas-Borja et al. (2022c) have recently published a comprehensive study on the effect of a large set of post-fire management techniques on vegetation diversity in wildfire-prone forest areas of the Iberian Peninsula in Spain. According to this study, species richness and diversity were not different between the treated forests, except for significant but small differences for some sites treated with log erosion barriers or mulching.

Generally, the study of the performance of post-fire techniques by analysis of the hydrological and ecological effects are carried out over the short-term, since the soil is more exposed to the hydrological risks a few months post wildfire (Francos et al., 2018; Lucas-Borja et al., 2021a). In addition, there are usually limited funds to do complete longer monitoring observations (Girona-García et al., 2021). In contrast, medium- and long-term studies are scarce (e.g., Alcañiz et al., 2016; Hedo et al., 2015; Niemeyer et al., 2020), and thus the performance of each post-fire management technique is far from being completely understood. This is important on the long-lasting changes in soil properties due to wildfire impacts, and mainly on post-fire restoration of vegetation cover and biodiversity, whose recovery times may also be very long (Díaz-Delgado and Pons, 2001; García-Orenes et al., 2017; Hedo et al., 2015; Robichaud et al., 2020). A clear understanding of time and extent required by soil and vegetation to recovery the pre-fire properties and original cover, structure and biodiversity is therefore essential. This knowledge supports the selection of the most efficient post-fire techniques, in order to minimise the failure and optimise the management costs. Moreover, it is essential to explore whether the soil changes due to wildfire and post-fire management and the recovery times of vegetation after this disturbance are interrelated. Although the scientific literature related to wildfire effects on forest ecosystems (e.g., soil and vegetation) is abundant (e.g., Carrari et al., 2022; Garrido-Ruiz et al., 2022; Gouveia et al., 2010; Nolan et al., 2021; Pérez-Cabello et al., 2021; Zituni et al., 2019), studies jointly exploring the dynamics of burnt and treated soil and post-fire regeneration of vegetation are much less, especially in the mid-term (Garrido-Ruiz et al., 2022; Granged et al., 2011; Spanos et al., 2005).

To fill the gap of medium-term observations about the soil characteristics and biodiversity in burnt forests after post-fire management, this study has evaluated the changes in the main physico-chemical properties of soil and plant diversity six years after a wildfire and post-fire treatments using contour felled log debris and log erosion barriers in a Mediterranean pine forest in comparison to unburnt, and burnt but untreated sites. We hypothesized that the changes in soil properties due to wildfire and post-fire management may noticeably drive plant diversity in semi-arid pine forests in the mid-term. The results of this study should indicate to forest managers the most resilient plant species after post-fire restoration several years after a wildfire under Mediterranean conditions.

2. MATERIAL AND METHODS

2.1 Study area

The study area was Sierra de Donceles forest (Hellín, Province of Albacete, Region of Castilla La Mancha, Central-Eastern Spain, Figures 1 and 2), which is located on the meso-Mediterranean bioclimatic belt. The climate of the area is Mediterranean semi-arid, Csa type according to the Köppen classification (Kottek et al., 2006). The mean annual temperature and precipitation are 16.6 °C and 321 mm. Rainfall is more abundant in autumn and spring (maximum in October, 44.5 mm), while the dry period lasts from June to September, with a relative humidity below 50% (data of 1990–2014, provided by the Spanish Meteorological Agency, AEMET). Elevation of the study area is 304 to 808 m. According to the Soil Taxonomy System (Soil Survey Staff, 2014), soils are Calcic Aridisols with loamy–sandy loam texture.

Vegetation belongs to the *Rhamno lycioidis-Querceto cocciferae* S., with Aleppo pine as dominant tree species and kermes oak as main shrub complex (Peinado et al., 2008). The natural vegetation consists of *Quercus coccifera* L., *Rhamnus lycioides* L. and *Rhamnus alaternus* L.

After 70 years without wildfires, in July 2012, 6500 ha of this forest area were burnt by a moderate to high severity fire (Figure 2). In September and October 2012, the regional forest managers implemented two post-fire management actions on some burnt hillslopes, to stabilize soil and reduce post-fire runoff and erosion in river channels. These hillslope stabilization techniques consisted of log erosion barriers (hereafter "LEB") and contour felled log debris (CFD) (Figure 2). In more detail, for LEB construction, felled burnt trees were installed along the contour lines at a mean density of 30 LEBs per ha and a mean length of 300 m per ha (each LEB was 10-m long). Each log is anchored in place, and the space between the log and soil surface is filled with soil, in order to create a small storage basin for water and sediment flows. CFDs were built using branches and small-felling burnt trees along the contour lines at a mean density of 17 CFD per ha and a mean length of 850 m per ha. In this case, logs are not anchored in place. Each LEB and CFD was 10-m and 50-m long (this lower length was due to the less concentrated material on ground) respectively. According to Girona-García et al. (2021), Lucas-Borja (2021) and Zema (2021), CFDs and LEBs are among the most used post-fire stabilisation techniques beside mulching with agricultural or forest residues. Therefore, the experimental sites may be considered as representative of semi-arid forests treated using common post-fire management techniques.

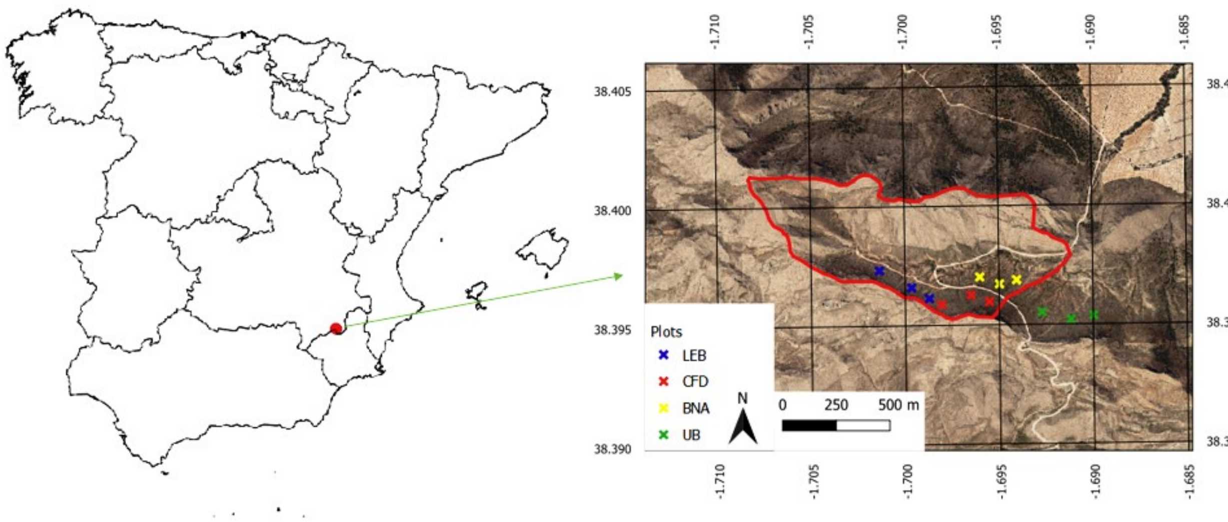


Figure 1 - Geographical location (left) and aerial map (right) of the study area (Hellín, Province of Albacete, Castilla La Mancha region, Spain). Legend: UB = unburnt; BNA = burnt and no action; CFD = contour felled log debris; LEB = log erosion barriers.

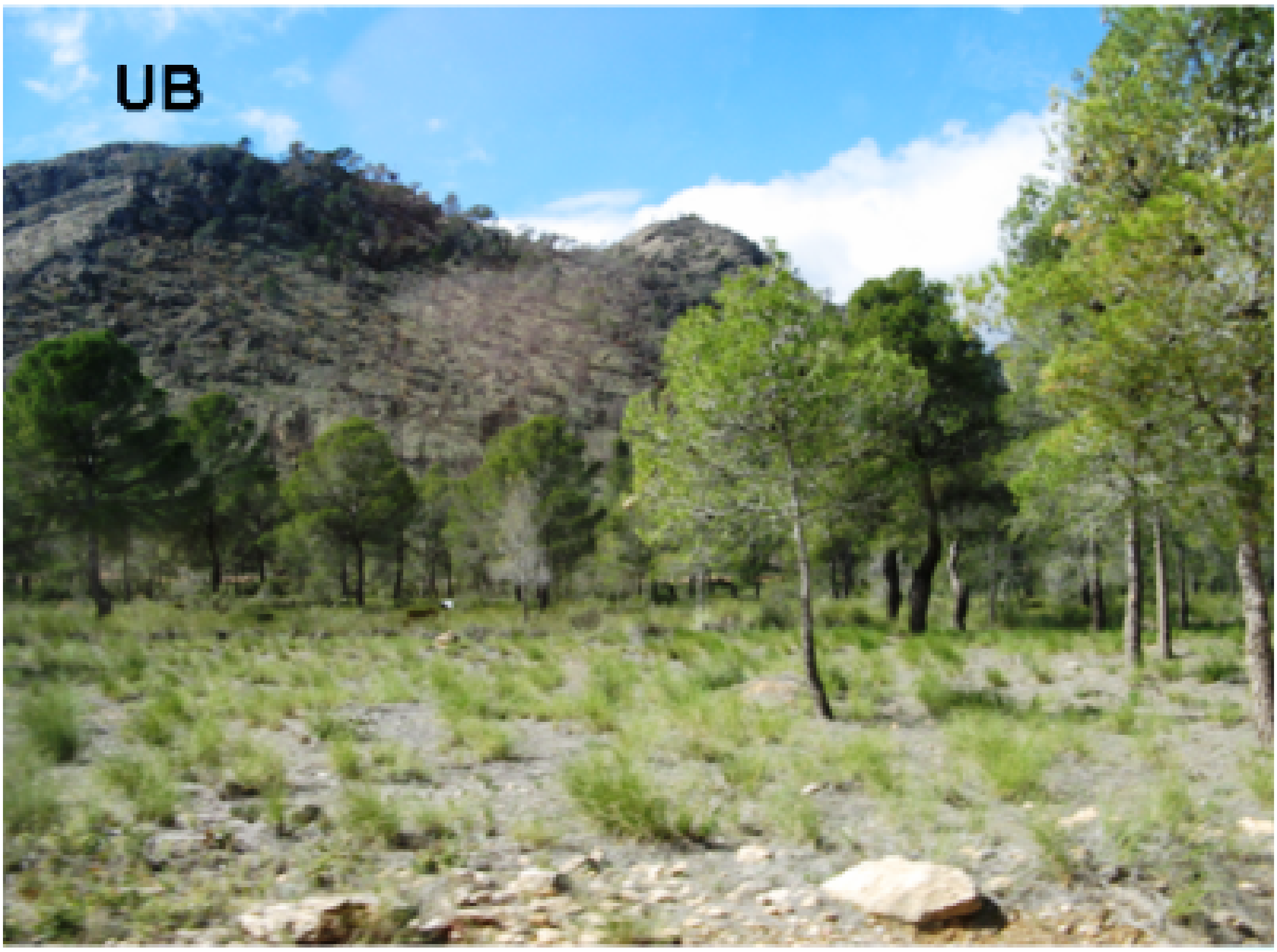


Figure 2 – Pictures of landscapes in the study area (Hellín, Province of Albacete, Castilla La Mancha region, Spain) under the four soil conditions (UB = unburnt; BNA = burnt and no action; CFD = contour felled log debris; LEB = log erosion barriers).

2.2 Experimental design

This study was conducted in a catchment of about three km^2 affected by a wildfire in July 2012. In autumn of 2012, stabilisation treatments were carried out on hillslopes in the studied catchment, and check dams were built at its outlet. The hillslope stabilisation treatments consisted of log erosion barriers (LEB) and contour-felled log debris (CFD). A LEB was built by felling burnt trees that are laid on the ground along the slope contour (Napper, 2006). Five years after fire and post-fire management (September 2017), 12 plots (each one of 20 × 20 m, equalling 400 m^2) were randomly installed in the study area. More specifically, three plots were selected in an unburnt area (hereafter "UB", 500 m far from the burnt area), while the remaining nine plots were installed in the burnt site. Of these plots, three were identified in an untreated area (BNA, burnt and no action), while two groups of three plots were installed in sites with CFDs or LEBs. Each CFD and LEB plot contained the small storage basin. All plots had a northern aspect, an average height of about 500 m, and a slope between 30% and 45%. The minimum and maximum reciprocal distances among plots were 300 and 500 m respectively. The minimum distance was chosen to minimize the soil spatial heterogeneity, while the maximum value allowed considering the plots as totally independent, and therefore avoided pseudo-replications. Therefore, the experimental design consisted of four soil conditions (UB, BNA, LEB and CFD), each with three replications, totally, 12 plots. The relatively low number of replicated plots is associated to the homogeneity of soil and plant characteristics in the areas, which will be quantitatively confirmed by the low coefficients of variability (always below 30% for soil properties and 10% for plant diversity) in these parameters, as reported in the following sections.

2.3 Data collection

2.3.1 Soil sampling and analysis

In May 2017, soil of plots was sampled and analysed to determine the main properties. In the CFD and LEB sites, nine samples per plot were collected (three groups of three replicated samples), of which one group in the storage basin behind the structures, and two other groups in the space immediately beyond or downstream of this basin. In UB and BNA sites, three groups of three replicated samples per plot were collected in as many randomly-selected points. Therefore, the total number of samples was 108, three groups of three replicated samples per 12 plots (Figure 2). After litter removal, each soil sample (600 g) was collected in the layer 0 to 5 cm of depth. The three replicated samples of each group were then mixed to obtain a composite sample. The 36 composite samples (nine per plot) were immediately transported to the laboratory and then dried for 48 hours at environmental temperature, sieved (2-mm diameter) and kept at 4 °C for 15 days until analysis. The following physico-chemical properties were analysed: (i) texture (clay, silt and sand contents, determined by the pipette method, Gee and Or, 2002); (ii) pH and electrical conductivity (EC) (both in deionized water, 1:2.5 and 1:5 w/w, respectively, at 20 °C); (iii) organic carbon (OC), by the potassium dichromate oxidation method, Nelson and Sommers, 1996); (iv) total nitrogen (TN, Bremner, 1982), and available phosphorus (P, Olsen, 1982). Based on OC measurements, the OM was calculated as the product of OC by 1.732.

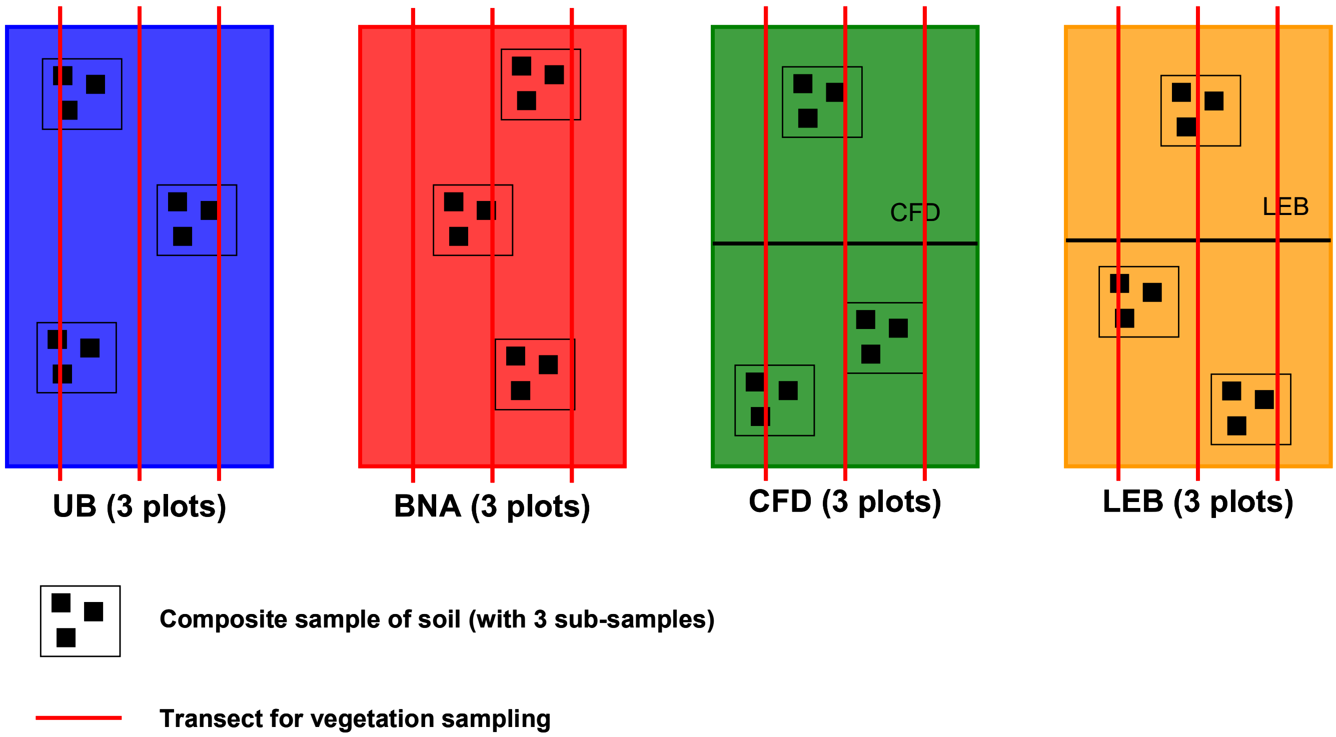


Figure 2 – Scheme of the experimental design for soil and vegetation sampling in the study area (Hellín, Province of Albacete, Castilla La Mancha region, Spain). Legend: UB = unburnt; BNA = burnt and no action; CFD = contour felled log debris; LEB = log erosion barriers.

2.3.2 Plant diversity analysis

In May 2017, a vegetation species survey was carried out to define the ecosystem structure for each soil condition. For this purpose, three 20-m long transects were set up along the longitudinal profile of each plot, one in the middle part and two others in its sides (Figure 2). Along each transect, the different vegetal species were identified, using the line intercept method (Elzinga et al., 2001). The regeneration mechanism - seeders or germinating plants (S), resprouters (SP), and facultative resprouters (FSP) - were identified for all plant species. These regeneration mechanisms were identified by field observations. The plant family and vegetation layer (herbaceous, shrub, tree) were also recorded for each species. From these surveys, the plant diversity in each plot was calculated, adopting the species richness (SR, the total number of the different species detected in each plot) and the Pielou's index (PI, Pielou, 1966), an index of species evenness). In more detail, this index, which indicates how the number of each species is close in each environment, was calculated according to the following equation:

$$PI = \frac{H}{H_{\max}} \qquad (1)$$

where H and H_{max} are the Shannon index (Shannon, 1948) and its maximum, respectively. The latter index is related to relative abundance of the different species in each plot, and is given by the following formula:

$$H = -\sum_{i=1}^{S} p_i \ln p_i \qquad (2)$$

where $p_i = \frac{n_i}{N}$ = frequency of "n_i" plants of the "i-th" species compared to the total number of plants "N" in the transect. PI ranges between 0 and 1, and a lower J expresses a low evenness in communities between the species, that is the presence of a dominant species. The values of SR and PI indexes were finally averaged among the three transects in each plot.

2.4 Statistical analysis

First, a one-way ANOVA was applied to all quantitative parameters that were related to soil properties and plant diversity. These parameters were the response variables, while the independent factor was the soil condition with four levels (UB, BNA, LEB and CFD). The data were square root-transformed when the ANOVA's assumptions of equality of variance and normal distribution were not satisfied. Using pairwise comparisons by Tukey's test (at $p < 0.05$), the statistical significance of the differences among the soil conditions in the response variables was evaluated.

Second, the ANOSIM (analysis of similarities) routine was performed to compare similarities in the vegetal species in each soil condition and among the different conditions. Then, a SIMPER (similarity percentage) analysis was carried out to interpret the differences among the soil conditions. This analysis calculates the contribution of the vegetal species to similarity, in order to identify the most characteristic species for each soil condition, based on similarity percentages. A noticeable similarity among plots of the same soil condition represents a low mean square distance in the range 0 to 100 and a distance of 0 or 100 indicates totally similar or totally different plant communities, respectively.

Third and finally, a Canonical Correspondence Analysis (CCA, Legendre, 1998) was developed to determine the relative importance of any soil properties on vegetal types. CCA is an ordination technique, which identifies axes from the response variables (in our case vegetation characteristics) as linear combination of independent variables (soil properties). This technique was adopted, considering its large use in ecology to derive from measurements information (e.g., soil properties, weather characteristics), influencing the composition of ecological communities, such as plants. Moreover, CCA should be preferred to PCA, when the response variables (such as the plant species) may have unimodal responses to the drivers (i.e., the independent variables). In other words, these response variables favour a certain range of the related parameters rather than lower and higher values that are quite rare, while PCA assumes a linear response between response and independent variables (Hammer et al., 2001).

Using CCA, the eigenvalues and eigenvectors of the matrix that contains the Chi-squared distances among the response variables (in our study, alternatively the family, regeneration mechanism and vegetation layer) were obtained. The eigenvalue gives a measure of the similarity accounted for the corresponding eigenvector. In this study, the ANOVA was carried out using XLSTAT release 2019 (Addinsoft, Paris, France), while, for ANOSIM and SIMPER, PRIMER software (Clarke and Gorley, 2015) was used. CCA was implemented using PAST release 4 software.

3. RESULTS

3.1 Variability of soil properties among the four soil conditions

According to one-way ANOVA, most of soil properties were significantly different ($F > 3.289$, $p < 0.05$) among the four soil conditions, with the exceptions of SaC ($F = 2.709$, $p = 0.061$) and EC ($F = 1.223$, $p = 0.317$) (Table 1). In more detail, although the soil texture and type of soils were the same, the SiC was significantly higher (49.5 ± 0.9%) in the soils sampled under CFD compared to the other soil conditions (except UB sites, 43.4 ± 1.52%), while the lowest (41.1 ± 2.99%) SiC was measured in BNA plots. The UB (8.74 ± 1.34%) and BNA (1.1 ± 0.25%) soils showed significantly higher ClC compared to CFD (1.10 ± 0.25%) and LEB (3.31 ± 0.62%) plots (Figure 4a).

The lowest pH was measured in the CFD soils (8.36 ± 0.02), and this value was significantly different from both UB (8.47 ± 0.02) and BNA (8.47 ± 0.04) plots, but not to the LEB soils (8.38 ± 0.01). EC was in the range 150 ± 5.73 mS/m (UB plots) to 176 ± 3.86 mS/m (LEB soils), without any significant differences among the four soil conditions (Figure 4b). The UB and BNA soil showed the similar OM contents (4.54 ± 0.18% and 4.40 ± 0.28%, respectively), and these values were significantly lower compared to CFD (6.04 ± 0.32%) and LEB (7.25 ± 0.68%) plots. TN was the highest in LEB soils (0.29 ± 0.02%), and these values were significantly higher compared to the other soil conditions. The UB and BNA plots showing the lowest TN (0.19 ± 0.01% for both), without any significant difference in comparison to CFD soils (0.23 ± 0.01%). The latter plots showed the highest P content (7.58 ± 1.38%), which was significantly different compared to both UB (3.62 ± 1.05%) and BNA (3.29 ± 0.47%) soils, but not to CFD plots (4.27 ± 0.74%) (Figure 4c).

Finally, the highest soil respiration was measured in LEB plots (1.49 ± 0.09 μg/h per gram of soil), while in the other soil conditions the CO_2 flux was significantly lower (from 0.89 ± 0.06 μg/h-g for UB plots, to 1.14 ± 0.10 μg/h-g for CFD plots), and the differences among these plots were not significant (Figure 5).

Table 1 - Results of ANOVA applied to the main properties of soils under four soil conditions (UB = unburnt; BNA = burnt and no action; CFD = contour felled log debris; LEB = log erosion barriers) six years after a wildfire in a semi-arid pine forest (Hellín, Castilla La Mancha, Spain).

Factor	**Variable**	**Degrees of freedom**	**Sum of squares**	**Mean squares**	**F**	**Pr > F**
Treatment	SaC	3	283.839	94.613	2.709	0.061
	SiC		407.95	135.983	4.027	**0.015**
	ClC		303.141	101.047	19.986	**< 0.0001**
	pH		0.092	0.031	6.235	**0.002**
	EC		3009.83	1003.277	1.223	0.317
	OM		49.411	16.47	20.152	**< 0.0001**
	TN		0.066	0.022	12.391	**< 0.0001**
	TP		104.536	34.845	4.106	**0.014**
	CO_2 flux		1.973	0.658	8.483	**< 0.0001**
	SR		38.333	12.778	3.239	**0.035**
	PI		0.026	0.009	2.186	**0.109**

Notes: SaC = sand content; SiC = silt content; ClC = clay content; EC = electrical conductivity; OM = organic matter; TN = total nitrogen; P = phosphorous; SR = species richness; PI = Pielou index.

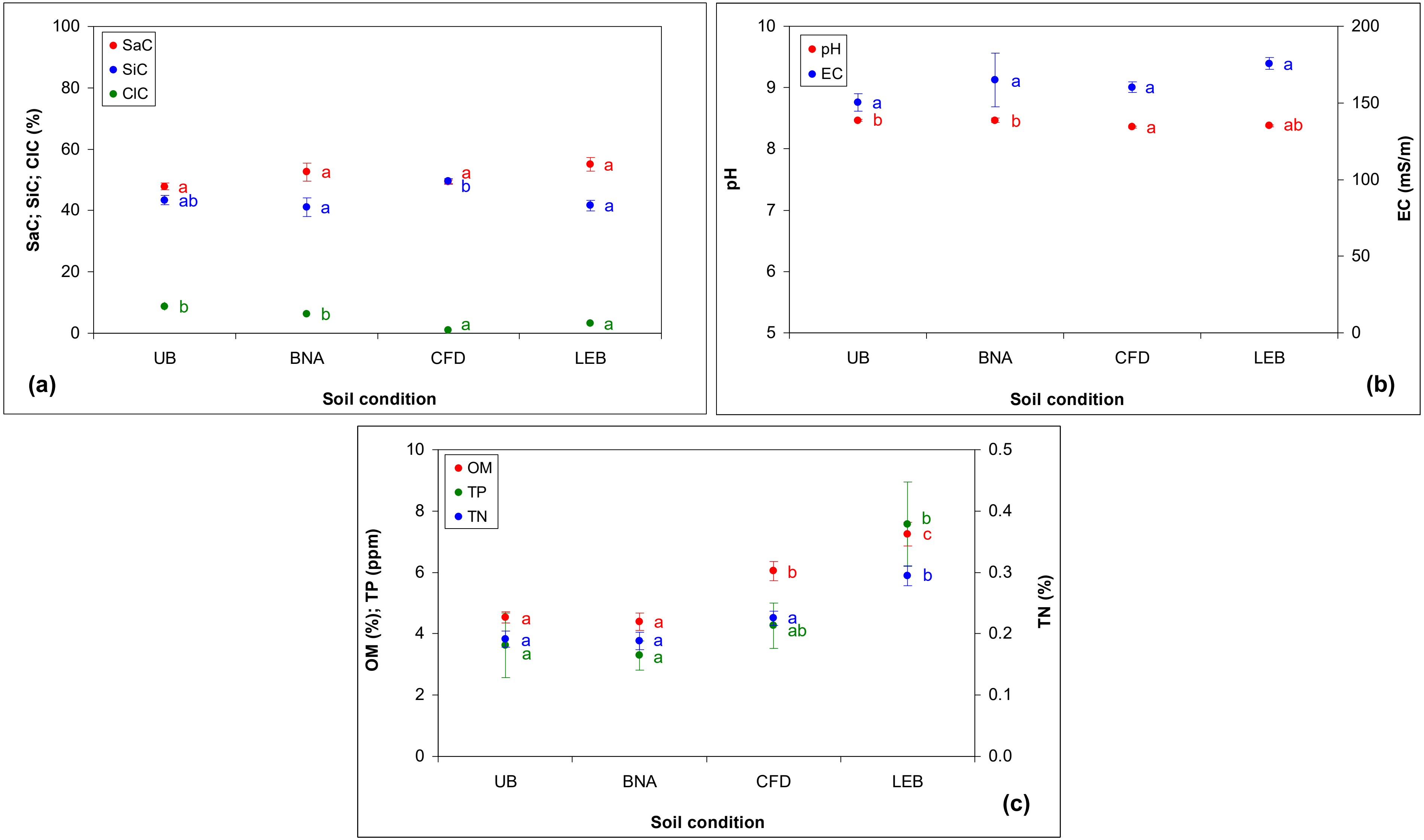


Figure 4 – Mean ± standard error (n = 9 composite samples) of the main properties of soils under four soil conditions (UB = unburnt; BNA = burnt and no action; CFD = contour felled log debris; LEB = log erosion barriers) six years after a wildfire in a semi-arid pine forest (Hellín, Castilla La

Mancha, Spain). (a) sand content (SaC), silt content (SiC) and clay content (ClC); (b) pH and electrical conductivity (EC); (c) organic matter (OM), total nitrogen (TN) and total phosphorous (TP). Different letters indicate significant differences among the soil conditions after Tukey's test ($p < 0.05$).

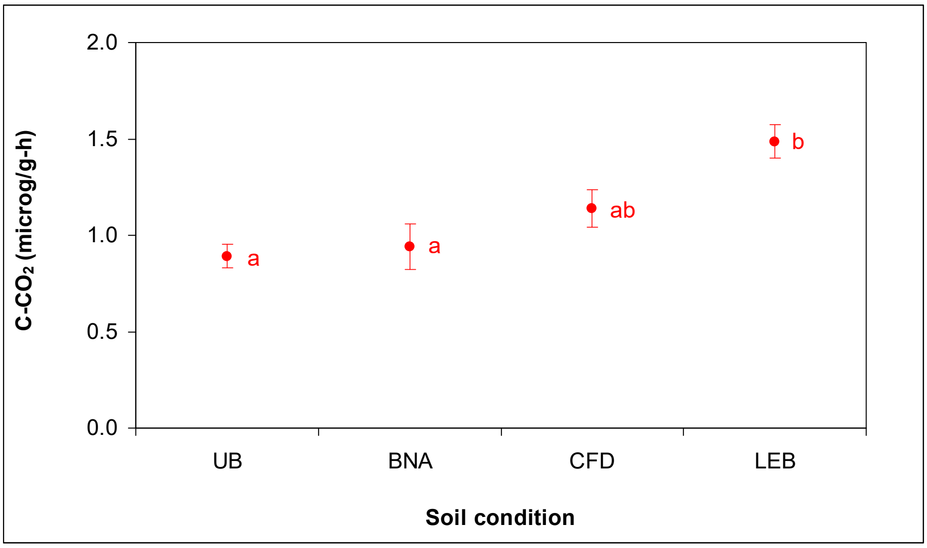


Figure 5 - Mean ± standard error (n = 9 composite samples) of soil fluxes of CO_2 ($C-CO_2$) under four soil conditions (UB = unburnt; BNA = burnt and no action; CFD = contour felled log debris; LEB = log erosion barriers) six years after a wildfire in a semi-arid pine forest (Hellín, Castilla La Mancha, Spain). Different letters indicate significant differences among the soil conditions after Tukey's test ($p < 0.05$).

3.2 Variability of plant diversity among the four soil conditions

The one-way ANOVA revealed that SR ($F = 3.239$, $p < 0.05$), but not PI ($F = 2.186$, $p = 0.109$) was significantly different among the four soil conditions (Table 1). More specifically, the BNA soils showed the highest SR (12.1 ± 0.72), and this value was significantly different only compared to the CFD plots, which showed the lowest SR (9.78 ± 0.74). The Pielou index was in the range 0.78 ± 0.03 (UB plots) to 0.86 ± 0.01 (LEB soils) without any significant differences among the four soil conditions (Figure 6).

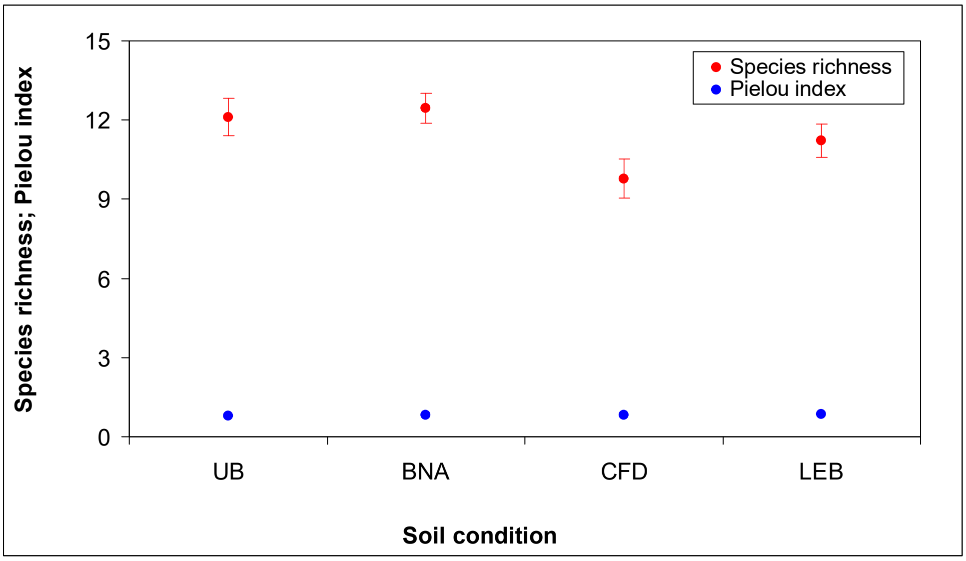


Figure 6 - Mean ± standard error (n = 3 transects per plot) of species richness and Pielou index under four soil conditions (UB = unburnt; BNA = burnt and no action; CFD = contour felled log debris; LEB = log erosion barriers) six years after a wildfire in a semi-arid pine forest (Hellín, Castilla La Mancha, Spain). Different letters indicate significant differences among the soil conditions after Tukey's test ($p < 0.05$).

Regarding to the distribution of plant family, the most abundant species (more than 100 individuals) were the Cistaceae, Leguminosae (except in UB plots), Pinaceae, and Poaceae, while the Ephedraceae, Liliaceae (except in LEB plots), Plantaginaceae, Rubiaceae, Rutaceae, and Thymelaceae were practically absent under all soil conditions (less than 10-20 individuals) (Figure 7a).

About the plant regeneration mechanism, while germinating and resprouting plants (the latter being facultative or resprouters) were equally distributed in UB and CFD plots (mean difference of 2.5-3%), the BNA and LEB soils showed a predominance of resprouters (facultative or not) on germinating species (+64.3% and 28.4%, respectively) (Figure 7b).

The shrub layer showed the highest percentage of individuals under all soil conditions (on average more than 90), while the trees were more abundant in UB and BNA soils (8%) and less numerous in LEB plots (5%). Herbaceous species were recorded only in UB and LEB plots (0.2-0.3% of the total species) (Figure 7c).

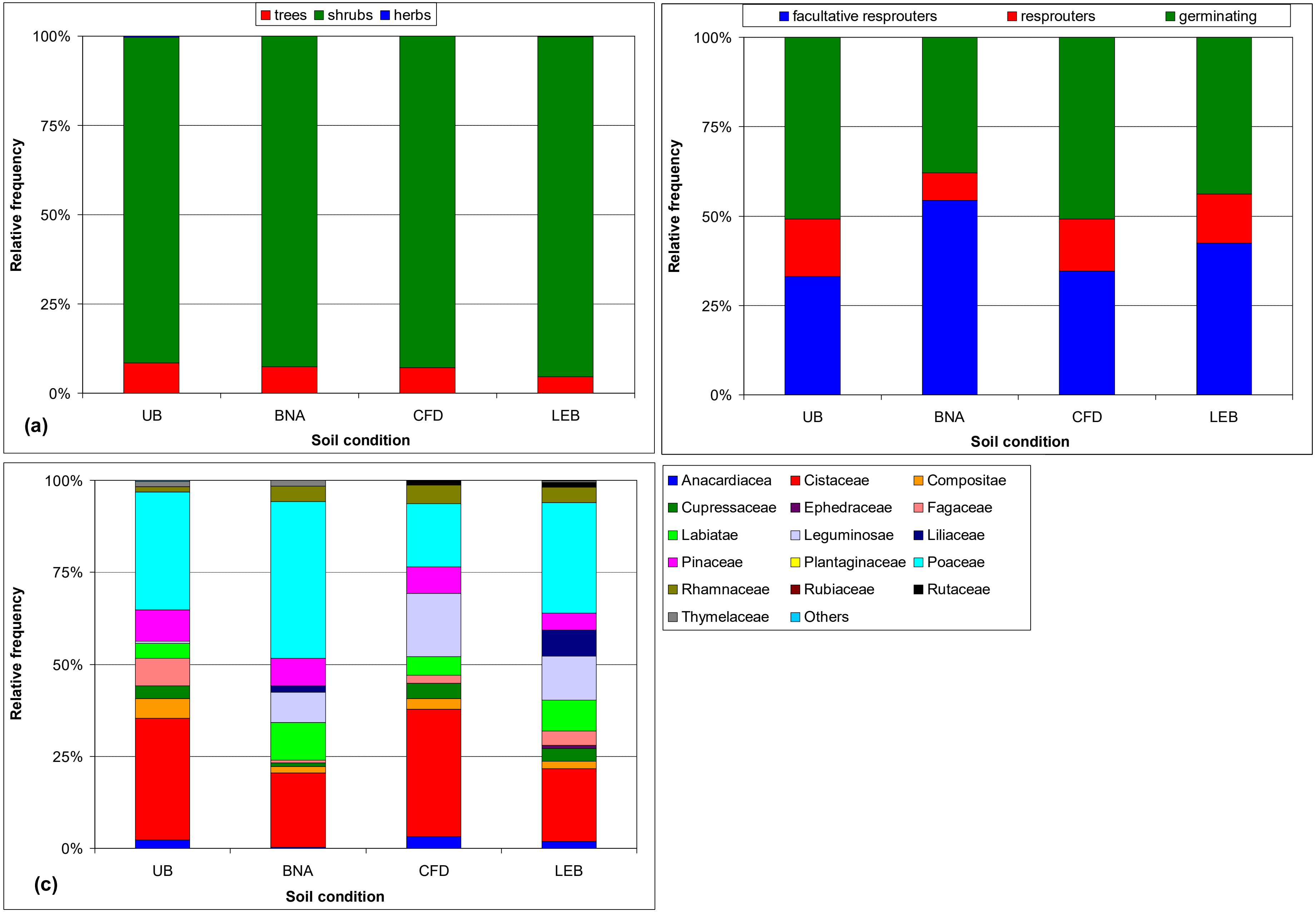

trees
shrubs
herbs
100%
75%
50%
25%
0%
Relative frequency
UB
BNA
CFD
LEB
(a)
Soil condition
facultative resprouters
resprouters
germinating
Relative frequency
Soil condition
Anacardiacea
Cistaceae
Compositae
Cupressaceae
Ephedraceae
Fagaceae
Labiatae
Leguminosae
Liliaceae
Pinaceae
Plantaginaceae
Poaceae
Rhamnaceae
Rubiaceae
Rutaceae
Thymelaceae
Others
Relative frequency
(c)
Soil condition

Figure 7 – Distribution of plant layer (a), regeneration mechanism (b), and family (c) among the different soil conditions (UB = unburnt; BNA = burnt and no action; CFD = contour felled log debris; LEB = log erosion barriers) six years after a wildfire in a semi-arid pine forest (Hellín, Castilla La Mancha, Spain).

The results of the analysis of similarities showed significant differences ($p < 0.001$) in plant diversity between all pairs of soil conditions with a mean global R value of 0.424, except between CFD and LEB ($p = 0.104$) (Table 2).

Table 2 – Analysis of similarities (ANOSIM) in plant diversity between pairs of soil conditions (UB = unburnt; BNA = burnt and no action; CFD = contour felled log debris; LEB = log erosion barriers) six years after a wildfire in a semi-arid pine forest (Hellín, Castilla La Mancha, Spain).

Soil conditions	**R statistic**	**Significance level (%)**	**Number ≥ observations**
UB vs. BNA	0.545	0.1	0
UB vs. CFD	0.434	0.1	0
UB vs. LEB	0.432	0.1	0
BNA vs. CFD	0.593	0.1	0
BNA vs. LEB	0.452	0.1	0
CFD vs. LEB	0.098	10.4	103

The similarity within each soil condition was homogeneous and in the range of around 46.2% (LEB plots) to 57.5% (BNA). *Rosmarinus officinalis*, *Brachypodium retusum* and *Pinus halepensis* were the species that mostly contributed to this similarity under all soil conditions, but also *Cistus albidus* and *Macrochloa tenacissima* were abundant in three soil conditions (UB, BNA and LEB), while, in burnt plots (treated or not), also *Anthyllis cytisoides* and *Cistus clusii* were common (Table 3).

The highest and lowest dissimilarity between pairs of soil conditions was detected between UB and LEB (61.6%), and LEB and CFD (54.3%), respectively. *Cistus albidus* and *Brachypodium retusum*, which were present under all soil conditions, most contributed to this dissimilarity. *Quercus coccifera* and *Halimium halimifolium* influenced the dissimilarity between UB on one side and burnt soils (treated or not) on the other side, while *Anthyllis cytisoides* and *Macrochloa tenacissima* made dissimilar BNA and burnt and treated soils and CFD and LEB plots, respectively (Table 1.SI).

Table 3 - Analysis of similarity percentages (SIMPER) in plant diversity within each soil condition (UB = unburnt; BNA = burnt and no action; CFD = contour felled log debris; LEB = log erosion barriers) six years after a wildfire in a semi-arid pine forest (Hellín, Castilla La Mancha, Spain).

Species	**Avg. Abundance**	**Avg. Similarity**	**Contribution (%)**	**Cumulative (%)**
Soil condition UB	Average similarity: 50.3%			
Brachypodium retusum	15.38	9.82	19.53	19.53
Cistus albidus	12.41	7.53	14.98	34.51
Pinus halepensis	9.20	6.69	13.30	47.81
Halimium halimifolium	8.63	4.81	9.56	57.37
Quercus coccifera	7.18	3.31	6.58	63.95
Klasea flavescens subsp. *leucantha*	6.23	3.17	6.30	70.25
Macrochloa tenacissima	5.72	3.00	5.96	76.21
Salvia rosmarinus	4.87	2.79	5.54	81.75
Fumana ericoides	4.45	1.88	3.75	85.50
Thymelaea argentata	3.32	1.68	3.35	88.85
Helianthemum cinereum	2.11	1.29	2.57	91.41
Soil condition BNA	Average similarity: 57.5%			
Macrochloa tenacissima	13.89	13.48	23.44	23.44
Brachypodium retusum	11.78	8.56	14.88	38.32
Fumana ericoides	8.36	7.36	12.80	51.12
Salvia rosmarinus	7.60	6.33	11.00	62.12
Pinus halepensis	7.63	6.00	10.44	72.56
Cistus clusii	6.28	4.70	8.17	80.73
Helianthemum cinereum	3.94	2.17	3.78	84.51
Thymelaea argentata	3.03	1.72	3.00	87.50
Anthyllis cytisoides	4.72	1.33	2.32	89.82
Rhamnus lycioides	4.04	1.23	2.13	91.96
Soil condition CFD	Average similarity: 49.5%			
Cistus albidus	11.05	8.35	16.87	16.87
Brachypodium retusum	9.55	8.12	16.41	33.28

Anthyllis cytisoides	10.10	7.74	15.64	48.91
Pinus halepensis	6.81	5.60	11.31	60.23
Salvia rosmarinus	5.50	4.38	8.84	69.07
Cistus clusii	5.50	3.72	7.52	76.59
Helianthemum cinereum	4.48	2.92	5.90	82.48
Juniperus oxycedrus	4.19	2.20	4.45	86.94
Rhamnus lycioides	4.61	2.09	4.21	91.15
Soil condition LEB	Average similarity: 46.2%			
Brachypodium retusum	9.98	9.10	19.70	19.70
Salvia rosmarinus	6.96	6.72	14.55	34.25
Cistus albidus	7.19	4.48	9.69	43.94
Anthyllis cytisoides	6.78	4.47	9.69	53.63
Macrochloa tenacissima	6.78	3.82	8.26	61.89
Pinus halepensis	4.81	3.41	7.39	69.28
Cistus clusii	4.06	3.27	7.08	76.36
Asphodelus cerasiferus	4.78	2.05	4.44	80.80
Fumana ericoides	2.87	1.56	3.37	84.17
Centaurea antennata	2.69	1.37	2.96	87.14
Quercus coccifera	3.30	1.08	2.35	89.48
Brachypodium phoenicoides	2.91	1.03	2.22	91.70

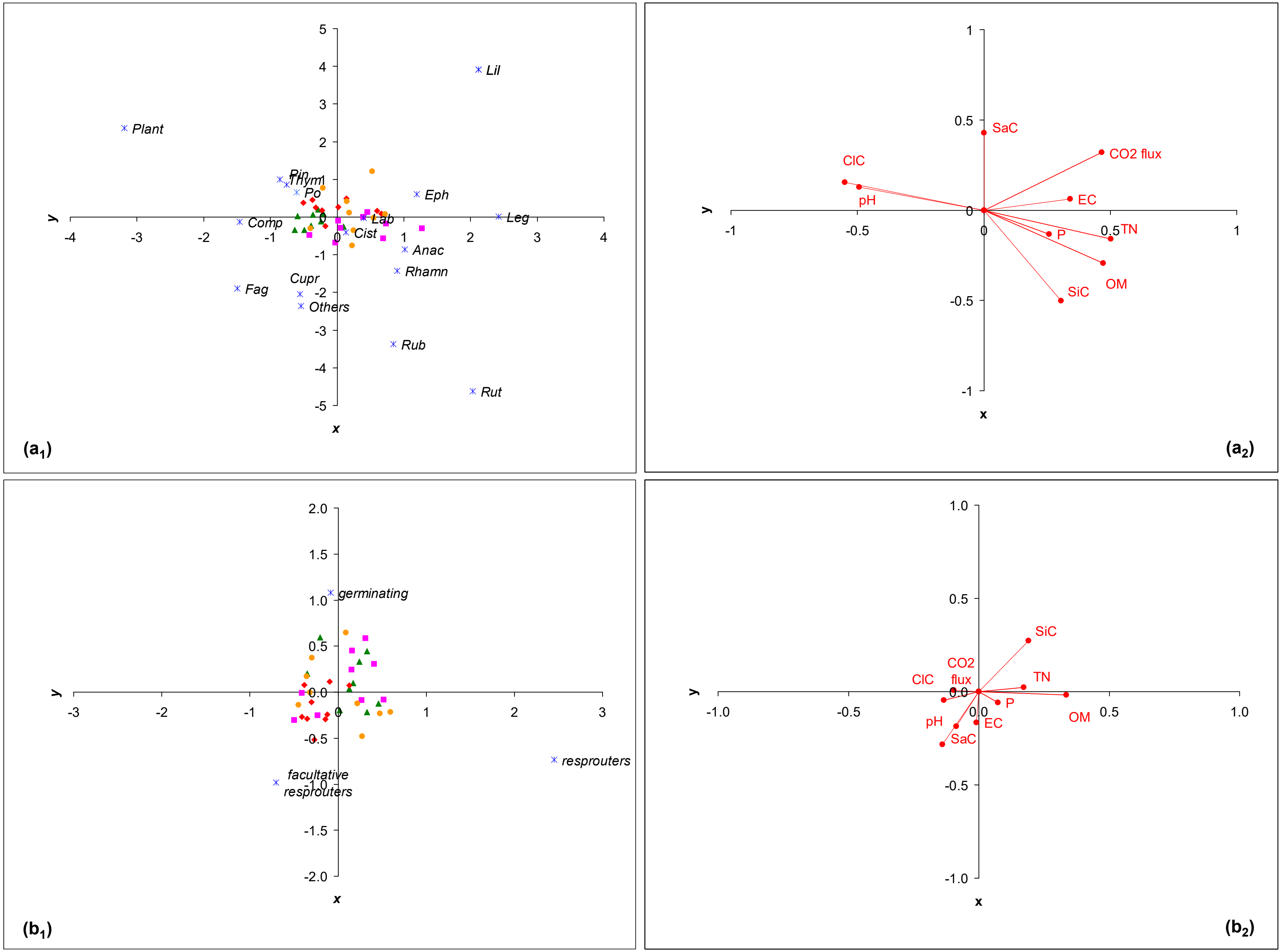
3.3 Relationships between soil properties and plant diversity

The two-axis provided by CCA explained 19.1%, 27%, and 24.2% of the total inertia in the original variables (main properties of soils, soil condition, and plant characteristics) in relation to family, regeneration mechanism, and layer of plants, respectively (Table 2.SI).

The analysis of relationships between soil properties and plant diversity using CCA showed associations between ClC and pH on one side, and Plantaginaceae (but also Compositae and Fagaceae by a lower extent) on the other side along the x-axis, while other families, such as Liliaceae and Leguminosae grown on soil with high CO_2 flux, and OM and TN contents. Moreover, Liliaceae, Rutaceae and Rubiaceae were arranged along a gradient driven by SaC and SiC (however, by loadings with different signs) on the y-axis. The latter families were more common on

CFD soils, while a higher presence of Plantaginaceae, Compositae and Fagaceae, but also of Thymelaceae, Pinaceae, Poaceae, and Cupressaceae was found in UB plots (Figure 8a).

It is worth to notice that soils with significantly higher OM (CFD plots) and TN (LEB plots) contents compared to BNA soils supported the presence of more resprouting species (Figure 8b). Finally, soils with high pH (UB and BNA plots) and OM (CFD plots) showed abundant tree and herbaceous species (Figure 8c).


(a1)
Lil
Plant
Pin
Thym
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Leg
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Rub
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x
y
(a2)
SaC
CO2 flux
ClC
pH
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TN
OM
SiC
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germinating
resprouters
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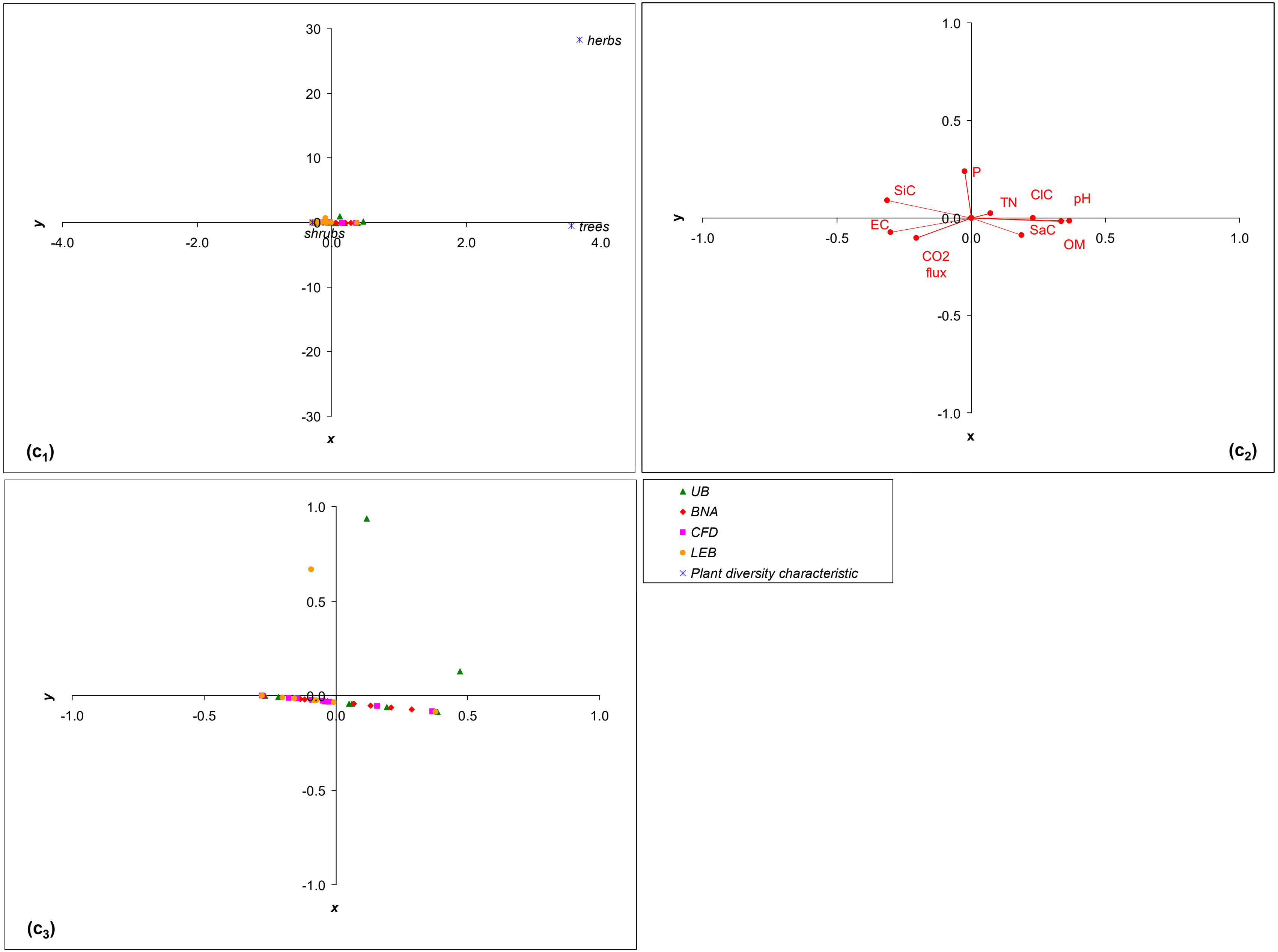
herbs
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flux
(c2)
(c3)
UB
BNA
CFD
LEB
Plant diversity characteristic

Figure 8 – Biplots of Canonical Correspondence Analysis showing associations between soil properties and plant diversity characteristics - plant family (a_1 and a_2), regeneration mechanism (b_1 and b_2), and layer (c_1. c_2, c_3 being a zoomed figure of c_1) - under four soil conditions (UB = unburnt; BNA = burnt and no action; CFD = contour felled log debris; LEB = log erosion barriers) six years after a wildfire in a semi-arid pine forest (Hellín, Castilla La Mancha, Spain). Legend: Anac = Anacardiacea; Cist = Cistaceae; Comp = Compositae; Cupr = Cupressaceae; Eph = Ephedraceae; Fag = Fagaceae; Lab = Labiatae; Leg = Leguminosae; Lil = Liliaceae; Pin = Pinaceae; Plant = Plantaginaceae; Poac = Poaceae; Rhamn = Rhamnaceae; Rub = Rubiaceae; Rut = Rutaceae; Thym = Thymelaceae.

4. DISCUSSIONS

4.1 Variability of soil properties among the four soil conditions

The forest soils in the study area were poor in organic matter and nutrients, and showed poorly developed profiles with a calcic horizon formed by the accumulation of carbonates; their edaphogenic processes were slow, due to the peculiar structure and functioning of their microbial communities (Maestre et al., 2015).

In general, the changes in soil texture due to fire and treatments were not significant. Only, a noticeably lower clay content was measured in the treated soils (mainly in plots with CFD), which could be due to erosion and sedimentation processes resulting from the presence of logs. The presence of small transverse structures on soils may have acted as obstacles for the water sediment flows, determining a selective sorting of the solid material (more or less similar as what can be observed in check dams built on torrent, e.g. Lucas-Borja et al., 2021b). The clayey sediments deposited behind the CFDs or LEBs (due to the milder slope upstream), while the downstream sites may have been subjected to local erosion (due to the unsaturated stream flow), flushing away the finer fractions of sediments. Moreover, in CFD plots, which can store much of the sediment generated in an average year (Wagenbrenner et al., 2006), these processes also led to a mobilization of silt, which was significantly increased. Literature shows that textural changes induced by fire are generally limited (Certini, 2005; Navidi et al., 2022; Zavala et al., 2014), but the clay fraction is the most sensitive both to high temperatures (Muñoz-Rojas et al., 2016) and to treatments, especially in Mediterranean semi-arid areas (Inbar et al., 2014). An enrichment in finer sediments is beneficial for some ecosystem functions such as water cycling in soils, since water retention capacity is enhanced and therefore plant growth is supported, which is essential in semi-arid environments affected by water shortage (Carmona-Yáñez et al., 2023; Pausas et al., 2004).

The medium-term values of pH and EC were not significantly affected by wildfire and post-fire management, apart from slight decreases in pH (significant only in CFD soils). Presumably, after changes in these properties due to fire (which tends to reduce pH and increase EC, due to ash and charred residues (Agbeshie et al., 2022; Pereira et al., 2018;

Ulery et al., 1993), the almost full restoration of pre-fire values was due to soil leaching caused by rainwater infiltration (Mataix-Solera and Cerdà, 2009; Muñoz-Rojas et al., 2016).

Organic matter (OM) content in undisturbed soil was quite low compared to the typical values shown by soils of semi-arid forests and scrublands (Caon et al., 2014). Compared to burnt and untreated plots, OM significantly increased in CFD (+37.5%) and mainly in LEB (+64.9%) soils. The same trends were detected for nutrients (namely nitrogen and phosphorous), with significant increases in CFD (+19.7% for TN, and +29.6% for P) and in LEB (+56.4% for TN and +130% for P) sites. These increases may be due to deposition of charred vegetation and burnt residues close to the structures, which is enhanced in soils treated with LEBs, which are less pervious to water and sediment flows and therefore are able to store more sediments carrying OM and nutrients (Pérez-Cabello et al., 2011; Robichaud et al., 2008; Wohlgemuth et al., 2009). As mentioned above, the transverse structures reduced the flows of water, sediments and dissolved and suspended compounds downstream, favouring the redistribution and storage of OM and nutrients on soils. In this regard, it is worth to mention that the increases in OM and TN detected in LEB soils were also significant when compared to CFD plots. This means that the stabilization treatments, which were timely implemented after the wildfire, were effective in limiting the fire-related declines of OM and nutrients (Caon et al., 2014), and this effectiveness was higher for LEBs. A higher content of OM and nutrients in soil support essential ecosystem functions, such as carbon stock storage and nutrient cycling (Lucas-Borja et al., 2022b; Pereira et al., 2023), which enhances plant growth in semi-arid soils that generally show low fertility (Caon et al., 2014).

Finally, soil respiration, which did not substantially vary between burnt and untreated areas, was higher in both CFD (+21.3%) and LEB (+58.1%, significantly in this case). This increase may be associated to the increased contents of OM and nutrients, which should have supported ash and litter incorporation and microbial decomposition (Luo and Zhou, 2010; Pereira et al., 2013).

4.2 Variability of plant diversity among the four soil conditions

It is well known that burning and subsequent plant re-establishment switch vegetation structure and plant community physiognomy (Williams et al., 2019). In our study, species richness and evenness as well distributions of species between vegetation layers and regeneration mechanisms were slightly influenced by soil disturbances resulting from wildfire and post-fire management, although a significant decrease in species richness was detected in CFD soils compared to both burnt and untreated plots. This is somewhat surprising, considering the beneficial effects of this treatment on organic matter and nutrient dynamics. However, this decrease is limited and does not lead to significant differences in comparison with the unburnt sites. This means that it is true that CFD may lead to lower plant diversity, but this treatment may also result in a more mature structure of vegetation, with tree species prevailing on herbaceous vegetation. This effect coincides with the chronosequence described for these zones by other authors, consisting of a first phase of dominance of herbaceous plants in post-fire vegetation, and a following phase with the increase in interspecific competition leading to the disappearance of the first colonizing herbaceous plants of the first phase, which result in an edaphic improvement (Moya et al., 2018).

The similar species richness recorded in the natural evolution of the burnt and untreated stand shows that the vegetation response to fire is favourable, and this confirms the high resilience to fire of these forest stands, thanks to the adaptation of Mediterranean species to this disturbance (Buhk et al., 2005). Despite the disappearance after the wildfire of the entire tree layer of *Pinus halepensis*, shrubs rapidly recolonize in the burnt sites, and a vertical stratification of the herbaceous and shrub layers towards the pre-fire level is observed.

In the post-fire natural evolution of vegetation, wildfire reduced Pinaceae (with regenerating *Pinus halepensis*) and Cistaceae, but not Poaceae, and noticeably increased Leguminosae compared to unburnt sites. The post-fire treatments altered this plant composition, showing further reductions in Poaceae and Pinaceae as well increases in Leguminosae (both in CFD and LEB sites) and Cistaceae (the latter only in CFD plots). The noticeable reductions detected in LEB sites may be due to the negative effect of the accumulation of residues on seed germination.

Moreover, the plant regeneration mechanisms are not significantly affected by the fire either post-fire management. Despite this lack of significance, both CFD and LEB treatments seem to balance the post-fire shift of germinating species to resprouters. Among the obligate seeders we highlight the dominance (in terms of composition) of the woody *Cistus clusii*, *Halimium halimifolium* and *Pinus halepensis*, and the herbaceous *Klasea flavescens*. The high germination response to fire of Cistaceae (*Cistus clusii* and *Halimium halimifolium*) has been documented in stands of the southeast of the Iberian Peninsula (Buhk and Hensen, 2005). Their germination is stimulated by fire, when the high temperatures break the dormancy of seeds, thus allowing the colonization of the new open spaces with its seedlings. In the case of *Pinus halepensis*, the dominant tree species in the burnt forest, abundant seeds are dispersed from the serotinous cones, whose opening is stimulated by the high temperatures during the fire. Finally, the composite *Klasea flavescens* shows a seed bank that is dispersed by wind. Within the facultative plants, the dominance of *Brachypodium retusum*, an abundant herbaceous plant in the pine forests of the area that plays an important role in soil protection (Raventós et al., 2012), can be considered as a beneficial effect of post-fire treatments against erosion in sites where the plant cover is compromised (Gimeno et al., 2005). The general decrease in resprouting species in the treated soils compared to the burnt and untreated plots leads to a slower vegetal regeneration patterns, since resprouting is the most rapid mechanism of post-fire plant regrowth, while the recovery of non-resprouting species is slower and depends on many factors, such as the plant maturity to produce seeds and the seed resistance to the fire (Bodí et al., 2012). However, the regeneration mechanisms detected for soils treated with LEBs and CFDs are very similar to the patterns in unburnt plots, and this means that the plant growth and forest productivity at the ecosystem level do not result in noticeable alterations due to the fire effects.

Regarding vegetation structure, post-fire treatments differently supported the vertical development of the tree layers. Tree plants were higher in CFD sites and herbaceous plants were more abundant in LEB areas (as noticed in UB plots), while shrubs were similarly distributed among the four soil conditions. The positive effects of LEBs on growth of herbaceous plants can be explained by the accumulation of resources (nutrients and water) close to the structures as well as by soil shading, with consequent improvement of microclimatic conditions. It is worth to notice that the decrease in herbaceous plants in CFD sites suggests that either these structures hamper site colonisation by these species, due to its shading effect, or that CFDs accelerate soil cover of woody species. This acceleration increases interspecific competition for resources (light, water and nutrients) that leads to an early disappearance of herbs.

If we consider that the communities dominated by resprouting species are more resistant to fire, given their shorter response to its impact as well as lower dependence on subsequent climatic conditions together with their lower flammability (Santana et al., 2018), this study shows that CFD structures induce less resilient communities to fire compared to LEB treatments, since the latter reduce the presence of resprouters, and specifically of Cistaceae, but do not alter the presence of resprouting plants that maintain similar growth dynamics in all soil conditions.

Overall, as demonstrated by Tangney et al. (2022), plant recovery processes after wildfires are temperature and moisture dependant. Therefore, different post-fire management strategies, which may change microclimatic conditions, result in delayed or failed emergence and survival of plants. Moreover, our results also have demonstrated that micro-edaphic conditions and species-specific factors may be linked to different plants adaptation capacity to after wildfire environmental conditions (Fernández-García et al., 2021). These insights into how vegetation is influenced by soil, and vice-versa in wildfire Mediterranean burnt areas are of capital importance to increase the success of forest restoration strategies.

5. CONCLUSIONS

This study has evaluated the changes in the main physico-chemical properties of soil and plant diversity six years after a wildfire and post-fire treatments using contour felled log debris (CFD) and log erosion barriers (LEB) in a Mediterranean pine forest in comparison to unburnt (UB), and burnt but untreated (BNA) sites.

Soil texture did not generally change after wildfire and treatments, except for significantly lower clay content in both treated soils, and higher silt fraction in plots with CFD. The long-term values of pH and EC were not significantly affected by wildfire and post-fire management, apart from slight decreases in pH (significant only in CFD soils). LEB soils showed significantly higher organic matter, nitrogen, phosphorous, and soil respiration compared to both UB and BNA plots, while only the increase in organic matter was significant for CFD soils.

A noticeable decrease in species richness was detected in CFD soils compared to BNA plots (showing the highest plant diversity), but this decrease was not significant compared to UB plots. Herbaceous plants were found only in UB and LEB sites, the latter showing a decrease in the tree species, while shrubs were equally distributed among the four soil conditions. Resprouting species increased in LEB and mainly in CFD sites compared to BNA area, and this shows the higher long-term resilience of areas treated with CFD to wildfire. Germinating species were present under all soil conditions, and especially in UB sites.

The analysis of relationships between soil properties and plant diversity using CCA showed that, when organic matter (CFD plots) and nitrogen (LEB plots) contents are noticeably higher compared to BNA soils, more resprouting species are detected. Moreover, significant increases in pH (UB and BNA plots) and organic matter (CFD plots) are associated to more abundant tree and herbaceous species.

Therefore, the working hypothesis that the changes in soil properties due to wildfire and post-fire management may noticeably drive plant diversity in semi-arid pine forests in the medium-term is confirmed by this study, which furthermore indicates to forest managers the most resilient plant species after post-fire restoration several years after a wildfire under Mediterranean conditions.

Overall, the post-fire treatments influence the process of burnt space recolonization by vegetation, altering the composition and structure of plant communities. The relationships between soil properties and plant diversity showed that there was a general tendency to recover pre-fire levels, which should not be considered as a sign of stability in the nutritional status of the ecosystem, but rather evidence of loss of fertility, due to erosion processes that will be compensated by the execution of post-fire treatments.

TABLES OF NOMENCLATURE

UB = unburnt

BNA = burnt and no action

CFD = contour felled log debris

LEB = log erosion barriers

SaC = sand content

SiC = silt content

ClC = clay content

EC = electrical conductivity

OM = organic matter

TN = total nitrogen

P = phosphorous

SR = species richness

PI = Pielou index

Anac = Anacardiacea
Cist = Cistaceae
Comp = Compositae
Cupr = Cupressaceae
Eph = Ephedraceae
Fag = Fagaceae
Lab = Labiatae
Leg = Leguminosae
Lil = Liliaceae
Pin = Pinaceae
Plant = Plantaginaceae
Poac = Poaceae
Rhamn = Rhamnaceae
Rub = Rubiaceae
Rut = Rutaceae
Thym = Thymelaceae
s = germinating
sp = resprouting
fsp = facultative resprouting
t = tree
s = shrub
h = herb.

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Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Maria Elena Gómez-Sánchez, Daniel Moya, Jorge de las Heras, Demetrio Antonio Zema, and Manuel Esteban Lucas-Borja. The first draft of the manuscript was written by Maria Elena Gómez-Sánchez, Demetrio Antonio Zema, and Manuel Esteban Lucas-Borja, and all authors commented on previous versions of the manuscript. The final revision was made by Dr. Pedro Antonio Plaza Alvarez, University of Castilla La Mancha, Albacete, Spain (pedro.plaza@uclm.es). All authors read and approved the final manuscript.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Supplementary Information

Table 1.SI - Analysis of similarity percentages (SIMPER) in plant diversity between pairs of soil conditions (UB = unburnt; BNA = burnt and no action; CFD = contour felled log debris; LEB = log erosion barriers) six years after a wildfire in a semi-arid pine forest (Hellín, Castilla La Mancha, Spain).

Species	**Avg. Abundance**	**Avg. Abundance**	**Avg. Dissimilarity**	**Contribution (%)**	**Cumulative (%)**
Soil conditions UB & BNA	UB	BNA	Average dissimilarity = 58.38		
Cistus albidus	12.41	0.00	6.34	10.85	10.85
Brachypodium retusum	15.38	11.78	4.85	8.31	19.16
Mcrochloa tenacissima	5.72	13.89	4.24	7.26	26.42
Halimium halimifolium	8.63	3.39	3.75	6.43	32.84
Quercus coccifera	7.18	1.13	3.51	6.01	38.85
Cistus clusii	1.13	6.28	2.85	4.88	43.73
Klasea flavescens subsp. *leucanta*	6.23	2.19	2.80	4.80	48.53
Fumana ericoides	4.45	8.36	2.71	4.63	53.16
Anthyllis cytisoides	0.00	4.72	2.45	4.20	57.36
Pinus halepensis	9.20	7.63	2.25	3.86	61.22
Rhamnus lycioides	2.35	4.04	2.23	3.82	65.04
Juniperus oxicedrus	4.24	1.05	2.20	3.76	68.80
Rosmarinus officinalis	4.87	7.60	2.07	3.55	72.35
Helianthemum cinereum	2.11	3.94	1.66	2.85	75.20
Pistacia lentiscus	2.97	0.50	1.65	2.83	78.03
Brachypodium phoenicoides	2.25	1.24	1.56	2.67	80.69
Helianthemum syriacum	2.46	1.21	1.47	2.52	83.22
Thymelaea argentata	3.32	3.03	1.46	2.50	85.72
Linum suffruticosum	0.00	2.74	1.38	2.37	88.09
Teucrium capitatum	1.25	1.77	1.21	2.07	90.16

Soil conditions UB & CFD	UB	CFD	Average dissimilarity = 60.83		
Anthyllis cytisoides	0.00	10.10	5.63	9.26	9.26
Brachypodium retusum	15.38	9.55	5.29	8.70	17.96
Cistus albidus	12.41	11.05	4.60	7.57	25.53
Halimium halimifolium	8.63	3.16	4.31	7.09	32.62
Quercus coccifera	7.18	1.41	3.93	6.46	39.08
Klasea flavescens subsp. *leucanta*	6.23	0.00	3.36	5.53	44.61
Cistus clusii	1.13	5.50	2.78	4.57	49.17
Macrochloa tenacissima	5.72	3.86	2.75	4.52	53.69
Juniperus oxicedrus	4.24	4.19	2.71	4.46	58.15
Pinus halepensis	9.20	6.81	2.70	4.44	62.59
Rhamnus lycioides	2.35	4.61	2.43	3.99	66.59
Fumana ericoides	4.45	0.96	2.33	3.84	70.42
Pistacia lentiscus	2.97	2.38	2.26	3.72	74.15
Helianthemum cinereum	2.11	4.48	2.13	3.51	77.65
Rosmarinus officinalis	4.87	5.50	2.09	3.43	81.08
Thymelaea argentata	3.32	0.00	1.82	2.99	84.07
Centaurea antennata	0.00	2.73	1.46	2.41	86.48
Helianthemum syriacum	2.46	0.00	1.39	2.29	88.77
Brachypodium phoenicoides	2.25	0.00	1.29	2.12	90.88
Soil conditions BNA & CFD	BNA	CFD	Average dissimilarity = 59.42		
Cistus albidus	0.00	11.05	6.43	10.82	10.82
Macrochloa tenacissima	13.89	3.86	5.73	9.64	20.46
Anthyllis cytisoides	4.72	10.10	4.95	8.33	28.79
Fumana ericoides	8.36	0.96	4.36	7.34	36.13
Brachypodium retusum	11.78	9.55	3.71	6.24	42.37
Rhamnus lycioides	4.04	4.61	2.87	4.83	47.20
Juniperus oxicedrus	1.05	4.19	2.60	4.37	51.58
Halimium halimifolium	3.39	3.16	2.51	4.23	55.81

Cistus clusii	6.28	5.50	2.48	4.17	59.97
Pinus halepensis	7.63	6.81	2.29	3.86	63.83
Helianthemum cinereum	3.94	4.48	2.21	3.72	67.55
Rosmarinus officinalis	7.60	5.50	2.11	3.56	71.10
Thymelaea argentata	3.03	0.00	1.74	2.93	74.03
Pistacia lentiscus	0.50	2.38	1.58	2.66	76.70
Centaurea antennata	0.50	2.73	1.57	2.65	79.34
Linum suffruticosum	2.74	0.00	1.54	2.60	81.94
Retama sphaerocarpa	2.18	0.35	1.31	2.21	84.15
Klasea flavescens subsp. *leucanta*	2.19	0.00	1.29	2.16	86.31
Quercus coccifera	1.13	1.41	1.26	2.11	88.43
Teucrium capitatum	1.77	0.00	0.97	1.64	90.07
Soil conditions UB & LEB	UB	LEB	Average dissimilarity = 61.55		
Brachypodium retusum	15.38	9.98	5.19	8.42	8.42
Cistus albidus	12.41	7.19	4.83	7.84	16.27
Halimium halimifolium	8.63	1.15	4.41	7.16	23.43
Anthyllis cytisoides	0.00	6.78	3.69	5.99	29.42
Quercus coccifera	7.18	3.30	3.54	5.76	35.18
Klasea flavescens subsp. *leucanta*	6.23	0.00	3.35	5.44	40.62
Macrochloa tenacissima	5.72	6.78	3.26	5.30	45.91
Pinus halepensis	9.20	4.81	3.12	5.07	50.98
Asphodelus cerasiferus	0.00	4.78	2.58	4.19	55.17
Juniperus oxicedrus	4.24	2.81	2.51	4.07	59.25
Rosmarinus officinalis	4.87	6.96	2.22	3.60	62.85
Fumana ericoides	4.45	2.87	2.14	3.48	66.32
Rhamnus lycioides	2.35	2.98	2.13	3.47	69.79
Cistus clusii	1.13	4.06	2.01	3.26	73.05
Pistacia lentiscus	2.97	1.66	2.00	3.25	76.30
Brachypodium phoenicoides	2.25	2.91	1.88	3.06	79.36

Thymelaea argentata	3.32	0.78	1.71	2.78	82.14
Centaurea antennata	0.00	2.69	1.52	2.46	84.60
Helianthemum syriacum	2.46	0.00	1.39	2.25	86.85
Helianthemum cinereum	2.11	2.11	1.30	2.11	88.96
Retama sphaerocarpa	0.00	1.96	1.07	1.73	90.69
Soil conditions BNA & LEB	BNA	LEB	Average dissimilarity = 56.33		
Macrochloa tenacissima	13.89	6.78	4.46	7.92	7.92
Cistus albidus	0.00	7.19	4.28	7.59	15.51
Anthyllis cytisoides	4.72	6.78	3.77	6.70	22.22
Brachypodium retusum	11.78	9.98	3.55	6.31	28.52
Fumana ericoides	8.36	2.87	3.32	5.89	34.41
Rhamnus lycioides	4.04	2.98	2.77	4.91	39.32
Asphodelus cerasiferus	0.00	4.78	2.69	4.77	44.09
Pinus halepensis	7.63	4.81	2.52	4.47	48.56
Cistus clusii	6.28	4.06	2.08	3.68	52.24
Halimium halimifolium	3.39	1.15	2.05	3.65	55.89
Quercus coccifera	1.13	3.30	2.00	3.54	59.43
Brachypodium phoenicoides	1.24	2.91	1.99	3.54	62.97
Helianthemum cinereum	3.94	2.11	1.98	3.51	66.48
Juniperus oxicedrus	1.05	2.81	1.87	3.33	69.80
Rosmarinus officinalis	7.60	6.96	1.76	3.12	72.92
Retama sphaerocarpa	2.18	1.96	1.68	2.98	75.90
Thymelaea argentata	3.03	0.78	1.60	2.85	78.75
Centaurea antennata	0.50	2.69	1.59	2.82	81.56
Linum suffruticosum	2.74	0.00	1.54	2.73	84.29
Klasea flavescens subsp leucanta	2.19	0.00	1.28	2.27	86.56
Pistacia lentiscus	0.50	1.66	1.14	2.02	88.58
Teucrium capitatum	1.77	0.00	0.97	1.72	90.30
Soil conditions CFD & LEB	CFD	LEB	Average dissimilarity = 54.34		

Cistus albidus	11.05	7.19	5.09	9.36	9.36
Anthyllis cytisoides	10.10	6.78	4.65	8.56	17.92
Macrochloa tenacissima	3.86	6.78	3.69	6.79	24.71
Brachypodium retusum	9.55	9.98	3.10	5.71	30.42
Rhamnus lycioides	4.61	2.98	3.05	5.61	36.03
Asphodelus cerasiferus	0.00	4.78	2.90	5.34	41.37
Juniperus oxicedrus	4.19	2.81	2.85	5.24	46.61
Cistus clusii	5.50	4.06	2.61	4.80	51.42
Pinus halepensis	6.81	4.81	2.55	4.69	56.10
Helianthemum cinereum	4.48	2.11	2.53	4.65	60.75
Quercus coccifera	1.41	3.30	2.41	4.44	65.19
Rosmarinus officinalis	5.50	6.96	2.28	4.20	69.38
Halimium halimifolium	3.16	1.15	2.20	4.05	73.43
Pistacia lentiscus	2.38	1.66	2.09	3.85	77.28
Centaurea antennata	2.73	2.69	2.05	3.77	81.05
Brachypodium phoenicoides	0.00	2.91	1.80	3.31	84.36
Fumana ericoides	0.96	2.87	1.69	3.12	87.48
Retama sphaerocarpa	0.35	1.96	1.28	2.35	89.83
Ephedra fragilis	0.00	1.60	0.97	1.78	91.61

Table 2.SI – Eigenvalues, and constrained and total inertia of the original variables (main properties of soils, soil condition, and plant family, regeneration mechanism, and layer of vegetation) on the axis provided by Canonical Correspondence Analysis (UB = unburnt; BNA = burnt and no action; CFD = contour felled log debris; LEB = log erosion barriers) six years after a wildfire in a semi-arid pine forest (Hellín, Castilla La Mancha, Spain).

Eigenvalues			**Constrained inertia (%)**			**Total inertia (%)**		
Family	*Regeneration mechanism*	*Layer*	*Family*	*Regeneration mechanism*	*Layer*	*Family*	*Regeneration mechanism*	*Layer*
0.127	0.041	0.013	39.350	85.070	79.670	11.780	22.950	19.250
0.079	0.007	0.003	24.430	14.930	20.330	7.316	4.027	4.914
0.050			15.480			4.637		
0.046			14.160			4.241		
0.012			3.819			1.144		
0.006			1.876			0.562		
0.003			0.875			0.262		
< 0.001			< 0.001			< 0.001		
< 0.001			< 0.001			< 0.001		