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

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Abstract

Straw and wood chips have been widely used as mulch materials to control post-fire erosion in burned forests. However, their effects on ecosystem multifunctionality (EMF) have been little explored. This information is essential to give forest managers insight about the effectiveness of these strategies for restoration of severely-burned forests. To fill this gap, this study has evaluated the short-term (one year after wildfire) changes in ecosystem properties (associated to soil characteristics), structure (linked to plant diversity), individual ecosystem functions, and EMF in a Mediterranean forest. This delicate ecosystem was burned by a wildfire and then mulched with straw or wood chips, and EMF in these conditions was compared to burned and untreated, and unburned sites. The results have shown that: (i) neither wildfire nor mulching significantly changed soil properties with the exception of pH; (ii) in contrast, ecosystem structure significantly declined in mulched plots due to wildfire, and mulching did not limit the alteration in species richness; (iii) among the analysed ecosystem functions, waste decomposition and nutrient cycling, which were significantly higher in unburned soils compared to burned sites, showed intermediate and similar values in mulched plots, while water cycle and wood production (the latter with the exception of unburned plots) were similar among all soil conditions, and climate regulation was significantly higher only in soils mulched with wood chips compared to burned sites ; (iv) EMF increased from burned and untreated soils to unburned sites; (v) mulching was effective at limiting the reduction in EMF due to wildfire, but only partially dampened the impact of the fire. Moreover, the combined analysis of ecosystem properties, structure and functions, and EMF revealed that: (i) all functions, except water cycle, were associated to one or more soil or vegetation parameters; (ii) species community composition noticeably influenced several ecosystem functions, and, therefore, EMF; (iii) species richness is a key driver of wood production; (iv) pH, which was found as the most influential soil property on ecosystem functions and EMF, may be considered as an important ecological predictor of forest functions in basic soils of Mediterranean forests. This study may be of practical importance for policymakers and land managers about the most effective actions to preserve the ecosystem EMF in fragile ecosystems, such as the Mediterranean wildfire-affected forest.

Keywords: ecosystem properties; ecosystem structure; ecosystem functions; soil characteristics; plant diversity; post-fire management.

1. INTRODUCTION

The functionality of the different forest components may be expressed by the ecosystem multifunctionality, which is defined by Byrnes et al. (2014), Maestre et al. (2012) and Mastrangelo et al. (2014) as “the simultaneous provision of multiple services and functions by landscape to society”. In forest ecosystems, these services/functions consist of nutrient cycling (e.g., availability and mineralization of nitrogen, phosphorous and other elements/compounds), climate regulation, water cycle, waste decomposition (e.g., lignin and cellulose degradation), and wood production (Aponte et al., 2013; Byrnes et al., 2014; Ushio et al., 2010). Moreover, all these functions are more and more important in endangered Mediterranean forests, where natural environmental stresses (i.e., climate change, pests and diseases, drought, natural fires) sum up to anthropogenic pressure (i.e., excessive harvesting, fraudulent fires, soil compaction due to machinery use), with great threatens for provisioning of ecosystem services. Therefore, a better understanding of how ecosystem multifunctionality develops in Mediterranean forests is essential, in order to limit ecosystem degradation and conserve its health (Ferguson, 1996; Lucas-Borja et al., 2021a), also in view of the forest ecosystem sustainability in the long term under the pressure of climate change (Bazzaz, 1979; Poorter et al., 2021). It is well known how these functions are highly dependent on soil properties and plant diversity (Zhou et al., 2022). According to (Lucas-Borja and Delgado-Baquerizo, 2019), plant diversity increases the heterogeneity of forest resources, such as litter composition and root exudates, which positively influence ecosystem multifunctionality. Plant composition significantly influences several enzymatic activities, specifically related to the cycles of nitrogen, phosphorus, carbon, and sulfur (Bastida et al., 2008; Hedo et al., 2015), and composition of microbial communities (i.e., dehydrogenase activity and soil respiration). In this regard, enzymatic activities are considered one of the best proxies of soil health and activity (Dick et al., 1997). Moreover, the specific composition of tree and other plant species may balance accumulation and loss of soil organic matter, thus supporting the equilibrium in the physico-chemical and microbiological soil properties (Entry and Emmingham, 1998). The latter are numerous, but some key properties are of paramount importance to ensure ecosystem multifunctionality. For instance, soil organic matter is associated to a large variety of other characteristics, such as water repellency, many carbon forms, soil respiration, enzymatic activities, aggregate stability, and content of nutrients (Bastida et al., 2007; Doerr et al., 2000; Entry and Emmingham, 1998). Content and quality of soil organic matter are therefore essential drivers of soil health and, more in general, of ecosystem multifunctionality, since organic compounds support productivity, biodiversity, and other ecosystem services (Lozano-García et al., 2016; van Leeuwen et al., 2014).

Most studies have focused on single ecosystem functions, such as, for example, soil carbon content and nutrients or hydrological aspects, rather than analyzing the overall ecosystem multifunctionality. The quantification and integration of different community-level properties in standardized indices is therefore advisable, in order to avoid a biased perception of ecosystem multifunctionality, especially when the forest ecosystem is subject to management. This information could lead to better management practices to effectively increase ecosystem health and functions. The use of the ecosystem multifunctionality index (hereafter "EMF"), which summarizes multiple variables that are related to single ecosystem functions into one value, provides a simple metric to assess the overall functioning of ecosystems or treatments within a specific ecosystem (Byrnes et al., 2014). This is important, since EMF makes possible the visualization of trade-offs between different ecosystem functions when evaluating overall ecosystem performance. Moreover, land managers, policy makers and stakeholders get from EMF very clear and concise information about the ecosystem functions after different management options. Overall, the focus on EMF has brought new perspectives on the importance of ecosystem functioning and on the impacts of global change drivers, such as the increases in temperature or the impacts of wetting-drying cycles (Lucas-Borja et al., 2021a).

Among the several disturbances that may affect forest ecosystems, wildfires play a severe impact on EMF, especially in Mediterranean areas (Shakesby, 2011; Wagenbrenner et al., 2021). In these geomorphological and climatic conditions, the wildfire effects may result in increased rates of soil and biodiversity losses (Lindenmayer and Noss, 2006; Nelson et al., 2022; Rodríguez et al., 2017). In Mediterranean forests, soils are shallow and poor in organic matter and nutrients (Cantón et al., 2011) and natural growth of vegetation is hampered by water scarcity (Caon et al., 2014). In order to reduce the soil degradation rates and quickly restore the plant diversity after a wildfire, it is essential to implement effective post-fire management actions (Girona-García et al., 2021; Lucas-Borja, 2021b). When successful, these actions may support the functionality of burned forests, with clear and positive effects on soil health and vegetation survival, and the associated ecosystem services (Neary et al., 2005; Pausas and Keeley, 2019; Pereira et al., 2021). However, post-fire management techniques are many and their impacts on forest components depend on fire severity, post-fire weather conditions, topography, and soil and plant characteristics (Agbeshie et al., 2022; Moody et al., 2013; Shakesby, 2011), and are thus characterized by a large variability. Therefore, there is no clear and unambiguous evidence about the effects of post-fire management on EMF in wildfire-affected forests with different characteristics. For instance, with regard to soil mulching, which is one of the most recommended techniques to restore soil and vegetation and to control surface runoff and erosion after a fire, research has widely explored its effectiveness on the post-fire hydrological and erosive response (e.g., Díaz et al., 2022; Fernández and Vega, 2016; Girona-García et al., 2021; Lopes et al., 2020). Generally speaking, mulching is effective at reducing the soil loss in burned areas (Carrà et al., 2022; Díaz et al., 2022; Fernández and Vega, 2014), although some negative impacts of mulching have been noticed (e.g., decreased water infiltration, displacement of mulch material by wind, diseases and insects brought by agricultural straw, and some cases of increases in post-fire soil erosion (Carrà et al., 2021; Robichaud, 2000). However, few studies have focused on the effects of soil mulching on EMF, due to the large variety of mulch materials (e.g., straw, forest residues, synthetic compounds), environmental characteristics (e.g., soil, vegetation, climate) and fire characteristics (e.g., severity, duration, frequency). In particular, the type of material used for mulching may play differentiated effects on each ecosystem function, due to the specific decomposition velocity into soil, application rates, and chemical composition (Bombino et al., 2021; Díaz et al., 2022; Prosdocimi et al., 2016). Straw and forest residues, such as wood chips, have been widely investigated in many environments for soil mulching after fires of different characteristics (Carrà et al., 2022; 2021; Fernández-Fernández et al., 2016; Lucas-Borja et al., 2021b; Prats et al., 2016), but their effects on EMF have been little explored, at least to our best knowledge. This information is essential to give forest managers insight about their effectiveness on restoration of soil quality and plant diversity in severely-burned forests. Therefore, the need to better understand the interrelationships between soil properties, plant diversity and ecosystem functioning for forest conservation is urgent, to favor one or another type of post-fire management and avoid ecosystem degradation (Wang et al., 2022a, 2022b).

To fill this gap, this study has evaluated the short-term changes in EMF in a Mediterranean forest burned by a wildfire and then mulched with straw or wood chips in comparison to burned and untreated, and unburned sites. To this aim, a case study of a pine forest of Castilla La Mancha (Central Eastern Spain) has been analyzed throughout one year after the wildfire, where the treatments were implemented three months after the wildfire and the changes in some ecosystem properties (associated to soil characteristics), structure (linked to plant diversity), individual functions, and EMF were monitored for nine months after mulching. The specific objectives of the study are: (i) evaluating whether some selected ecosystem properties, structure, individual functions, and EMF are influenced by wildfire and post-fire mulching using straw or wood chips in comparison to the unburned sites; and (ii) exploring the possible associations among the ecosystem functions and EMF on one side and the soil properties and plant diversity characteristics on the other side in semi-arid Mediterranean forests. The hypothesis of this study is that post-fire forest management using straw and wood chips is beneficial to EMF.

2. MATERIAL AND METHODS

2.1. Study area

The study area is a pine forest in the municipality of Liétor (geographical coordinates: 38º30’41” N; 1º56’35” W, Region of Castilla La Mancha, Spain) (Figure 1). This forest area has an elevation between 520 and 770 m a.s.l., is exposed to north-west, and its slope range between 15 and 25%. The climate, which is typical of many Mediterranean areas, is "cold semi-arid" (BSk type), according to the Köppen classification (Kottek et al., 2006). The annual temperature is on average 16.6 °C, and the precipitation is 321 mm/yr, according to the weather data of the last 20 years, meteorological station of Hellín, about 20 km far from Liétor (Spanish Meteorological Agency, AEMET). Soils are classified as Calcic Aridisols (Nachtergaele 2001), and their texture is sandy loamy.

Overstorey vegetation includes a tree layer of *Pinus halepensis* Mill. (natural and reforested stands of Aleppo pine, about 60-70 years old) and a shrub layer of *Quercus cocciferae* (kermes oak) (Peinado et al., 2008). The pre-fire tree density and height were between 500 and 650 trees/ha and 7 to 14 m, respectively. *Rosmarinus officinalis* L., *Brachypodium retusum* (Pers.) Beauv., *Cistus clusii* Dunal, *Lavandula latifolia* Medik., *Thymus vulgaris* L., *Helichrysum stoechas* L., *Macrochloa tenacissima* L., *Quercus coccifera* L. and *Plantago albicans* L. compose the understorey vegetation.

In July 2021, a wildfire burned ground vegetation and litter as well as tree crowns (mortality of 100%) in about 2500 ha of the studied forest (Figure 1). Soil burn severity was classified as “high”, according to Vega et al. (2013), which is based on visual indicators to identify burn severity of soil (Parson et al., 2010).

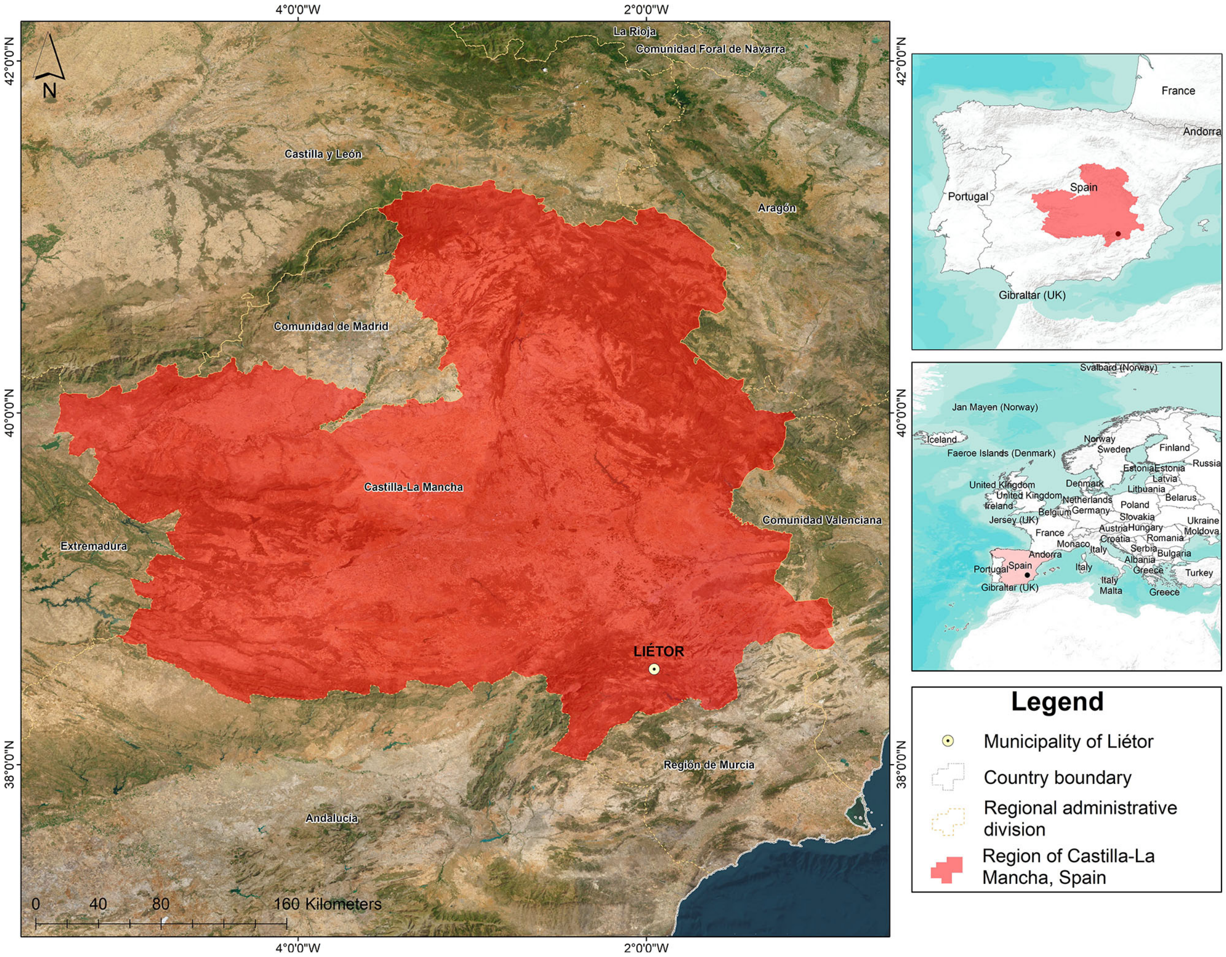


Figure 1 - Location of the study area (Liétor, Castilla La Mancha, Central-Eastern Spain).

Immediately after the wildfire, the regional Forest Service treated part of burned forest area with mulches of wheat straw, and another part with wood chips, in order to reduce the possible post-fire increases in surface runoff and erosion.

The selected experimental site is representative of recently burned forest areas of the Mediterranean environment. The absence of active forest management in the last decades, coupled to the homogeneous ecological, physiographical, and climatic conditions of the study area, allow the associations of changes in forest ecosystem structure, functions and properties to wildfire and post-fire management strategies.

2.2. *Experimental design*

A site of 700 ha was selected in the forest one week after the wildfire. In this site, 27 plots (each of 10 m x 10 m, covering 100 m^2) were defined at a minimum reciprocal distance of approximately 500 metres, to avoid pseudo-replication. Of these plots, eight were installed in a burned but not treated site, while other 16 plots were located in burned and mulched sites. Mulching was carried out in late October 2021 (three months after the wildfire) in two burned sites: in the first site, wheat straw was used, while pine wood chips were distributed in the second site. Eight plots were therefore considered in each site. The main characteristics (mean values) of the mulch materials were the following: (i) dose of 0.3 (wood chips) and 0.2 (straw) kg/m^2; (ii) length of 3-10 (wood chips) and 5-25 (straw) cm; (iii) width of 2-4 (wood chips) and 0.25-1.0 (straw) cm; (iv) thickness of 1-2 (wood chips) and 0.1-0.7 (straw) cm; (v) density: 500-550 (wood chips) and 80-100 (straw) kg/m^3.

The application doses were adopted based on indications by the forest services of the Iberian Peninsula, since these values were widely recommended in literature (e.g., Girona-García et al., 2021; Kim et al., 2008; Lucas-Borja et al., 2019). During the one-year observation period (between July 2021 and July 2022), the rainfall was 413 mm, distributed in 236 events up to 43.4 mm (March 2022), while the maximum intensity was 58 mm/h in 30 minutes.

Finally, a further group of three plots was identified in an unburned area in proximity of the burned sites, and assumed as control.

The experimental design therefore consisted of four soil conditions (unburned soil, burned and untreated soil, burned soil mulched with straw, and burned soil mulched with wood chips) × eight replicated plots (except the UB site, where the replicated plots were three). Hereafter, the four soil conditions will be indicated as “B” for burned soils, “M(WC)” for soils mulched with wood chips, “M(WS)” for plots treated with straw mulch and “UB” for unburned soils.

2.3. *Soil sampling and analysis*

Soil was sampled in the 27 plots in July 2022 - 12 months after the wildfire and 9 after the post-fire treatments - collecting 27 samples of 600 g from the top 5 cm of surface. Each soil sample contained six sub-samples of 100 g collected in randomly-selected points (at a reciprocal distance higher than 5 m), in order to capture the potential variability of soil properties at each plot. Prior to sampling, the litter layer was removed from the soil surface. After collection, each sample was brought to laboratory, where it was passed through a 2-mm sieve and then stored at 4 °C until the analyses in the following day.

The following soil physico-chemical properties were determined on the collected samples: (i) texture (contents of sand, silt and clay), according to the method of Guitian Ojea and Carballas (1976); (ii) pH and electrical conductivity (EC), determined in distilled water, at a soil:solution ratio of 1:2.5 by a multiparameter portable device (Hanna Instruments® model HI2040-02, Gipuzkoa, Spain); (iii) total organic carbon (TOC), by the potassium dichromate oxidation method (Nelson and Sommers, 1996) and multiplication of the resulting organic matter content by 0.58 (Brady et al., 2008; Guo and Gifford, 2002); (iv) total nitrogen (TN), using Kjeldhal's method as modified by (Mulvaney and Bremner, 1978); (v) phosphorous (P) and cations (potassium, K^+, calcium, Ca^{2+}, and sodium, Na^+), by ICP spectrometry after nitric-perchloric acid digestion; (vi) carbonates (CO_3^-), using the methods by Ulmer et al. (1992). The Kjeldahl method measures organic and ammonia nitrogen, but, due the low presence of nitrites and nitrates this method is representative of TN. Nitrites are unstable forms of nitrogen, since these compounds are easily oxidised to nitrates, and nitrates are generally leached into the deeper layers of soil, and therefore their contributions to TN were negligible.

Regarding the enzymatic activities, basal soil respiration (BSR, expressed as mg C-CO_2 kg^{-1} day^{-1} of dry soil) was measured using an infrared CO_2 sensor (IRGA S151, Qubit Systems Inc., Canada). Soil dehydrogenase activity (DHA, expressed as μmol INTF $hour^{-1}$ g^{-1} of dry soil) was determined by the reduction of p-iodonitrotetrazolium chloride (INT) to p-iodonitrotetrazolium formazan (INTF) following Garcia et al. (1997). Urease activity (UA), expressed as μmol N-NH^{4+} $hour^{-1}$ g^{-1} of dry soil), was measured using urea as a substrate and a borate buffer at pH of 10 (Kandeler and Gerber, 1988). The activity of alkaline phosphatase (Alk-PA) and β-glucosidase (BGA), both expressed as μmol pNP $hour^{-1}$ g^{-1} of dry soil, were determined using the methods by Tabatabai and Bremner (1969) and Eivazi and Tabatabai (1977) , respectively. The values of all soil properties were finally averaged among the samples collected in each plot, and then standardized using Eq. 3 (see section 2.6.3).

2.4. Characterization of soil hydrology

Soil hydrological properties were analyzed in terms of surface runoff and soil loss. These variables were determined in a previous study (Díaz et al., 2022) using a Eijelkamp® portable rainfall simulator (Hlavčová et al., 2019; Iserloh et al., 2013). To summarize, the simulator was placed over the ground on a surface area of 0.3 m x 0.3 m, and the height and intensity of the simulated rainfall was setup at 26.7 mm and 320 mm/h, while its duration was 300 s. Throughout the rainfall simulation, the runoff water and sediments were collected in a small bucket. The runoff height in the bucket was measured by a meterstick and subtracted from the rainfall height. The runoff coefficient was calculated as the ratio between the collected runoff and the rainfall depth. The mixtures of water and sediments were finally transported to the laboratory in small bottles, and then oven dried at 105 °C for 24 h. The weight of the sediments was then referred to the area unit, to calculate the soil loss.

2.5. Vegetation survey

A survey of vegetal species was carried out in May 2022 in three 10-m long transects for each plot (right, middle and left). Along each transect, the different vegetal species were identified using the line intercept method (Elzinga et al., 2001). Moreover, tree basal area (TBA) was calculated in each plot, after measuring the cross-sectional area of all trees at breast height using a measuring tape.

2.6. Characterization of forest ecosystem components

In this study, the forest components were characterized in terms of ecosystem properties (associated to soil characteristics), structure (linked to plant diversity), and functions, all of which expressed by a dataset of relevant indicators, in order to define the EMF index. This characterization follows the scheme of Table 1.

Table 1 – Characterization of forest ecosystem components with relevant indicators in the study area (Liétor, *Castilla La Mancha*, Central-Eastern Spain).

Categories	**Properties**	**Indicators**	**Description**
Ecosystem structure	Plant diversity	Species richness	Plant cover recovery after wildfire and effects of post-fire management strategies on plants
		Pielou index	
Ecosystem properties	Physico-chemical soil properties	Soil texture (sand, silt, and clay contents)	Recovery of physico-chemical soil properties after wildfire and effects of post-fire strategies on soil physico-chemical soil properties
		pH	
		EC	
		Carbonates	
Ecosystem functions	Nutrient cycling	Total nitrogen	Soil nutrient recovery after wildfire and effects of post fire strategies on soil nutrients
		Phosphorous	
		Potassium	
		Sodium	
		Calcium	
	Climate regulation	Total Organic Carbon	Climate regulation recovery after wildfire and effects of post-fire strategies on climate
	Waste decomposition	Dehydrogenase activity	Soil enzymatic activity recovery after wildfire and effects of post-fire strategies on soil enzymatic activity
		β-glucosidase activity	
		Urease activity	
		Phosphatase activity	
		Basal soil respiration	
	Wood production	Tree basal area	Wood resources and plant productivity
	Water cycle	Surface runoff coefficient	Water regulation recovery after wildfire and effects of post-fire strategies on water in soil
		Soil loss	

2.6.1. Characterization of ecosystem properties

Ecosystem properties were analyzed using the following soil physico-chemical parameters: (i) texture (sand, silt and clay contents, indicated as SaC, SiC and ClC, respectively); (ii) pH; (iii) electrical conductivity (EC); (iv) carbonate content ($CaCO_3$). The values of all soil properties were then averaged among the samples collected in each plot.

2.6.2. Characterization of ecosystem structure

Several authors are currently considering plant diversity as an ecosystem function or service (e.g., Smukler et al., 2010; van Der Plas et al., 2016a; 2016b). In this study, a special attention was given to plant diversity, which was used as unique descriptor of ecosystem structure, since post-fire vegetation restoration until the pre-fire levels of biodiversity is one of the most important targets for land managers (Lucas-Borja et al., 2021b).
Ecosystem structure was considered a descriptor of plant diversity and was characterized using species richness (SR) and Pielou index (PI) as plant diversity indicators. In more detail, SR is the total number of different species detected in each plot, while PI (Pielou, 1966), which is an index of species evenness, indicates to how close in numbers each species in a given environment is. PI was calculated according to the following equation:

$$PI = \frac{H}{H_{\max}} \qquad (2)$$

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:

$$H = -\sum_{i=1}^{S} p_i \ln p_i \qquad (3)$$

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 value expresses a scarce evenness in communities between the species, that is the presence of a dominant species. The values of plant diversity indexes were finally averaged among the three transects in each plot.

2.6.3. Characterization of ecosystem functions and EMF

EMF index is a simple but powerful index to evaluate ecosystem multifunctionality by a quantitative approach, especially when the ecosystem functions under consideration are many and human impacts (such as forest management or fraudulent wildfires) act as ecosystem disturbance (Lucas-Borja et al., 2021a). This methodology shows some limitations, such as, for instance, the underestimation of large impacts of a single function compared to other, and the difficulty to distinguish among functions, if they are all at high/low level or one at high and the other at low level (Byrnes et al., 2014), but it is easy to apply and meaningful.

Five ecosystem functions were considered to calculate the EMF index using the indicators of Table 1. More specifically, these indicators were first classified into five categories corresponding to five ecosystem functions: (i) nutrient cycling (TN, P, K, Na, and Ca contents of soil); (ii) climate regulation (soil TOC): (iii) waste decomposition (DHA, BGA, UA, Alk-PA, and BSR); (iv) wood production (basal area); (v) and water cycle (surface runoff volume and soil loss) (Table 1). The indicators were standardized using equation (3):

$$EF' = [EF - \min(EF)]/[\max(EF) - \min(EF)] \quad (3)$$

where EF' and EF indicate the transformed and original values of each ecosystem function, respectively. Therefore, the values of EF' were in the range 0 to 1.

Then, EMF was calculated by averaging the values of the ecosystem functions (Jing et al., 2020). Eq. (3) was also used to standardize the indicators that are related to ecosystem properties and structure.

2.7. Statistical analysis

First, a one-way ANOVA was used to evaluate the effects of soil conditions on ecosystem properties, structure, functions, and EMF. The equality of variance and normal distribution are assumptions of the statistical tests; these assumptions were evaluated by normality tests or were square root-transformed, when they did not exhibit a normal distribution. The differences in each soil property among factors were evaluated using the pairwise comparison by Tukey's test (at $p < 0.05$).

Moreover, an ANOSIM (analysis of similarities) routine was used to compare similarities within each soil condition and between pairs. In a robust classification, similarities in the same soil condition should be higher than the similarities among different conditions. A SIMPER (similarity percentage) analysis was carried out to find possible differences among soil conditions. In more detail, this analysis identifies the most common species for each soil condition by calculating their contribution to similarity, based on similarity percentages. A noticeable similarity inside the same soil condition results in a low mean square distance over a range 0 to 100 (in other words, if the distance is 0, the similarity is total, while a distance of 100 means totally different plant communities between pairs of soil conditions).

Then, two multidimensional scaling (MDS) analyses identified the level of similarity among plant community species, and soil conditions, respectively.

Finally, a Spearman correlation heatmap including the correlation coefficients between ecosystem functions and EMF on one side, and species richness, Pielou index, axis of the MDS of plant community species (MDS 1 and 2), soil texture (sand, silt and clay contents), pH and EC.

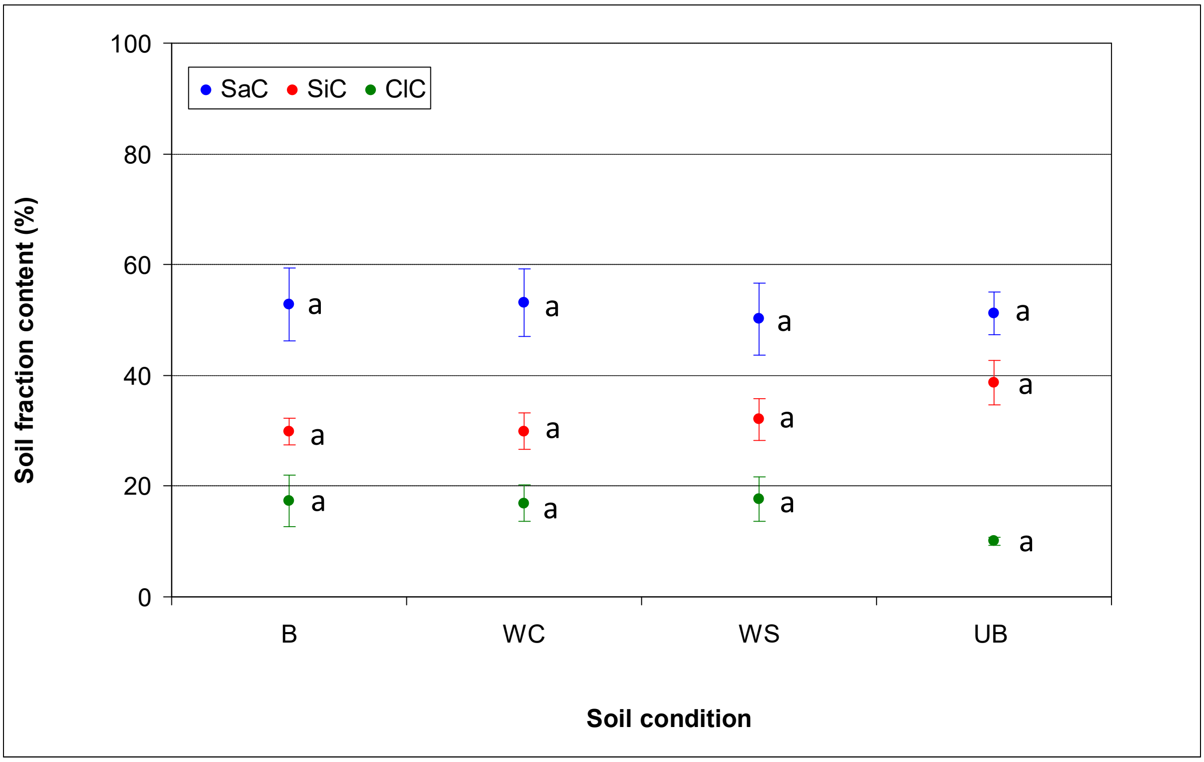
XLSTAT release 2019 and PRIMER V.7 (Clarke and Gorley, 2015) were used for the statistical analyses.

3. Results

3.1. Changes in ecosystem properties among the four soil conditions

ANOVA revealed that, of the analyzed ecosystem properties, only pH (F = 28.658, $p < 0.0001$) was significantly different among the four soil conditions (Table 1.SI).

In more detail, no changes were found in soil texture (SaC, SiC, and ClC), which was practically the same as in UB conditions after the wildfire and soil treatments. Sand content (in the range 53.1 ± 6.07%, WC plots, to 50.2 ± 6.47%, WS) was prevalent, while the silt and clay fractions were variable between 29.9 ± 3.30% (WC) and 38.7 ± 4% (UB) and between 10.1 ± 0.71% (UB) and 17.7 ± 4.03% (WS). The values of pH, which was the lowest in UB plots (8.48 ± 0.10), increased in burned soils up to 9.03 ± 0.07 (B plots), with no difference compared to the mulched soils (9 ± 0.06, WS and 9.02 ± 0.05, WC). Also EC and carbonate contents did not change due to wildfire and mulching effects, varying in the range 5.73 ± 0.27% (UB soils) to 25.3 ± 6.2% (WS) and 0.16 ± 0.02 (UB plots) to 0.21 ± 0.07 mS/cm (B), respectively (Figure 2).



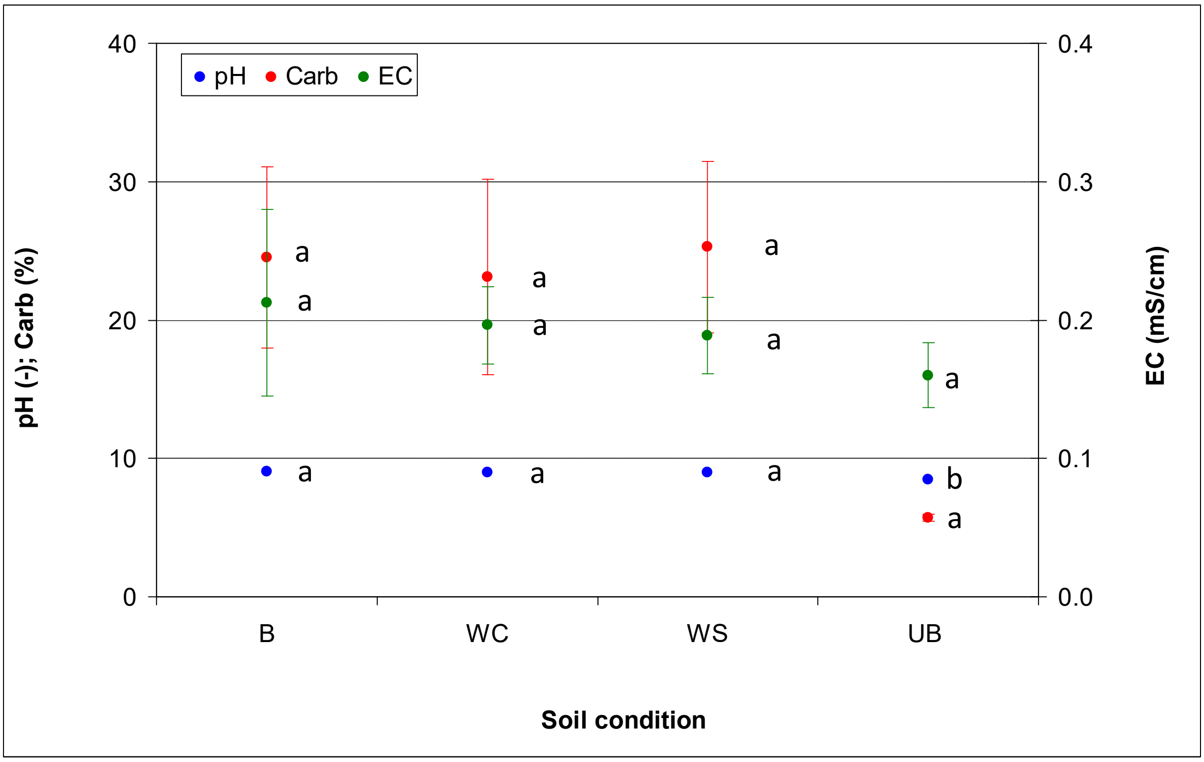


Figure 2 - Mean ± standard error of ecosystem properties (sand, silt and clay contents, pH, carbonate content, and electrical conductivity) under four soil conditions (B = burned; WC = mulched with wood chips; WS = mulched with straw; UB = unburned and not treated) in a pine forest (Liétor, Castilla La Mancha, Spain). Different letters indicate significant differences after Tukey's test at $p < 0.05$.

3.2. Changes in ecosystem structure among the four soil conditions

According to ANOVA, only species richness was significantly different among the soil conditions ($F = 3.147$, $p < 0.01$) (Table 1.SI). The UB soils showed the highest species richness (16.7 ± 2 species), a value that was significantly different compared to all the remaining soil conditions. The lowest richness was surveyed in WS plots (5.5 ± 0.71), the WC and B soils showing intermediate values (6.25 ± 0.79 and 6.88 ± 1.15). Species evenness, measured by Pielou index, was very similar among the four soil conditions, with UB showing the highest value (0.97 ± 0.01), a value that is significantly different only compared to WC soils (0.93 ± 0.01) (Figure 3).

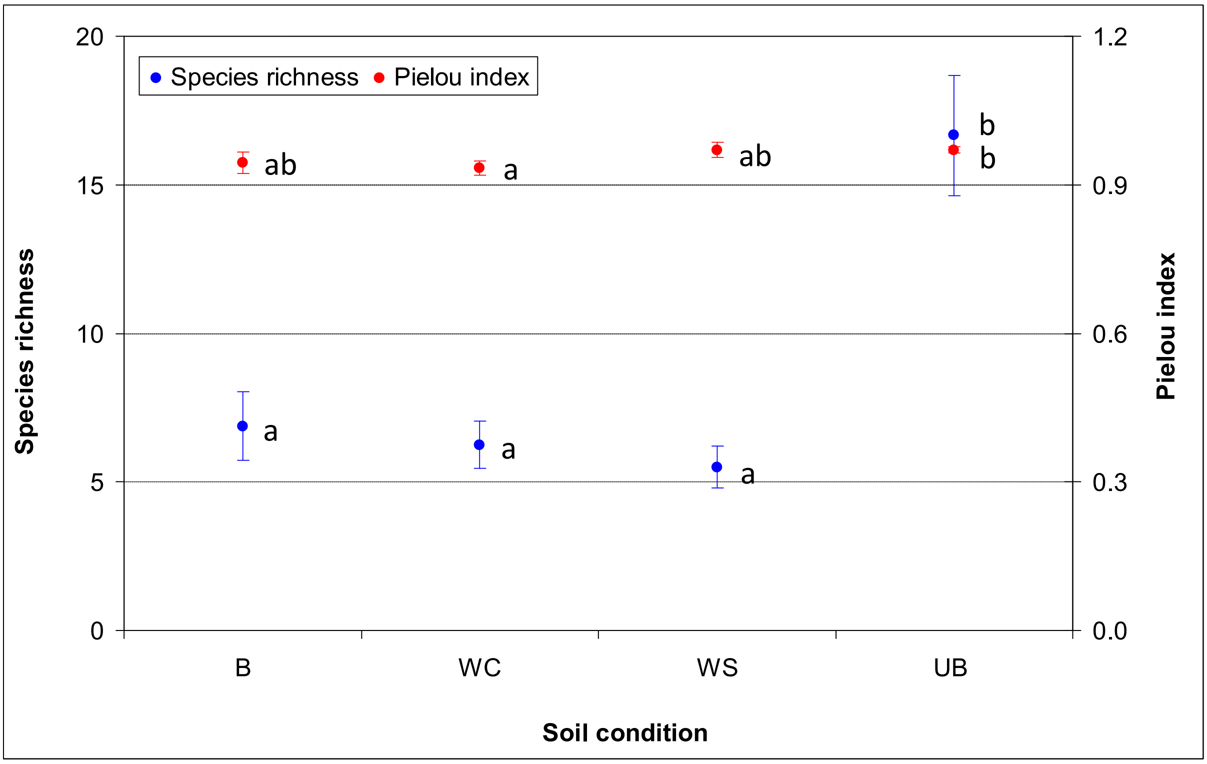


Figure 3 - Mean ± standard error of ecosystem structure (species richness and Pielou index of vegetation) under four soil conditions (B = burned; WC = mulched with wood chips; WS = mulched with straw; UB = unburned and not treated) in a pine forest (Liétor, Castilla La Mancha, Spain). Different letters indicate significant differences after Tukey's test at $p < 0.05$.

ANOSIM did not show significant differences in plant community species of WC and WS soils (significance level higher than 5%), but evidenced a significant variability between B and UB plots (significance level lower than 5%). In general, plant community species in mulched soils were not significantly different compared to burned soils and unburned plots (significance level higher than 5% in both cases) (Table 2.SI). The MDS analysis pointed out that WC and WS soils are clustered together with B plots, while UB soils are separated from burned sites (with or without mulching) (Figure 4). UB soils showed the highest average similarity in plant community species (67.84%), while the lowest value was measured in WS (27.56%) and WC (30.13%) plots. *Macrochloa tenacissima* L. was the most common species, and mostly contributed with *Pinus halepensis* M. to similarity inside each soil condition. *Brachypodium* *phoenicoides* L. and *Reseda phyteuma* L. noticeably supported this similarity in the burned sites (treated or not) (Table 3.SI). *Thymus vulgaris* L., *Rhamnus lycioides* L. subsp. *Lycioides*, *Pinus halepensis* M., *Quercus coccifera* L. and *Helichrysum stoechas* L. were the species that most contributed to dissimilarity between B and UB plots (average value of 72.7%) (Table 3.SI).

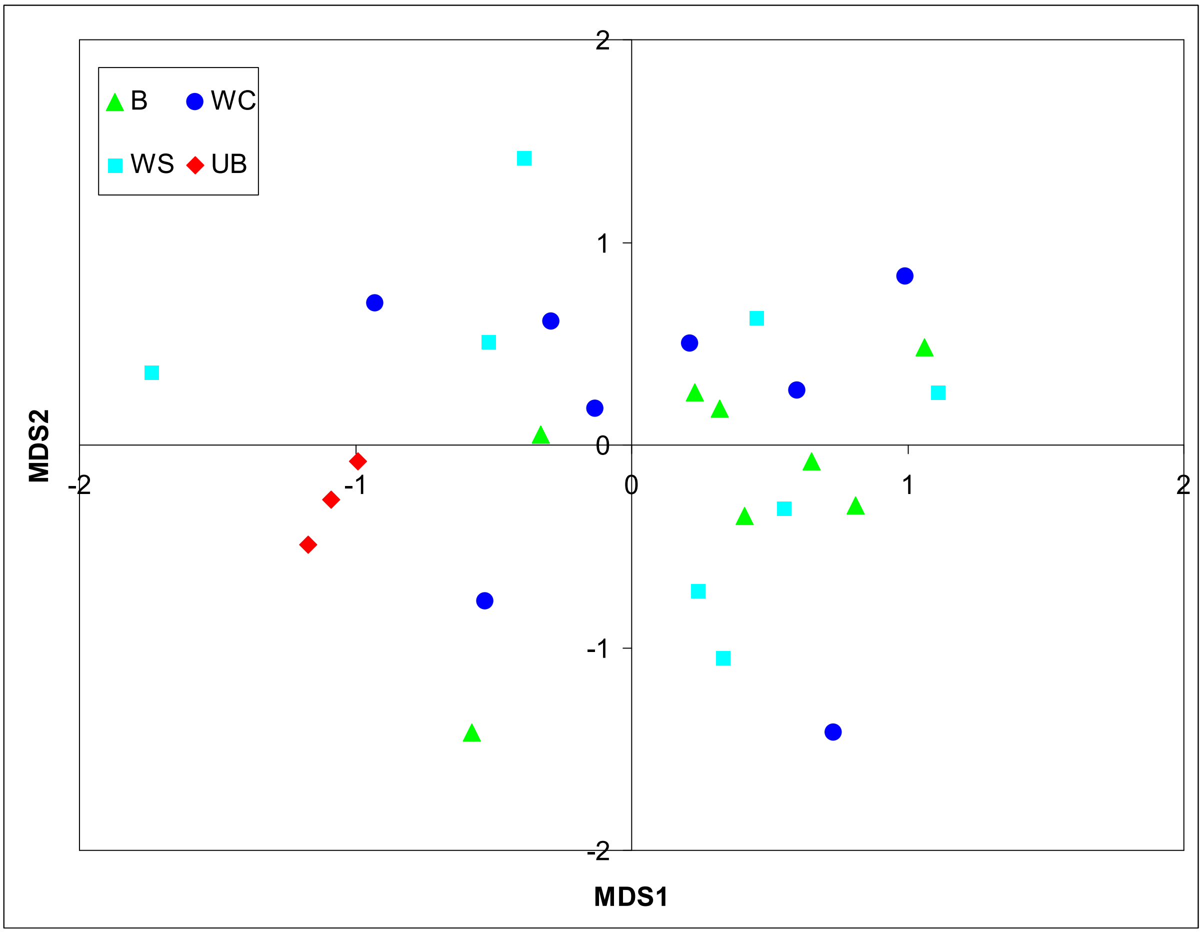


Figure 4 - Multidimensional Scaling (MDS) plot applied to plant community species surveyed under four soil conditions (B = burned; WC = mulched with wood chips; WS = mulched with straw; UB = unburned and not treated) in a pine forest (Liétor, Castilla La Mancha, Spain).

3.3. Changes in ecosystem functions and multifunctionality among the four soil conditions

Table 5.SI reports the values of variables used to calculate the ecosystem functions and EMF under the four soil conditions. The ANOVA applied to these variables showed that, among the

ecosystem functions, only waste decomposition ($F = 3.347$, $p < 0.05$) and wood production ($F = 79.888$, $p < 0.0001$) were significantly different among the four soil conditions. These differences were reflected by EMF, which was significantly influenced by the soil condition ($F = 12.928$, $p < 0.0001$) (Table 1.SI). In more detail, waste decomposition and nutrient cycling functions were lower in B soils, and this value was significantly different only when compared to UB plots, which showed the highest values. Also climate regulation function in B soils was the lowest, and this value was significantly different from WC soils, which showed the highest values. Only UB soils evidenced a wood production function, while no statistically significant differences were detected in the water regulation function among the different soil conditions. The combination of these ecosystem functions gave the highest EMF in UB soils, which was significantly different compared to both B - showing the lowest value - and WC, but not to WS soils (Figure 5).

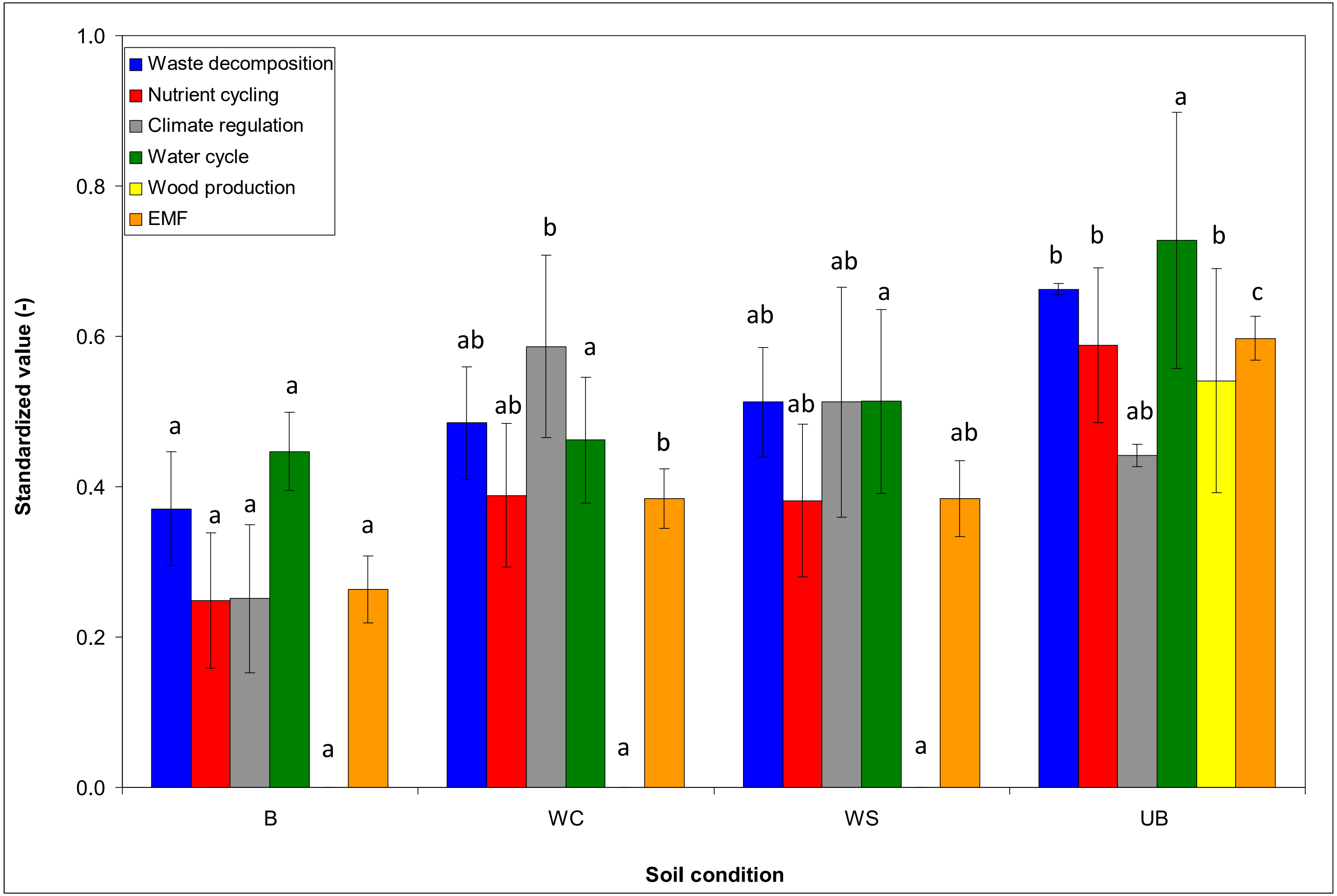

Waste decomposition
Nutrient cycling
Climate regulation
Water cycle
Wood production
EMF
Standardized value (-)
1.0
0.8
0.6
0.4
0.2
0.0
a
a
a
a
a
a
ab
ab
b
a
a
b
ab
ab
ab
a
a
ab
b
b
ab
a
b
c
B
WC
WS
UB
Soil condition

Figure 5 – Mean ± standard error of ecosystem functions and multifunctionality (EMF) under four soil conditions (B = burned; WC = mulched with wood chips; WS = mulched with straw; UB = unburned and not treated) in a pine forest (Liétor, Castilla La Mancha, Spain). Different letters indicate significant differences after Tukey's test at $p < 0.05$.

ANOSIM revealed that UB soils were significantly different compared to all the remaining soil conditions (significance level lower than 5%), while WC and WS plots showed the highest similarity (Table 6.SI). MDS analysis showed a gradient in ecosystem functionality, which was mainly driven by waste decomposition, wood production, water regulation, and EMF (Figure 6). Due to this gradient, observations may be grouped into two separate clusters (B, WC and WS soils in one cluster, and UB soils in another cluster).

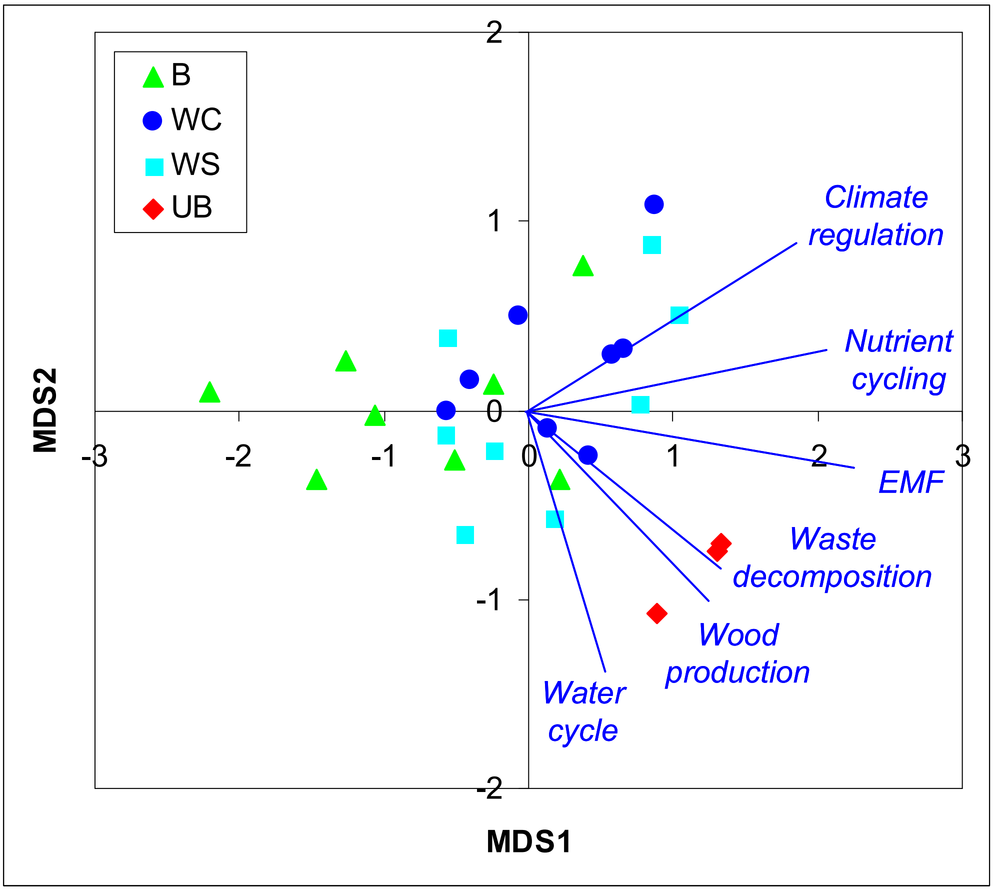
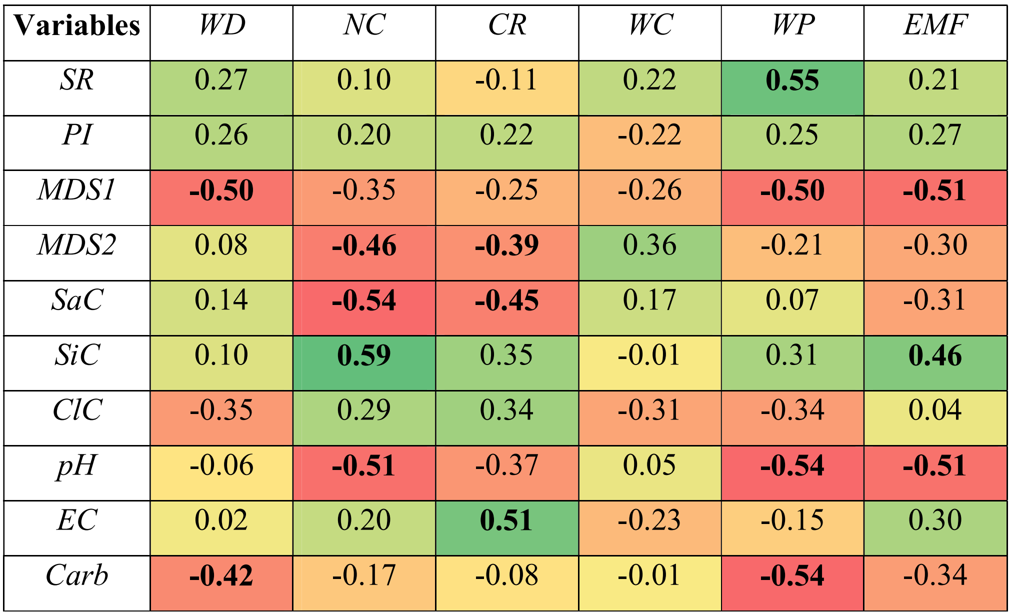


Figure 6 - Multidimensional Scaling (MDS) plot applied to ecosystem functions and multifunctionality (EMF) under four soil conditions (B = burned; WC = mulched with wood chips; WS = mulched with straw; UB = unburned and not treated) in a pine forest (Liétor, Castilla La Mancha, Spain). Vectors show the direction of an increasing ecosystem function in relation to the axes, where vector length is proportional to the correlation between the function and axes.

3.4. Associations between ecosystem functions, structure, and properties

Clear correlations were found between ecosystem functions and parameters that are associated to ecosystem properties and structure. More specifically, waste decomposition was correlated to MDS1 and carbonates (negative correlation), while nutrient cycling to MDS2, sand content, pH (negative correlation) and silt content (positive correlation). Moreover, climate regulation was negatively correlated to MDS2 and sand content, and positively correlated to electrical conductivity, while wood production was positively correlated to species richness and negatively correlated to MDS1, pH and carbonates. Finally, EMF was positively correlated to silt content and negatively correlated to MDS1 and pH (Figure 7).



Variables	*WD*	*NC*	*CR*	*WC*	*WP*	*EMF*
SR	0.27	0.10	-0.11	0.22	**0.55**	0.21
PI	0.26	0.20	0.22	-0.22	0.25	0.27
MDS1	**-0.50**	-0.35	-0.25	-0.26	**-0.50**	**-0.51**
MDS2	0.08	**-0.46**	**-0.39**	0.36	-0.21	-0.30
SaC	0.14	**-0.54**	**-0.45**	0.17	0.07	-0.31
SiC	0.10	**0.59**	0.35	-0.01	0.31	**0.46**
ClC	-0.35	0.29	0.34	-0.31	-0.34	0.04
pH	-0.06	**-0.51**	-0.37	0.05	**-0.54**	**-0.51**
EC	0.02	0.20	**0.51**	-0.23	-0.15	0.30
Carb	**-0.42**	-0.17	-0.08	-0.01	**-0.54**	-0.34

Figure 7 - Spearman correlation heatmap reporting the correlation coefficients between forest functions - waste decomposition (WD), nutrient cycling (NC), climate regulation (CR), water cycle (WC), wood production (WP), and multifunctionality (EMF) - and species richness (SR), Pielou index (PI), axis of the multidimensional scaling analysis of plant community species (MDS 1 and MDS2), soil texture (sand, silt and clay contents, SaC, SiC and ClC), pH, carbonate content (Carb) and electrical conductivity (EC) in a pine forest (Liétor, Castilla La Mancha, Spain). Negative to zero to positive correlations are reported in red to yellow to green colours, respectively. Statistically significant correlation coefficients ($p < 0.05$) are shown in bold.

4. Discussions

It is well known that wildfires alter the functioning and diversity of forests (Bodí et al., 2012), and the effects of post-fire management may sum up to these changes (Lucas-Borja et al., 2021b). Proper post-fire management is essential to ensure the diversity and functionality of a forest (Charnley et al., 2017). In this study, neither wildfire nor post-fire treatments using mulching (wood chips and straw) significantly changed soil properties with the exception of pH in unburned soils. In general, soil texture does not overcome significant alterations due to fire (Agbeshie et al., 2022; Certini, 2005; Zavala et al., 2014) or mulching (Carra et al., 2021; Prosdocimi et al., 2016), while pH and EC are significantly influenced by this disturbance, due to denaturation of organic acids (Certini, 2005), incorporation of ash (Fonseca et al., 2017; Scharenbroch et al., 2012; Úbeda and Outeiro, 2009), release of soluble ions during the combustion of organic matter (Alcañiz et al., 2016), and formation of black carbon (Alcañiz et al., 2020; Certini, 2005). The variability of pH due to fire is associated to the quick decomposition of litter, which produces acidic substances in the topsoil under suitable sunlight and temperature conditions (Wang et al., 2012). Although not common, the lack of variations in EC and carbonate content of burned soils may be explained by leaching due to early rainfalls after the wildfires, which should have restored the pre-fire contents of ions and carbonates. Mulching is a lower disturbance for soil compared to wildfire (de Pagter et al., 2023), and therefore the lack of variability in those soil properties between treated and untreated soils is somewhat expected. Other studies have confirmed that ecosystem properties, including soil physico-chemical characteristics (such as texture, pH, EC, and carbonates), are essential factors for EMF (e.g., Bárcena et al., 2014; Lucas-Borja et al., 2021a; Nave et al., 2013).

Ecosystem structure was significantly altered by wildfire in comparison to unburned sites, as shown by the high decline in species richness surveyed in both treated (-62.8% of species) and untreated soils (-64.8%). Fire removed almost all ground vegetation, and this resulted in a loss of vegetal species, which may be noticeable (Pausas et al., 2008; Tessler et al., 2016). Mulching did not increase this richness, but did not altered vegetation evenness. Other studies carried out in Mediterranean forests and subjected to wildfire and mulching showed an increased species richness and evenness (Lucas-Borja et al., 2022b; Ortega et al., 2022). These authors explained this increase by the better edaphic conditions that favour post-fire recruitment of new plants, especially in semi-arid areas (for instance, thanks to sunlight interception), where the water shortage is a limiting factor towards plant growth. In other environments, Morgan et al. (2015) and Jonas et al. (2019) reported increases in species richness, but no differences in species diversity as a response to mulching. These investigations were carried out longer after fire and post-fire treatments, while, in our study, the vegetation survey was carried out few months after these disturbances.

Only few ecosystem functions were influenced by wildfire and mulching. In more detail, waste decomposition and nutrient cycling were significantly higher only in unburned soils compared to burned sites, while showing intermediate and similar values in mulched plots. Water cycle and wood production (the latter with the exception of unburned plots) were similar among all soil conditions. Moreover, for almost all the ecosystem functions no significant differences were found between soils treated with the two mulch materials. This is justified by the low time elapsed from their distribution, which did not result in different decomposition and mineralisation rates (Ortega et al., 2022; Prosdocimi et al., 2016). Waste decomposition and wood production depend on enzymatic activities (including basal soil respiration) and tree basal area, respectively. In comparison to other soil properties, enzymatic activities respond more quickly to changes in forest ecosystems, serving as an early indicator of biological change (Hu and Liu, 2006). Other studies indicated that soil enzymatic activities play an important impact on EMF (Delgado-Baquerizo et al., 2020). Almost all enzyme contents in the analysed soils followed a gradient B < WC/WS < UB, which explains the lower waste decomposition function found in burned and untreated sites. Lower enzymatic activities are common in wildfire-affected sites in comparison to unburned soils (e.g., Gómez-Sánchez et al., 2019; Lucas-Borja et al., 2021a). The latter authors stated that the decrease in enzyme contents in burned soils is a clear effect of wildfire, since the high temperature due to soil heating destroys a large amount of enzymes (Barreiro et al., 2010). However, mulching is effective in limiting this decrease also in the short-term. The addition of organic residues to soil plays a positive effect on biochemical activities, thanks to the accumulation of organic matter and nutrients and their subsequent decomposition in soil (Bastian et al., 2009; Lucas-Borja et al., 2020a). Lucas-Borja et al. (2022a; 2020b) also reported increased soil respiration and activity of microorganisms after post-fire mulching using straw. According to these authors, the accumulation of organic matter coming from the burned plant material (Rodríguez et al., 2017) continue until these mineralised materials have been consumed (Muñoz-Rojas et al., 2016) and their decomposition ends (Lucas-Borja et al., 2020c). Moreover, the differences in the quantity and quality of plant roots and litter inputs to soil play a noticeable influence on the enzymatic and microbial activity and biogeochemical cycles in forests (Lucas-Borja et al., 2021a). The different plant diversity among the four soil conditions differently influence these processes (Bell et al., 2015; Liu et al., 2019; Turbé et al., 2010). The higher wood production shown by unburned soils was obviously due to the presence of undisturbed tree vegetation, which is instead totally absent in burned areas.

Regarding the other ecosystem functions, climate regulation, which was higher in mulched sites compared to burned and untreated soils (significantly only in the case of the use of wood chips), was positively affected by the supply of vegetal residues to soil with mulching, even in comparison to unburned areas (although not significantly), while wildfire resulted in a noticeable decrease in TOC. According to the literature, mulching with organic residues generally helps to store more organic matter in soil, with beneficial effects on soil fertility, structure and microbial activity (Bombino et al., 2021; Cerdà et al., 2016; Prosdocimi et al., 2016). Organic matter from decomposition is supplied to soil, and this modifies both structure and mechanical characteristics, such as the cohesion (Lucas-Borja and Delgado-Baquerizo, 2019). When stored in soil, organic matter stock is a reservoir of nutrients for plant growth and development (Duan et al., 2019). Soil organic matter in forests mainly derives from above-ground litter and vegetation biomass (Shao et al., 2017), and is associated to several environmental factors, such as soil respiration - depending on litter quality and root system characteristics - water content and temperature (Vesterdal et al., 2012; Zhang et al., 2023). Nutrient cycling function followed the same gradient as waste decomposition, and this may be clearly explained by the similar dynamics between enzymatic activities on one side, and contents of nutrients and ions on the other side. In other words, all these organic compounds and cations decreased after the wildfire in comparison to unburned sites, due to several factors, such as soil leaching after rainstorms as well as volatilization and mineralization of nitrogen and phosphorous (Agbeshie et al., 2022; Certini, 2005; Zavala et al., 2014). This decrease was limited in burned and mulched soils, due to vegetation interception of a part of rainwater, lower aeration of soil, and partial incorporation and mineralization of fresh organic residues. Water cycle function was lower in burned soils compared to unburned sites, in particular in the absence of post-fire treatments, although not significantly. Surface runoff and erosion generally increase in the short-term after a wildfire, but the magnitude of this increase may be different due to several factors, such as soil type, fire characteristics and severity, weather patterns (Moody et al., 2013; Shakesby, 2011). Mulching is generally effective at reducing this increase, although the pre-fire hydrological and erosive response is far to be restored (Girona-García et al., 2021; Robichaud et al., 2010; Zema, 2021). This positive effects on hydrology of burned soils is mainly due to rainwater interception (which reduces runoff volume and rainsplash erosion), which is essential in the water cycle process (Bulcock and Jewitt, 2012). Moreover, this function was slightly and non-significantly higher in the soils mulched with straw compared to the plots treated with wood chips. In a previous study by Díaz et al. (2022), carried out in the same area and under the same soil conditions (except unburned soils) using a rainfall simulator, surface runoff and soil loss were lower in the mulched soils compared to the burned plots. Moreover, these authors found that the straw mulch was more effective in decreasing the runoff coefficient and mainly soil loss compared to plots treated with wood chips. Lucas-Borja et al. (2021a) demonstrated lower nutrient cycling, climate regulation, waste decomposition, wood production and water cycle functions in burned but untreated sites compared to unburned areas, with a noticeable decline in forest EMF decline due to fire. These authors evaluated also the effects of some post-fire management strategies, such as log erosion barriers and contour felled log debris, showing no statistical differences between treated and unburned sites, although demonstrating significantly improved level of EMF compared to burned and untreated areas (Lucas-Borja et al., 2021a).

EMF was noticeably influenced by the differences in waste decomposition, nutrient cycling, climate regulation, and wood production. Similarly as detected for the individual functions, EMF significantly increased from burned and untreated soils to unburned sites, the burned and mulched plots showing intermediate - and similar to each other - values. This distinction resulted in a clear differentiation between unburned and burned (treated or not) soils, shown by the MDS analysis. This means that the mulching was effective at limiting the reduction in EMF due to wildfire, but its effect was not able to restore the pre-fire values in the short-term. Moreover, the soils treated with the two mulch materials may be grouped in the same cluster, and this can be explained by the large similarity of soil properties and species composition between the two sites (Gómez-Sánchez et al., 2019).

All the ecosystem functions, except water cycle, are associated to one or more soil or vegetation parameters. In general, it has been acknowledged that plant diversity is a crucial factor influencing the forest ecosystem's structure and functions (Garcia et al., 2005). It is also worth to notice how species community composition (expressed in this study by the MDS axes) drives several functions, and, as a consequence, EMF. Plant diversity can alter several ecosystem components, such as the soil physico-chemical properties and microbial community (Ushio et al., 2010) as well as the nutrient content, respiration and total carbon, and enzymatic activities (Lucas-Borja et al., 2021a). As such, plant diversity is fundamental in the initial stages after wildfires to support forest functions in Mediterranean ecosystems (Maestre et al., 2012). This result closely agrees to the findings of Lucas-Borja et al. (2021a), who demonstrated significantly correlations - with positive or negative signs - between EMF as well as nutrient cycling, climate regulation, waste decomposition, wood production and water cycle on one side, and multidimensional scaling axes associated to plant diversity characteristics on the other side. This indicates that fire-related changes in plant communities can alter many ecosystem functions. Also other studies have demonstrated the effects of plant diversity on EMF (Bradford et al., 2014; López-Rojo et al., 2019; Lucas-Borja and Delgado-Baquerizo, 2019). Species richness is an influential factor for wood production, with parallel increases between these parameters (shown by the positive and significant coefficient of correlation). This is in line with other studies, which have demonstrated close inter-relations among soil properties, plant characteristics, and ecosystem functions. For instance, Hou et al. (2019) has shown that many abiotic and biotic factors influence the effects of vegetation composition on soil processes and properties. Also the tree species impact the ecosystem functions, because the trees and understory vegetation affect the soil properties altering pH, root systems, and litter characteristics (Heděnec et al., 2023; Prescott and Grayston, 2013; Thoms and Gleixner, 2013). Also pH, whose role on soil dynamics and plant growth is essential, influences most ecosystem functions and multifunctionality, which increase with soil acidity. Therefore, in close agreement to Lucas-Borja and Delgado-Baquerizo (2019), pH in similar types of Mediterranean forest soils showing a noticeable alcalinity may be considered as an important ecological predictor of forest functions.

5. Conclusions

This study has evaluated the short-term changes in ecosystem multifunctionality of a Mediterranean forest burned by a wildfire and then mulched with straw or wood chips in comparison to burned but untreated sites.

The results have shown that: (i) neither wildfire nor post-fire treatments using mulching significantly changed soil properties of the ecosystem with the exception of pH; (ii) in contrast, ecosystem structure significantly declined due to wildfire, and mulching (either with straw or wood chips) did not limit the alteration in species richness; (iii) of the analyzed ecosystem functions, waste decomposition, and nutrient cycling, which were significantly higher in unburned soils compared to burned sites, showed intermediate and similar values in mulched plots, while water cycle and wood production (the latter with the exception of unburned plots) were similar among all soil conditions, and climate regulation was significantly higher only in soils mulched with wood chips compared to burned sites; (iv) no significant differences were found in all ecosystem functions between the two mulch materials; (v) EMF, which was noticeably influenced by those differences in the individual ecosystem functions, increased from burned and untreated soils to unburned sites; (vi) a clear distinction only between unburned and burned (treated or not soils) was shown by MDS analysis, indicating that mulching only partially dampened the impact of the fire on EMF.

The combined analysis of ecosystem properties, structure and functions, and EMF revealed that: (i) all functions, except water cycle, were associated to one or more soil or vegetation parameters; (ii) species community composition noticeably influenced several ecosystem functions, and, therefore, EMF; (iii) species richness is a key driver of wood production; (iv) pH, which was found as the most influential soil properties on ecosystem functions and EMF, may be considered as an important ecological predictor of forest functions in similar types of Mediterranean forests.

Overall, since mulching of burned soils using wheat straw or wood chips significantly increases EMF in the study area, the working hypothesis of this study that post-fire treatments with those natural mulches is beneficial to multi-functionality of Mediterranean forest ecosystems can be in general accepted, although the treatment can not fully restore each ecosystem function to the pre-fire conditions.

Possible limitations of this study are (i) the limited spatial (plot) and temporal (short term, that is few months after wildfire and mulching) scales of monitoring and (ii) artificial rainfalls simulated by small portable devices, which do not consider the variability of precipitation amount and intensity, and of soil moisture and type. Upscaling in space and time is needed to resolve the first limitation, in order to measure the spatial variability as well as the mid- and long-term impacts of the effects of wildfire and post-fire management. Surface runoff and soil loss monitoring at hillslope scale and under natural precipitation on soils with different types and water content is advisable, in order to capture the effectiveness of mulching to limit post-fire runoff and erosion under variable precipitation and soil characteristics.

In spite of these possible limitations, this study may be of practical importance for policymakers, and land managers, who may derive useful indications about the most effective actions to preserve the ecosystem multi-functionality in delicate ecosystems, such as the Mediterranean forests. Understanding the effects of wildfire and post-fire management on multiple forest ecosystem systems and functions in semi-arid areas is crucial to better predict how future threatens (such as wildfire and climate change) may be limited in the near future.

Acknowledgements

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SUPPLEMENTARY MATERIAL

Table 1.SI - Results of one-way ANOVA applied to ecosystem functions and multifunctionality (EMF) under four soil conditions (B = burned; WC = mulched with wood chips; WS = mulched with straw; UB = unburned and not treated) in a pine forest (Liétor, Castilla La Mancha, Spain).

Factor	**Degree of freedom**	**Sum of squares**	**Mean squares**	**F**	**Pr > F**
Soil condition	3	Waste decomposition			
		0.204	0.068	3.347	**0.037**
		Nutrient cycling			
		0.293	0.098	2.683	0.070
		Climate regulation			
		0.513	0.171	2.920	0.056
		Water regulation			
		0.274	0.091	2.433	0.091
		Wood production			
		1.387	0.462	79.888	**< 0.0001**
		EMF			
		0.296	0.099	12.928	**< 0.0001**
		Species richness			
		299.255	99.752	22.706	**< 0.0001**
		Pielou index			
		0.007	0.002	2.486	0.086
		Sand Content			
		47.984	15.995	0.105	0.957
		Silt Content			
		125.972	41.991	1.002	0.410
		Clay Content			

		156.966	52.322	0.887	0.463
		pH			
		1.304	0.435	28.658	**< 0.0001**
		Carbonates			
		1155.041	385.014	2.419	0.092
		Electrical conductivity			
		0.008	0.003	0.351	0.789

Table 2.SI - Analysis of similarity percentages (ANOSIM) in plant community species between pairs of soil conditions (B = burned; WC = mulched with wood chips; WS = mulched with straw; UB = unburned and not treated) in a pine forest (Liétor, Castilla La Mancha, Spain).

Soil conditions	**R statistic**	**Significance level (%)**	**Number ≥ observations**
B vs. WC	-0.021	58.6	585
B vs. WS	-0.036	65.8	657
B vs. UB	0.667	0.6	1
WC vs. WS	-0.115	94.3	942
WC vs. UB	0.164	21.2	35
WS vs. UB	0.075	30.3	50

Table 3.SI - Analysis of similarity percentages (SIMPER) in plant diversity within each soil condition (B = burned; WC = mulching with wood chips; WS = mulching with straw; UB = unburned and not treated) in a pine forest (Liétor, Castilla La Mancha, Spain).

Species	**Avg. Abundance**	**Avg. Similarity**	**Contribution (%)**	**Cumulative (%)**
Soil condition B	Average similarity: 42.67			
Macrochloa tenacissima L.	0.61	16.08	37.67	37.67
Helianthemum syriacum (Jacq.) Dum.	0.29	6.08	14.25	51.92
Brachypodium phoenicoides L.	0.29	5.77	13.51	65.44
Coris monspeliensis L.	0.27	4.64	10.86	76.30
Pinus halepensis M.	0.21	3.66	8.57	84.87
Reseda phyteuma L.	0.17	2.66	6.24	91.11
Soil condition WC	Average similarity: 30.13			
Macrochloa tenacissima L.	0.44	9.24	30.67	30.67
Brachypodium phoenicoides L.	0.37	7.99	26.51	57.19
Reseda phyteuma L.	0.17	2.75	9.12	66.31
Pinus halepensis M.	0.21	2.51	8.34	74.66
Helianthemum syriacum (Jacq.) Dum.	0.12	2.05	6.79	81.45
Brachypodium retusum (Pers.) Beauv.	0.23	1.69	5.62	87.06
Atractylis humilis L.	0.14	1.22	4.05	91.11
Soil condition WS	Average similarity: 27.56			

Macrochloa tenacissima L.	0.39	9.67	35.08	35.08
Pinus halepensis M.	0.27	3.92	14.23	49.31
Coris monspeliensis L.	0.18	3.03	11.01	60.32
Brachypodium phoenicoides L.	0.20	3.00	10.87	71.19
Reseda phyteuma L.	0.16	2.15	7.79	78.98
Pistacia lentiscus L.	0.17	1.37	4.96	83.95
Anthyllis cytisoides L.	0.13	1.34	4.87	88.81
Atractylis humilis L.	0.11	1.27	4.61	93.42
Soil condition UB	Average similarity: 67.84			
Rhamnus lycioides L. subsp. Lycioides	0.61	8.83	13.01	13.01
Macrochloa tenacissima L.	0.61	8.83	13.01	26.02
Pinus halepensis M.	0.61	8.83	13.01	39.03
Thymus vulgaris L.	0.61	8.83	13.01	52.04
Linum narbonense L.	0.31	4.29	6.33	58.37
Anthyllis cytisoides L.	0.31	4.29	6.33	64.70
Helichrysum stoechas L	0.32	4.29	6.33	71.02
Dorycnium pentaphyllum Scop.	0.29	3.63	5.35	76.37
Argyrolobium zanonii	0.18	1.46	2.16	78.53
Teucrium capitatum L.	0.16	1.24	1.82	80.35
Rosmarinus Officinalis L.	0.16	1.24	1.82	82.18
Asparagus horridus L.	0.16	1.24	1.82	84.00
Helianthemum cinereum (Cav.) Pers. subsp. Cinereum	0.16	1.24	1.82	85.83

Pistacia lentiscus L.	0.16	1.24	1.82	87.65
Centaurea antennata D.	0.16	1.24	1.82	89.47
Globularia alypum L.	0.16	1.24	1.82	91.30

Table 4.SI - Analysis of similarity percentages (SIMPER) in plant diversity between pairs of soil conditions (B = burned; WC = mulching with wood chips; WS = mulching with straw; UB = unburned and not treated) in a pine forest (Liétor. Castilla La Mancha. Spain).

Species	**Avg. Abundance**		**Avg. Similarity**	**Contribution (%)**	**Cumulative (%)**
Soil conditions B & WC	*Average dissimilarity = 63.27*				
	Group B	*Group WC*			
Macrochloa tenacissima L.	0.61	0.44	1.09	12.16	12.16
Brachypodium phoenicoides L.	0.29	0.37	1.23	8.33	20.49
Coris monspeliensis L.	0.27	0.05	1.20	8.03	28.52
Helianthemum syriacum (Jacq.) Dum.	0.29	0.12	1.44	7.33	35.86
Pinus halepensis M.	0.21	0.21	1.24	7.31	43.16
Quecus coccifera L.	0.16	0.13	0.68	7.17	50.33
Brachypodium retusum (Pers.) Beauv.	0.07	0.23	0.80	6.93	57.27
Atractylis humilis L.	0.10	0.14	0.77	6.06	63.32
Reseda phyteuma L.	0.17	0.17	1.24	5.59	68.92
Cistus albidus L.	0.00	0.16	0.55	4.60	73.52
Pistacia lentiscus L.	0.03	0.12	0.63	4.32	77.84

Rhamnus lycioides L. subsp. Lycioides	0.05	0.08	0.50	3.55	81.39
Anthyllis cytisoides L.	0.09	0.03	0.69	3.31	84.70
Carex sp.	0.08	0.04	0.82	3.07	87.77
Asparagus horridus L.	0.07	0.05	0.75	3.00	90.76
Soil conditions B & WS	*Average dissimilarity = 63.13*				
	Group B	*Group WS*			
Macrochloa tenacissima L.	0.61	0.39	1.27	11.82	11.82
Pinus halepensis M.	0.21	0.27	1.29	9.22	21.04
Helianthemum syriacum (Jacq.) Dum.	0.29	0.13	1.36	9.11	30.14
Brachypodium phoenicoides L.	0.29	0.20	1.24	7.99	38.13
Coris monspeliensis L.	0.27	0.18	1.24	7.88	46.01
Quecus coccifera L.	0.16	0.08	0.61	7.03	53.04
Reseda phyteuma L.	0.17	0.16	1.11	6.50	59.54
Brachypodium retusum (Pers.) Beauv.	0.07	0.17	0.66	5.94	65.48
Pistacia lentiscus L.	0.03	0.17	0.75	5.61	71.09
Anthyllis cytisoides L.	0.09	0.13	0.91	5.13	76.22
Atractylis humilis L.	0.10	0.11	0.94	4.67	80.90
Carex sp.	0.08	0.03	0.80	2.80	83.69
Rhamnus lycioides L. subsp. Lycioides	0.05	0.05	0.52	2.43	86.12
Asparagus horridus L.	0.07	0.00	0.56	2.38	88.50
Rosmarinus Officinalis L.	0.08	0.00	0.74	2.28	90.79

Soil conditions WC & WS	*Average dissimilarity = 68.31*				
	Group WC	*Group WS*			
Macrochloa tenacissima L.	0.44	0.39	1.32	11.45	11.45
Pinus halepensis M.	0.21	0.27	1.10	8.71	20.16
Brachypodium phoenicoides L.	0.37	0.20	1.38	8.69	28.84
Brachypodium retusum (Pers.) Beauv.	0.23	0.17	0.90	8.16	37.01
Pistacia lentiscus L.	0.12	0.17	0.92	6.72	43.73
Atractylis humilis L.	0.14	0.11	0.83	6.10	49.82
Helianthemum syriacum (Jacq.) Dum.	0.12	0.13	1.08	6.09	55.91
Reseda phyteuma L.	0.17	0.16	1.09	6.02	61.93
Coris monspeliensis L.	0.05	0.18	1.05	5.71	67.64
Quecus coccifera L.	0.13	0.08	0.62	5.38	73.02
Cistus albidus L.	0.16	0.05	0.65	5.11	78.13
Anthyllis cytisoides L.	0.03	0.13	0.77	4.23	82.36
Rhamnus lycioides L. subsp. Lycioides	0.08	0.05	0.51	3.42	85.78
Teucrium capitatum L.	0.06	0.07	0.75	3.22	88.99
Linum narbonense L.	0.06	0.00	0.56	1.98	90.98
Soil conditions B & UB	*Average dissimilarity = 72.71*				
	Group B	*Group UB*			
Thymus vulgaris L.	0.00	0.61	5.55	9.62	9.62

Rhamnus lycioides L. subsp. Lycioides	0.05	0.61	3.02	8.90	18.53
Pinus halepensis M.	0.21	0.61	1.93	6.43	24.96
Quecus coccifera L.	0.16	0.30	1.11	5.27	30.22
Helichrysum stoechas L	0.00	0.32	4.29	4.97	35.20
Linum narbonense L.	0.00	0.31	4.43	4.94	40.14
Euphorbia segetalis L.	0.03	0.30	1.06	4.51	44.64
Helianthemum syriacum (Jacq.) Dum.	0.29	0.00	1.44	4.47	49.11
Brachypodium phoenicoides L.	0.29	0.30	1.37	4.45	53.57
Dorycnium pentaphyllum Scop.	0.02	0.29	2.29	4.27	57.84
Coris monspeliensis L.	0.27	0.00	1.15	4.16	61.99
Anthyllis cytisoides L.	0.09	0.31	1.89	3.69	65.68
Macrochloa tenacissima L.	0.61	0.61	0.91	3.42	69.09
Argyrolobium zanonii	0.00	0.18	1.36	2.84	71.93
Brachypodium retusum (Pers.) Beauv.	0.07	0.15	1.37	2.75	74.69
Reseda phyteuma L.	0.17	0.00	1.06	2.65	77.34
Centaurea antennata D.	0.00	0.16	1.34	2.62	79.96
Globularia alypum L.	0.00	0.16	1.34	2.62	82.58
Teucrium capitatum L.	0.00	0.16	1.35	2.61	85.19
Helianthemum cinereum (Cav.) Pers. subsp. Cinereum	0.00	0.16	1.35	2.61	87.81
Pistacia lentiscus L.	0.03	0.16	1.27	2.47	90.28
Soil conditions WC & UB	*Average dissimilarity = 72.51*				

	Group WC	*Group UB*			
Thymus vulgaris L.	0.00	0.61	5.76	9.73	9.73
Rhamnus lycioides L. subsp. Lycioides	0.08	0.61	2.60	8.70	18.44
Pinus halepensis M.	0.21	0.61	1.59	6.62	25.06
Macrochloa tenacissima L.	0.44	0.61	1.23	5.03	30.10
Helichrysum stoechas L	0.00	0.32	4.39	5.03	35.13
Brachypodium phoenicoides L.	0.37	0.30	1.41	4.91	40.03
Quecus coccifera L.	0.13	0.30	1.12	4.77	44.80
Euphorbia segetalis L.	0.00	0.30	1.05	4.65	49.46
Dorycnium pentaphyllum Scop.	0.00	0.29	2.79	4.62	54.08
Anthyllis cytisoides L.	0.03	0.31	2.75	4.57	58.64
Brachypodium retusum (Pers.) Beauv.	0.23	0.15	1.35	4.06	62.70
Linum narbonense L.	0.06	0.31	2.19	4.04	66.74
Cistus albidus L.	0.16	0.15	1.20	3.66	70.40
Pistacia lentiscus L.	0.12	0.16	1.31	3.23	73.63
Argyrolobium zanonii	0.00	0.18	1.37	2.87	76.50
Reseda phyteuma L.	0.17	0.00	1.13	2.66	79.16
Centaurea antennata D.	0.00	0.16	1.35	2.65	81.81
Globularia alypum L.	0.00	0.16	1.35	2.65	84.47
Rosmarinus Officinalis L.	0.03	0.16	1.27	2.50	86.96

Helianthemum cinereum (Cav.) Pers. subsp. Cinereum	0.03	0.16	1.27	2.49	89.45
Atractylis humilis L.	0.14	0.00	0.63	2.45	91.90
Soil conditions WS & UB	*Average dissimilarity = 72.46*				
	Group WS	*Group UB*			
Rhamnus lycioides L. subsp. Lycioides	0.05	0.61	3.33	9.19	9.19
Thymus vulgaris L.	0.07	0.61	2.66	8.93	18.12
Pinus halepensis M.	0.27	0.61	1.37	6.05	24.17
Helichrysum stoechas L	0.00	0.32	4.61	5.12	29.29
Linum narbonense L.	0.00	0.31	4.77	5.09	34.37
Quecus coccifera L.	0.08	0.30	1.08	4.92	39.29
Euphorbia segetalis L.	0.04	0.30	1.09	4.69	43.98
Brachypodium phoenicoides L.	0.20	0.30	1.32	4.67	48.65
Macrochloa tenacissima L.	0.39	0.61	1.29	4.60	53.25
Dorycnium pentaphyllum Scop.	0.03	0.29	2.20	4.28	57.52
Brachypodium retusum (Pers.) Beauv.	0.17	0.15	1.24	3.86	61.39
Anthyllis cytisoides L.	0.13	0.31	1.67	3.64	65.03
Pistacia lentiscus L.	0.17	0.16	1.31	3.42	68.45
Coris monspeliensis L.	0.18	0.00	0.96	2.98	71.43
Argyrolobium zanonii	0.00	0.18	1.38	2.92	74.35
Centaurea antennata D.	0.00	0.16	1.36	2.70	77.05

Globularia alypum L.	0.00	0.16	1.36	2.70	79.75
Rosmarinus Officinalis L.	0.00	0.16	1.37	2.69	82.45
Asparagus horridus L.	0.00	0.16	1.37	2.69	85.14
Helianthemum cinereum (Cav.) Pers. subsp. Cinereum	0.00	0.16	1.37	2.69	87.83
Reseda phyteuma L.	0.16	0.00	0.80	2.69	90.52

Table 5.SI – Mean ± standard error of variables use to calculate the ecosystem functions under four soil conditions (B = burned; WC = mulching with wood chips; WS = mulching with straw; UB = unburned and not treated) in a pine forest (Liétor, Castilla La Mancha, Spain).

Parameter	**Measuring unit**	**Statistics**	**Soil condition**			
			B	*WC*	*WS*	*UB*
DHA	µmol INTF g^{-1} soil h^{-1}	Mean	4.30	4.74	4.61	6.15
BGA	µmol PNF g^{-1} soil h^{-1}		0.32	0.40	0.45	0.48
Alk-PA	µmol PNF g^{-1} soil h^{-1}		4.30	5.15	5.40	6.66
UA	µmol $N\text{-}NH_4^+$ g^{-1} soil h^{-1}		1.81	1.91	1.55	2.71
BSR	mgC-CO_2 kg^{-1} day^{-1}		45.50	52.10	59.91	52.55
RC	%		-0.64	-0.56	-0.46	-0.26
SL	tons/ha		-0.81	-0.95	-1.02	-0.75
Ca	meq 100 g^{-1}		42.58	44.55	45.00	49.22
K	meq 100 g^{-1}		0.76	1.12	0.96	0.84
Na	meq 100 g^{-1}		0.05	0.09	0.09	0.12
P	ppm		8.75	11.63	11.38	20.73
TN	%		0.17	0.19	0.19	0.31
TOC	%		3.14	4.77	4.41	4.06
TBA	m^2 ha^{-1}		0.00	0.00	0.00	2.98
DHA	µmol INTF g^{-1} soil h^{-1}	Standard error	0.41	0.38	0.43	0.19
BGA	µmol PNF g^{-1} soil h^{-1}		0.07	0.06	0.05	0.01

Alk-PA	µmol PNF g^{-1} soil h^{-1}		0.67	0.82	0.81	0.12
UA	µmol N-NH_4^+ g^{-1} soil h^{-1}		0.42	0.33	0.50	0.01
BSR	mgC-CO_2 kg^{-1} day^{-1}		4.93	9.56	5.56	0.92
RC	%		0.05	0.10	0.09	0.03
SL	tons/ha		0.22	0.19	0.28	0.63
Ca	meq 100 g^{-1}		2.29	2.40	2.42	2.60
K	meq 100 g^{-1}		0.20	0.26	0.19	0.06
Na	meq 100 g^{-1}		0.01	0.02	0.02	0.02
P	ppm		3.34	3.51	4.49	6.02
TN	%		0.03	0.03	0.05	0.04
TOC	%		0.48	0.59	0.75	0.07
TBA	m^2 ha^{-1}		0.00	0.00	0.00	0.82

Notes: DHA = Dehydrogenase activity; BGA = β-glucosidase activity; UA = Urease activity; Alk-PA = Alkaline-phosphatase activity; BSR = basal soil respiration; RC = runoff coefficient; SL = soil loss; Ca = calcium; K = potassium; Na = sodium; P = phosphorous; TN = total nitrogen; TOC = total organic carbon; TBA = tree basal area.

Table 6.SI - Analysis of similarity percentages (ANOSIM) in ecosystem functions and ecosystem multifunctionality (EMF) between pairs of soil conditions (B = burned; WC = mulched with wood chips; WS = mulched with straw; UB = unburned and not treated) in a pine forest (Liétor, Castilla La Mancha, Spain).

Soil conditions	**R statistic**	**Significance level (%)**	**Number ≥ observations**
B vs. WC	0.166	5.6	55
B vs. WS	0.081	16.9	168
B vs. UB	0.739	**0.6**	1
WC vs. WS	-0.113	93.6	935
WC vs. UB	0.796	**0.6**	1
WS vs. UB	0.548	**0.6**	1