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Changes in soil functionality eight years after fire and post-fire hillslope stabilisation in Mediterranean forest ecosystems

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TO:
Editorial Office
Geoderma

Dear Editor,

Thank you very much for the second opportunity to revise our work according to yours and reviewers' suggestions. Please note that we have deeply revised all raised concerns by reviewers.

We hope all changes help to improve the quality of our work, making it acceptable for publication.

Sincerely,

On behalf of all authors,
Manuel Esteban, Lucas-Borja
Albacete, 9th of February 2021

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Changes in soil functionality eight years after fire and post-fire hillslope stabilisation in Mediterranean forest ecosystems

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Abstract

Contour-felled log debris (CFD) and log erosion barriers (LEB) are two restoration practices used worldwide on hillslopes to avoid soil erosion after wildfires. Although significant work has evaluated the effectiveness of these practices on soil loss prevention, their effects on soil properties have been little researched to date. Here, the effects of CFD and LEB treatments on several physico-chemical and biological soil properties were investigated across four post-fire zones in Mediterranean forest (Sierra de Los Donceles, Spain). Results suggest that post-fire management similarly altered the recovery of microbiological soil properties and soil functionality for both CFD and LEB treatments. Post-fire management enhanced soil organic matter (SOM) and basal respiration, while suppressing soil microbial activities. SOM enhancement at our plots may have been associated with suppressed soil microbial decomposition activity due to post-fire increases in electrical conductivity. Plots with post-fire management recovered microbiological soil properties better than unmanaged burn plots, but not to the same level as nearby unburned plots~~ that were not burned~~. LEB and CFD may not only be effective in retaining sediments, but also in improving post-fire microbiological soil properties in comparison to unmanaged plots. However, after eight years of post-fire management, soil microbiological soil properties did not completely recover compared to unburnt areas. That is, fire may shift the development trajectory of microbiological soil properties so that they may no longer be able to return to the same unburnt conditions. Post-fire restoration plans should consider the use of LEB and CFD when aiming to aid soil-related ecosystem recovery processes after wildfires.

Keywords: Post-fire restoration practices; log erosion barriers; contour-felled log debris; microbiological soil properties; wildfire; Organic matter

1. Introduction

Global warming has decreased precipitation and increased temperatures in the Mediterranean Basin, significantly impacting the region's forests (Lindner et al., 2010). An increased frequency and severity of summer droughts are expected to significantly increase the number of wildfires and the extent of burned areas. The direct and indirect effects of fires on forest soil and vegetation are well documented in the scientific literature (Certini, 2005; Lucas- Borja et al.,2021), including post-fire nutrient losses via increased runoff and erosion rates (Mataix-Solera et al., 2009; Muñoz-Rojas et al., 2016; Robichaud et al., 2000). Post-fire management actions are, therefore, needed to reduce soil losses and complement natural regenerative processes for ecosystem recovery after wildfires (Mataix-Solera et al., 2009). Among the post-fire restoration techniques, hillslope stabilisation treatments are commonly implemented to decrease soil degradation by reducing runoff and erosion rates (Fernández and Vega, 2016; Shakesby, 2011). These stabilization treatments, such as grass seeding, anchored log erosion barriers (LEB), contour-felled log debris (CFD) or mulching, keep soil in-place after fire by preventing particle detachment and subsequent deposition in unwanted areas (Robichaud et al., 2000). Treatments that utilize post-fire woodland materials (like burned, dead fuel, and log debris) are commonly implemented, as they not only prevent soil losses, but also accelerate the decomposition and incorporation of endogenous biomass into soil and reduce fuel load. In general, post-fire hillslope treatments have been demonstrated to be effective in lowering runoff, peak flows and sediment yields from burnt watersheds however, treatment effectiveness depends on structure design, season of construction and fire severity (Badía et al., 2014; P. R. Robichaud et al., 2008).

A large body of literature has evaluated the effect of hillslope stabilisation techniques (e.g., CFD and LEB) on soil erosion and runoff (e.g.,Albert-Belda et al., 2019; Fernández et al., 2019; Jourgholami et al., 2020). Less research is available regarding the effect on soil chemical properties after hillslope stabilisation treatments (Wittengberg et al., 2020), and with regard to the recovery of microbiological soil properties, the available literature is almost absent, leaving these impacts not well understood to date. Specifically, hillslope stabilisation treatments, while preventing erosion, may engender soil physicochemical properties that play key ecological roles in burned forests through influencing the composition and activity of soil biota (Killham, 1994). By trapping seeds or generating higher soil moisture nearby felled burned branches or logs, post-fire management structures may change vegetation composition and cover, which alters forest structure after wildfires (Rago et al., 2020). The quantity and quality of the burned material falling from branches and log debris structures may also generate changes in soil properties (Lucas- Borja et al., 2021).

Since the soil is a mosaic of metabolic processes, the use of a single parameter to study the response of soil functionality (i.e., the ability of soil systems to simultaneously provide multiple ecosystem functions) is not enough (Lucas- Borja et al., 2011). Thus, many authors have proposed the use of several indicators to assess soil (multi)functionality that may be used as early indicators of soil stress or restoration (e.g. (Lucas-Borja and Delgado-Baquerizo, 2019). Biochemical and microbiological indicators related to soil microbial activity are of paramount importance for maintaining soil functionality—with many extracellular enzymes directly affecting soil N, P and C cycling (urease, phosphatase and β-glucosidase, respectively) and some general microbial indicators such as respiration or intracellular dehydrogenase activity. Moreover, as key microbiological soil properties, soil respiration, microbial biomass carbon and enzyme activities are all closely tied to C, N and P cycling, organic matter decomposition and formation (Gutknecht et al., 2010). Soil enzymes, in particular, are considered biomarkers of the functional ability of microbial communities; thus soil respiration and enzymes may be ideal indicators of change, disturbance or stress in the soil community (Aon et al., 2001). These soil properties are currently considered sensitive indicators of soil functionality and, thereby, have implications for the establishment of native plant communities and cover (Bastida et al., 2008)—and these implications may extend to post-fire hillslopes. Indeed, enzymes and respiration have been widely used together as soil functionality indicators to evaluate degradation in Mediterranean forest ecosystems (Lucas-Borja, 2015;).

Due to the number and complexity of post-fire effects on soils, very little guidance is currently available to plan possible countermeasures against soil degradation (Lucas-Borja et al., 2020b). Even observational information about changes in these microbiological indicators in wildfire-affected forests with hillslope soil stabilization is severely lacking (barring a single study: Gómez-Sánchez et al., 2019). Wildfires and subsequent post-fire management effects on microbiological soil properties have been little researched to date, which may hinder our ability to understand the effects of these management practices on soil multifunctionality. To fill this gap, this study aims at evaluating the effects of two common post-fire hillslope stabilisation techniques (LEB and CFD) on soil functionality eight years after a wildfire, using microbiological soil properties (urease, phosphatase and β-glucosidase soil enzyme activities, soil respiration or intracellular dehydrogenase activity) as indicators of the functional ability in soil microbial communities. The changes in these indicators in treated hillslopes have been compared to those monitored in unburned and burned areas without post-fire restoration actions, assumed as control. We hypothesized that hillslope stabilisation techniques will enhance soil functionality in fire-affected areas compared to unmanaged post-fire hillslopes. Specifically, we aim to answer the following questions:

a) Can CFD affect soil indicators differently than LEB?

b) Do intra- and extra-cellular soil enzymes or chemical soil indicators (e.g., soil pH, electrical conductivity or soil organic matter) differentially respond to CFD v LEB?

This research will help to demonstrate whether soil multifunctionality is affected by post-fire management treatments, and how they can promote microbiological soil properties recovery after wildfire in the mid-term in comparison with untreated areas.

2. Material and methods

2.1. Study area

Sierra de Los Donceles forest is located close to Hellín (province of Albacete, south-east Spain). The forest is situated at an elevation ~~located~~ between 304 m to 808 m in the pre-Baetic mountain chain, inside the Sierra de los Donceles catchment, neighbouring the Mundo (north) and Segura (south) Rivers. The forest is located in the meso-Mediterranean bioclimatic belt (Rivas-Martínez et al., 2002).. The mean annual temperature and precipitation are 16.6°C and 321 mm, respectively. The maximum seasonal precipitation inputs are concentrated in October (44.5 mm) and May (39.6 mm) (1990-2014, data provided by the Spanish Meteorological Agency and Gómez-Sánchez et al. (2017)). The geology is typical pre-Baetic Mountains, with limestone and dolomite outcrops alternating with marly intercalations that date back to the quaternary. According to the USDA Soil Taxonomy System, soils are Calcic Aridisols with loamy to sandy loam texture. Vegetation belongs to the *Querco cocciferae-Pino halepensis S.* series. Before the fire of 2012, the natural vegetation was mature Aleppo pine stands with a companion shrub layer which, in combination, formed a dense cover in all plots (Table 1). Aleppo pine covers much of the tree vegetation layers (tree, shrub and herb), and oak represents a large cover in the shrub layer (Peinado Lorca et al., 2008). These oaks form an intricate mass of thorny nanophanerophyte, e.g., kermes oak (*Quercus coccifera*), black hawthorn (*Rhamnus lycioides*), Italian buckthorn *(Rhamnus alaternus)*, grey asparagus (*Asparagus horridus*) and other inerms (*Pistacia lentiscus, Genista spartioides subsp. retamoides*). Esparto grass (*Stipa macrochloa*), also abundant in the area, were used from the 17th century until halfway through the 20th century as an economic driver because it is a fibre producer. These spartals were the main historic disturbance of forest stands in the area and favoured their growth. The progressive abandonment and the reforestation carried out by the public administration have shaped a forest landscape composed of spontaneous Aleppo pines, growing in shaded areas and watercourses. In the 1980s, the Aleppo pine was repopulated in accessible public lands with little soil along with thermophile scrublands in sunny spots (spartals and rosemary scrublands). Records of forest fires began in Spain in 1968. In the Sierra Donceles forest, two fires have taken place: a first fire in 1994, which was caused by lightning and affected 46 ha, and an arson fire in July

2012, which devastated roughly 6500 ha of Mediterranean maquis. It is the effects of this 2012 fire that are investigated in this study.

2.2. Experimental design and sampling

This study was conducted in a three km^2 catchment last ~~of about three km^2~~ affected by fire in~~the last fire of~~ July 2012. In autumn 2012, stabilisation treatments were carried out on hillslopes in the studied basin, and check dams were built at its outlet. The hillslope stabilisation treatment consisted of log erosion barriers (LEB) and contour-felled log debris (CFD). A LEB was built by felling burned trees that are laid on the ground along the slope contour (Napper, 2006). Each log was anchored in-place, avoiding any space between the log and soil surface to create a storage basin upstream of the LEB, where the water and sediment flows are trapped. Earthen berms were sometimes installed to reduce the share of water circumventing the log sides. In the study basin, the stabilisation treatment was operated at a mean density of 30 LEBs ha^{-1} with a mean length of 10 metres (for a linear density of 300 linear meters of logs per hectare). These densities were limited by the scarce availability of wood material, due to the unsuitable type of vegetation in the area (small-diameter and low-density trees). The CFD treatment consisted of branch and small felling burned trees, which were laid on the ground along the slope contour, as for LEB. In this case, logs were not anchored. The mean treatment density was 17 CFD ha^{-1} with a mean length of 50 m (corresponding to 850 linear m ha^{-1}) given the less compacted and concentrated material for building the CFD.

In October 2020, ten 20 x 20 m plots randomly distributed were set up in the burned and treated forest areas, five in the areas with CFD, and five other plots in the areas with LEB. Five additional plots were set up in the burned and unmanaged areas (hereinafter "burned and no action plots", "Bna"), and five plots were located in an unburned area inside the forest (UB plots), very close to the burned area. All plots were separated from each other around 200 meters (Fig. 1) to be considered totally independent. All the plots were located at a mean altitude of about 500 m a.s.l., at a slope of 30 to 45% and exposed to north (Table 1 and Fig. 1). Three soil composited samples (each of 600 g) were collected in each plot. Each composite sample consisted of six subsamples randomly collected in an individual plot, to be representative of the entire area. The samples were collected from the surface soil layer (0-10 cm) after litter removal, sieved (2-mm diameter) and kept at 4ºC until analyzed. Soil analyses were carried out within 15 days after sampling. Plot burn severity characterization was made using the normalized burn ratio index (NBR) calculated in the study area by Gómez-Sánchez et al. (2017). Information on the vegetation cover stoniness and depth of soils, and plant characteristics (cover and species composition) was derived using three 10 x 1-m transects in each treatment area (Table 2).

2.3. Soil analyses

2.3.1. Physico-chemical indicators

Soil pH and electrical conductivity (µS/cm) were determined in a 1:5 (w/v) aqueous solution. Soil organic matter (OM, % of dry soil) was measured using the potassium dichromate oxidation method (Nelson and Sommers, 1996).

2.3.2. Biochemical and microbiological indicators

As biochemical and microbial soil indicators, microbial biomass carbon (MBC, mg C kg^{-1}) was determined by the fumigation-extraction methods (Vance et al., 1987) and basal soil respiration (µg CO_2 $hour^{-1}$ g^{-1} soil) was measured in a multiple sensor respirometer (Micro-Oxymax, Columbus, OH, USA). With regard to the soil enzymatic activities, soil dehydrogenase activity (μg_{INTF} g^{-1} $hour^{-1}$ g^{-1} soil) was determined as the reduction of p-iodonitrotetrazolium chloride (INT) to piodonitrotetrazolium formazan by modifying the method reported by Von Mersi and Schinner, (1991). Urease activity ($\mu mol_{N\text{-}NH4+}$ $hour^{-1}$ g^{-1} soil) was measured according to the method of Tabatabai (1994), using urea as the substrate and borate buffer (at pH = 10) (Kandeler and Gerber, 1988). Acid phosphatase ($\mu mol_{p\text{-}NP}$ $hour^{-1}$ g^{-1} soil) and β-glucosidase ($\mu mol_{p\text{-}NP}$ $hour^{-1}$ g^{-1} soil) activities were determined according to Tabatabai and Bremner (1969) and Eivazi and Tabatabai (1977). Protease activity ($\mu mol_{p\text{-}NP}$ $hour^{-1}$ g^{-1} soil) was evaluated using the modified method of Ladd and Buttler (1972).

2.4. Statistical analysis

To determine whether there were any statistically significant differences in soil pH and electrical conductivity among groups treated with the hillslope stabilization techniques (i.e., Bna, CFD, LEB and UB), one-way analysis of variance (ANOVA) was performed. If there were significant treatment effects, Tukey's HSD (Honestly-significant-difference) test was performed to compare the differences between groups. Differences were considered significant at $p < 0.05$. To determine the treatment effects on soil functionality, we calculated an averaging metric (Jing et al., 2020) of soil multifunctionality through taking the mean of eight z-score standardized indictors of soil functionality. We first conducted one-way ANOVA and Tukey's HSD test for indicators of soil functionality and soil multifunctionality. We then conducted non-metric multidimensional scaling (NMDS) to visualize differences in soil multifunctionality using the Euclidean distance of the eight z-score standardized indicators of soil functionality. Analysis of variance using distance matrices was used to compare differences in soil multifunctionality among groups treated with the hillslope stabilization techniques. Finally, a correlation analysis was conducted to determine whether there were any significant bivariate associations among soil pH, electrical conductivity and eight indicators of soil functionality. Because there were only five samples per treatment, we only visualized the bivariate associations between soil organic matter content and soil enzymatic activities using their mean values and standard errors. All statistical analyses were carried out in R version 4.0.2 (R Development Core Team, 2020). Data cleaning and plotting were conducted using the tidyverse package. Tukey's HSD test was conducted using the multcomp package. NDMS and analysis of variance using distance matrices were conducted using the vegan package. Correlation matrix chart were created using the Performance Analytics package (R Development Core Team, 2020).

3. Results

Our result found significant differences among physico-chemical and microbiological soil properties at each experimental condition. In relation to physico-chemical soil properties, results showed that soil pH (8.3-8.6) and soil OM content (6.3-6.9%) were similar across all plots (Table 3). In addition, mean electrical conductivity was higher for CFD (147 µS/cm) than LEB (207 µS/cm), but only LEB was markedly different from the burned control (Table 3, Fig. 1 supplementary material). Regarding microbiological soil parameters, results showed that soil respiration was greater by ~2 µg CO_2 $hour^{-1}$ g^{-1} soil for CFD and LEB compared to unmanaged burnt plots; whereas, MBC (2260-2500 mg C kg^{-1}) was similar across all plots (Table 3, Fig. 2 supplementary material). Moreover, LEB plots had significantly higher dehydrogenase and urease soil enzymes activities compared to Bna, while CFD plots had significantly higher dehydrogenase and acid phosphatase activity compared to Bna (Table 3). Finally, we note that no significant differences were found between CFD and LEB for all surveyed soil enzymes. Based on microbiological soil properties, our results showed the lowest soil multifunctionality for the Bna plots, the highest for UB, and an intermediate value for both treatments, CFD and LEB (Table 3). This indicates that soil multifunctionality was enhanced by the treatments over unmanaged burnt slopes. Finally, CFD and LEB have high OM content, but low urease, acid phosphatase, protease, and β-glucosidase activities. By contrast, Bna has low OM content and low enzymatic activities, suggesting increasing in OM in CFD and LEB is related to low enzyme activity. There were clear differences in dehydrogenase activity among CFD, LEB and UB (Fig. 2).

Correlations among physico-chemical and microbiological soil properties (Table 4) show that electrical conductivity is inversely correlated with pH ($r = -0.75$, significantly at $p < 0.001$) and directly correlated with OM ($r = 0.50$, significantly at $p < 0.05$). Moreover, electrical conductivity and pH are also correlated with some enzymatic activities (e.g., electrical conductivity with protease activity, $r = -0.68$, $p < 0.001$, pH with PA, $r =0.69$, $p < 0.001$, and with urease activity, $r = 0.72$, $p < 0.001$). Strong correlations are evident between almost all the enzymes, with the highest coefficients of correlations found between β-glucosidase and acid phosphatase activities ($r = 0.93$, $p < 0.001$) (Table 4). MBC was directly correlated to OM ($r = 0.55$, $p < 0.05$), while no significant correlations were found between soil respiration and the other analyzed indicators (Table 4).

The nonmetric multidimensional scaling (NMDS) ~~routine~~ statistical procedure significantly ($p = 0.001$; analysis of variance using distance matrices) grouped two of the soil treatments (CFD and LEB) in one cluster, depending on the physico-chemical properties and enzymatic activities of soils (Fig. 3). Two other distinct clusters can be identified in Bna and UB soils (Fig. 3). Finally, a soil multifunctionality metric—evaluated by combining all the indicators measuring the soil mcirobial biomass and microbial activities—was the highest in UB soils (0.70 ± 0.11 unitless) and the lowest in Bna plots (-0.83 ± 0.07). The soils affected by wildfire and then treated showed intermediate but very similar values of multifunctionality (0.07 ± 0.05) and (-0.07 ± 0.06) for CFD and LEB plots, respectively) (Fig. 4).

4. Discussion

In our study, a clear, mid-term, post-fire recovery in soil multifunctionality was detected 8 years after the implementation of LEB and CFD compared to unmanaged burned soils. We note that the observed LEB and CFD post-fire recovery in soil multifunctionality did not reach the level of the undisturbed (unburnt) forest soils. Since the experimental plots were located in sites subject to the same burn severity and with very similar climatic and geomorphological conditions, the changes in soil properties are likely to be attributed to the effects of hillslope stabilization techniques. These results generally agree with the scant past work. In fact, several studies have detected changes in the soil properties after fire and post-fire restoration (González-Pérez et al., 2004), such as increases in soil pH (Mataix-Solera et al., 2002; Ulery et al., 1993), diminished aggregate stability (DeBano, 2000), changes in the nutrient availability and water retention (Certini, 2005) and modifications of enzymatic activities (Lucas-Borja et al., 2020b; Mataix-Solera et al., 2009). Specifically, past work found wildfire significantly reduced pH (which was a short lived impact, in general) and increased the electrical conductivity of soils compared to the unburned soils, while leaving the OM content constant (Mataix-Solera et al., 2009). An increase in electrical conductivity is also in agreement with past literature, since this soil property can experience sudden increases immediately after fire (Mataix-Solera et al., 2009; Muñoz-Rojas et al., 2016). In our study, the LEB treatment significantly increased soil electrical conductivity. This increase may be attributed to the "barrier effect" of LEB, which due to the burning, accumulates ions, minerals, carbon and other nutrients from burned forest fuel, the former litter layer and the burned topsoil (Caon et al., 2014; Gómez-Sánchez et al., 2019).. Contrary to past work, our study found that both the post-fire CFD and LEB resulted in no change to soil pH. The decrease in soil pH after fire reported in past research, however, is slight and gradually returns to the original pre-fire values due to the washout effect (Lucas-Borja et al., 2020b; Mataix-Solera et al., 2009; Muñoz-Rojas et al., 2016). Overall, the direct effects of treatments on microbiological soil properties is one possible mechanism, which has been consistently reported in earlier studies, while the novel findings in this work are that treatment may indirectly influence microbiological soil properties through changes in soil electrical conductivity or pH.

Soil OM content is, arguably, one of the most important indicators of functionality among the soil physico-chemical properties, since OM enhances functions related to plant growth (e.g., water retention, nutrient storage and dynamics) (Muñoz-Rojas et al., 2016) while also supporting plant productivity, biodiversity and other ecosystem services (Gómez-Sánchez et al., 2019; Lucas-Borja et al., 2020a). The OM content of soils was affected by LEB and CFD treatments, yielding values that were higher than burned unmanaged soils—and even higher compared to the unburned sites (although not significant). This soil OM stabilization by LEB and CFD may be beneficial to vegetation recovery. The observed increases in SOM may be due to the release of burnt materials in the treated areas, enhanced by both the vegetal residues falling from the structures and their effectiveness in slowing down water drainage/flow while trapping and retaining sediment (~~Peter R~~ Robichaud et al., 2008; Wohlgemuth et al., 2009) . The hydrological and sedimentological effects of vegetal residues are particularly noticeable in forests under semi-arid climatic conditions (Fernández et al., 2011; Gómez-Sánchez et al., 2019) but prone to runoff and erosion hazards, due to the high erosivity of rainfall concentrated in few events per year. In general, post-fire hillslope stabilization techniques similar to LEB and CFD can create a physical barrier against soil OM loss (Badía-Villas et al., 2014). Moreover, the wood and the plant residues used for CFD and LEB construction, respectively, modify the microclimatic conditions of soil and provide sources of OM due to its decomposition, and this enhances the biological activity of soil (Lucas- Borja et al., 2016~~n.d.~~; Robichaud et al., 2000).

The increase in soil OM recorded in LEB and CFD also appears to have improved the quantity and activity of microorganisms, as reflected by the increased MBC and soil respiration detected in the CFD- and LEB-treated soils (differences that are more substantial when compared to unburned soils). These differences were presumably due to the accumulation of biodegradable plant material (Lucas-Borja et al., 2016; Rodríguez et al., 2017). Increases in MBC and soil respiration were found also after post-fire restoration with straw mulch by Lucas-Borja et al. (2020) and with LEB and CFD (Lucas- Borja et al., 20210). Additionally, Goméz-Sanchez et al. (2019) detected significantly higher soil respiration in LEB-treated soils higher compared to the unburned soils, while the MBC was significantly higher in burned and CFD- or LEB-treated burned areas.

The increased quantity and activity of soil microorganisms can even last for some years after fire (Gómez-Sánchez et al., 2019; Lucas-Borja et al., 2020b), until mineralised materials are consumed (Muñoz-Rojas et al., 2016). This is in accordance with Badía et al. (2014), who stated that post-fire management actions can still be active some years after a wildfire on soils without plant cover. With regard to the enzymatic activity, the latter plays an important role in catalysing biological reactions (Lucas-Borja et al., 2020b; Mataix-Solera et al., 2009). In general, all the enzymatic activities monitored in this study are well correlated with each other. As expected (Lucas- Borja et al., 2021) the untreated burned soils showed lower values of the related indicators compared to the unburned plots or the soils that were subject to the treatments. This is a clear effect of wildfire, in which, due to the high soil temperature, a large amount of the enzymes are destroyed (Barreiro et al., 2010). Lucas-Borja et al. (2021) attributed the differences in enzymatic activities between unburned and untreated burned soils to the nutrient cycling, climate regulation, waste decomposition, wood production, and water regulation functions, which were lower in the soils subject to wildfire. Also Goméz-Sanchez et al. (2019) detected a different behaviour in the intracellular (dehydrogenase) and extracellular soil enzymes (β-glucosidase, urease and acid phosphatase) among burned (treated or not with LEB and CFD) and unburned soils, with the highest values of dehydrogenase activity in the burned plots. This difference may be explained by the fact that dehydrogenase is not active as extracellular enzymes in soil (Błońska et al., 2017; Lucas-Borja et al., 2020b).

Implementing hillslope stabilization techniques appears to help reduce enzyme content depletion due to wildfire—although soil enzymes did not recover to the pre-fire (unburned) conditions in this study, particularly for urease, acid phosphatase and β-glucosidase. This recovery may be attributed to two factors: (i) the materials that these techniques allow to accumulate (organic matter and nutrients) act as a barrier against washing downstream, thereby aiding in their own decomposition (Lucas-Borja et al., 2020b); and (ii) an increase in exchangeable cations (Rodríguez et al., 2017), which continues until mineralised materials have been consumed (Muñoz-Rojas et al., 2016). This result is supported by the positive correlations between the soil respiration and the soil OM content (Goméz-Sanchez et al., 2019). Also, Lucas-Borja et al. (2020) attributed the higher microbiological effects detected in burned and mulched soils compared to untreated plots to the accumulation and decomposition of organic matter (shown by higher ß-glucosidase) and nutrients (response of urease and acid-phosphatase activity) due to the application of vegetal residues biodegradable, as well as to energy released by soil microorganisms. These authors also observed a lack of variation in dehydrogenase activity in the soils with application of OM and suggested that this result was likely due to dehydrogenase activity lacking sensitivity to seasonality and site effects—rather than management practices (Lucas-Borja et al., 2020). In general, the enzymatic activities of soils treated with both LEB and CFD techniques were similar for this study. This is in accordance with Goméz-Sanchez et al. (2019), who reported similar trends in extracellular soil enzymes among LEB and CFD treatments, and with Lucas- Borja et al. (2021), who reported that the same post-fire management strategies do not statistically differ when comparing the managed soils (with LEB or CFD) with unburned soils. Some other studies conducted in Mediterranean areas reported a lower sensitivity of this enzymatic activity to management practices compared to season and site effects (Quilchano and Marañón, 2002). Both the variations measured for urease and β-glucosidase were similar between LEB and CFD (as also noticed by Goméz-Sanchez et al., 2019), which, however, remained significantly lower compared to the unburned soils. In particular, β-glucosidase has a very important role on degradation of organic compounds that facilitates soil enzyme activities (Lucas-Borja and Delgado-Baquerizo, 2019; Sardans et al., 2008)). The acid-phosphatase activity recovered better in LEB-treated soils, and this recovery may be explained by its comparatively stronger relationship with the timing of plant recovery, when roots become the main resource (Gómez-Sánchez et al., 2019; López-Poma and Bautista, 2014).

An important outcome of the study is that both the post-fire management techniques led to an increase in soil OM compared to the burned and not treated plots—with even higher values than in the pre-fire conditions (shown by comparison to the unburned soils). Simultaneous increases in the enzymatic activities observed in this study were not proportional to those recorded for soil OM. Moreover, while noticeable increases in some enzymatic activities were recorded with the OM content in unburned soils (e.g., protease, dehydrogenase and active phosphatase), the trends for one or both post-fire techniques were lower (e.g., LEB and CFD for protease, LEB for dehydrogenase or CFD for active phosphatase) or even declining (e.g., LEB for urease and active phosphatase). This means that the soil functionality may not depend only on the quantity of the OM applied to the soil, but rather on the quality of OM compounds supplied with the restoration techniques. Another important result of this study is the high correlation between the soil pH and extracellular enzymatic activities. This result is accordance with Sinsanbaugh et al. (2008), who stated that the enzymatic potential for hydrolyzing the labile components of soil OM is tied not only to substrate availability and the stoichiometry of microbial nutrient demand, but also to soil pH. The enzymatic potential for oxidizing the recalcitrant fractions of soil OM, which is an approximate control on soil OM accumulation, is most strongly related to soil pH (Sinsabaugh et al., 2008). Therefore, the soil pH, which is much easier to measure compared to the enzymatic activities, may be assumed as an immediate indicator of soil multifunctionality and therefore its quality, at least for rapid estimations.

5. Conclusions

This study confirms that soil multifunctionality (based on multiple enzymatic measurements) is depleted by wildfire compared to the unburned plots in a Mediterranean forest ecosystem. However, findings demonstrate that both of the evaluated post-fire hillslope stabilization techniques (contour felled debris and log erosion barriers) successfully limited the post-fire decay in soil functionality, although it was not restored to pre-fire levels. The effects of the two hillslope stabilization techniques on soil multifunctionality were similar and, thus, the working hypothesis that these hillslope stabilisation techniques enhance soil functionality in fire-affected areas can be confirmed. Although the burned and treated soils underwent increases in organic matter content after post-fire management, the increases in the enzymatic activities were not so high. This result suggests that soil functionality does not depend only on the quantity of the organic matter applied to the soil, but on the interaction of various effects produced by the restoration techniques on the studied parameters. Finally, the high correlation detected between the soil acidity and the enzymatic activities (except dehydrogenase) suggests adopting pH as a quick and easy indicator of soil functionality at least for rough estimations, since it appears to be a proxy of the enzymatic potential for oxidizing the recalcitrant fractions of soil organic material. Overall, the results of the study may contribute to the selection of effective post-fire management actions seeking to prevent degradation of soil functionality.

Acknowledgements

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Reviewer #1: The revised Figure 1 is much appreciated, and I agree that Figure 3 works better as a table. The removal of many of the abbreviations really helps improve its readability. For example, the results (~Line 273) are vastly improved. All in all, this revision requires minor editorial updates that are necessary for me to review next round.

Dear Reviewer, thank you very much for your help and suggestions during the review process of our work. Please see a detailed response below. We hope our work helps to improve the quality of the manuscripts. Sincerely

There are some remaining issues. Here are some suggestions.

L33: could you simply say "not to the same level as nearby unburned plots" ??
Done

L138: "the forest is situated at an elevation between …"
Done

L171: "This study was conducted in a three km2 catchment last affected by fire in July 2012"
Done

L235: need to define "HSD"
Done

L292: what does 'routine significantly' to '… grouped' mean?
Done

L347: need to fix Robichaud reference
Done

L356: still has an 'n.d.' for this reference
Done

L360: should be "CDF- and LEB-treated …"
Done

L575: Lucas-Borja has an extra space here and below in your bibliography software. You should really fix that, given that you're the lead author. And probably self-citing yourself a bit much here…
Done

L618: I don't think 'An. Int. J.' is necessary
Done

L653: Need "Robichaud, P.R., ed., …"
Done

Figure 1: The legend shows "Burned no action plots (BNA)" but it should use (Bna) - however, it really should be BNA in the text - either way, just be consistent.
Done

Figure 2: The DHA and UA don't have any x-axis - was this intentional? Or should it be OM content?

Intentional. Points indicate the mean values (n = 5) of organic matter content and enzyme activity.

Table 2 caption needs to say "Vegetation cover, stoniness, …"
Done

Table 4 has two bold entries that are missing a sig digit - 0.5 and 0.4 should be 0.50 and 0.40
Done

Reviewer #2: I read this revised manuscript about changes in soil functionality eight years after fire with great interest. The authors have done a great job at addressing all my comments and, as far as I can see, they have also provided compelling replies to the comments of the other reviewer. I think the paper is publishable as is.

Dear Reviewer, thank you very much for your help and suggestions during the review process of our work. Sincerely

Highlights

- This work evaluates the effectiveness of postfire strategies on soil functionality
- Fire may shift the trajectory of microbiological soil properties
- Post-fire management altered microbiological soil properties and soil functionality
- Contour-felled log debris CFD and log erosion barriers LEB post-fire management enhanced soil organic matter

Changes in soil functionality eight years after fire and post-fire hillslope stabilisation in Mediterranean forest ecosystems

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Abstract

Contour-felled log debris (CFD) and log erosion barriers (LEB) are two restoration practices used worldwide on hillslopes to avoid soil erosion after wildfires. Although significant work has evaluated the effectiveness of these practices on soil loss prevention, their effects on soil properties have been little researched to date. Here, the effects of CFD and LEB treatments on several physico-chemical and biological soil properties were investigated across four post-fire zones in Mediterranean forest (Sierra de Los Donceles, Spain). Results suggest that post-fire management similarly altered the recovery of microbiological soil properties and soil functionality for both CFD and LEB treatments. Post-fire management enhanced soil organic matter (SOM) and basal respiration, while suppressing soil microbial activities. SOM enhancement at our plots may have been associated with suppressed soil microbial decomposition activity due to post-fire increases in electrical conductivity. Plots with post-fire management recovered microbiological soil properties better than unmanaged burn plots, but not to the same level as nearby unburned plots. LEB and CFD may not only be effective in retaining

sediments, but also in improving post-fire microbiological soil properties in comparison to unmanaged plots. However, after eight years of post-fire management, soil microbiological soil properties did not completely recover compared to unburnt areas. That is, fire may shift the development trajectory of microbiological soil properties so that they may no longer be able to return to the same unburnt conditions. Post-fire restoration plans should consider the use of LEB and CFD when aiming to aid soil-related ecosystem recovery processes after wildfires.

Keywords: Post-fire restoration practices; log erosion barriers; contour-felled log debris; microbiological soil properties; wildfire; Organic matter

1. Introduction

Global warming has decreased precipitation and increased temperatures in the Mediterranean Basin, significantly impacting the region's forests (Lindner et al., 2010). An increased frequency and severity of summer droughts are expected to significantly increase the number of wildfires and the extent of burned areas. The direct and indirect effects of fires on forest soil and vegetation are well documented in the scientific literature (Certini, 2005; Lucas- Borja et al.,2021), including post-fire nutrient losses via increased runoff and erosion rates (Mataix-Solera et al., 2009; Muñoz-Rojas et al., 2016; Robichaud et al., 2000). Post-fire management actions are, therefore, needed to reduce soil losses and complement natural regenerative processes for ecosystem recovery after wildfires (Mataix-Solera et al., 2009). Among the post-fire restoration techniques, hillslope stabilisation treatments are commonly implemented to decrease soil degradation by reducing runoff and erosion rates (Fernández and Vega, 2016; Shakesby, 2011). These stabilization treatments, such as grass seeding, anchored log erosion barriers (LEB), contour-felled log debris (CFD) or mulching, keep soil in-place after fire by preventing particle detachment and subsequent deposition in unwanted areas (Robichaud et al., 2000). Treatments that utilize post-fire woodland materials (like burned, dead fuel, and log debris) are commonly implemented, as they not only prevent soil losses, but also accelerate the decomposition and incorporation of endogenous biomass into soil and reduce fuel load. In general, post-fire hillslope treatments have been demonstrated to be effective in lowering runoff, peak flows and sediment yields from burnt watersheds however, treatment effectiveness depends on structure design, season of construction and fire severity (Badía et al., 2014; P. R. Robichaud et al., 2008).

A large body of literature has evaluated the effect of hillslope stabilisation techniques (e.g., CFD and LEB) on soil erosion and runoff (e.g.,Albert-Belda et al., 2019; Fernández et al., 2019; Jourgholami et al., 2020). Less research is available regarding the effect on soil chemical properties after hillslope stabilisation treatments (Wittengberg et al., 2020), and with regard to the recovery of microbiological soil properties, the available literature is almost absent, leaving these impacts not well understood to date. Specifically, hillslope stabilisation treatments, while preventing erosion, may engender soil physicochemical properties that play key ecological roles in burned forests through influencing the composition and activity of soil biota (Killham, 1994). By trapping seeds or generating higher soil moisture nearby felled burned branches or logs, post-fire management structures may change vegetation composition and cover, which alters forest structure after wildfires (Rago et al., 2020). The quantity and quality of the burned material falling from branches and log debris structures may also generate changes in soil properties (Lucas- Borja et al., 2021).

Since the soil is a mosaic of metabolic processes, the use of a single parameter to study the response of soil functionality (i.e., the ability of soil systems to simultaneously provide multiple ecosystem functions) is not enough (Lucas- Borja et al., 2011). Thus, many authors have proposed the use of several indicators to assess soil (multi)functionality that may be used as early indicators of soil stress or restoration (e.g. (Lucas-Borja and Delgado-Baquerizo, 2019). Biochemical and microbiological indicators related to soil microbial activity are of paramount importance for maintaining soil functionality—with many extracellular enzymes directly affecting soil N, P and C cycling (urease, phosphatase and β-glucosidase, respectively) and some general microbial indicators such as respiration or intracellular dehydrogenase activity. Moreover, as key microbiological soil properties, soil respiration, microbial biomass carbon and enzyme activities are all closely tied to C, N and P cycling, organic matter decomposition and formation (Gutknecht et al., 2010). Soil enzymes, in particular, are considered biomarkers of the functional ability of microbial communities; thus soil respiration and enzymes may be ideal indicators of change, disturbance or stress in the soil community (Aon et al., 2001). These soil properties are currently considered sensitive indicators of soil functionality and, thereby, have implications for the establishment of native plant communities and cover (Bastida et al., 2008)—and these implications may extend to post-fire hillslopes. Indeed, enzymes and respiration have been widely used together as soil functionality indicators to evaluate degradation in Mediterranean forest ecosystems (Lucas-Borja, 2015;).

Due to the number and complexity of post-fire effects on soils, very little guidance is currently available to plan possible countermeasures against soil degradation (Lucas-Borja et al., 2020b). Even observational information about changes in these microbiological indicators in wildfire-affected forests with hillslope soil stabilization is severely lacking (barring a single study: Gómez-Sánchez et al., 2019). Wildfires and subsequent post-fire management effects on microbiological soil properties have been little researched to date, which may hinder our ability to understand the effects of these management practices on soil multifunctionality. To fill this gap, this study aims at evaluating the effects of two common post-fire hillslope stabilisation techniques (LEB and CFD) on soil functionality eight years after a wildfire, using microbiological soil properties (urease, phosphatase and β-glucosidase soil enzyme activities, soil respiration or intracellular dehydrogenase activity) as indicators of the functional ability in soil microbial communities. The changes in these indicators in treated hillslopes have been compared to those monitored in unburned and burned areas without post-fire restoration actions, assumed as control. We hypothesized that hillslope stabilisation techniques will enhance soil functionality in fire-affected areas compared to unmanaged post-fire hillslopes. Specifically, we aim to answer the following questions:

a) Can CFD affect soil indicators differently than LEB?

b) Do intra- and extra-cellular soil enzymes or chemical soil indicators (e.g., soil pH, electrical conductivity or soil organic matter) differentially respond to CFD v LEB?

This research will help to demonstrate whether soil multifunctionality is affected by post-fire management treatments, and how they can promote microbiological soil properties recovery after wildfire in the mid-term in comparison with untreated areas.

2. Material and methods

2.1. Study area

Sierra de Los Donceles forest is located close to Hellín (province of Albacete, south-east Spain). The forest is situated at an elevation between 304 m to 808 m in the pre-Baetic mountain chain, inside the Sierra de los Donceles catchment, neighbouring the Mundo (north) and Segura (south) Rivers. The forest is located in the meso-Mediterranean bioclimatic belt (Rivas-Martínez et al., 2002).. The mean annual temperature and precipitation are 16.6°C and 321 mm, respectively. The maximum seasonal precipitation inputs are concentrated in October (44.5 mm) and May (39.6 mm) (1990-2014, data provided by the Spanish Meteorological Agency and Gómez-Sánchez et al. (2017)). The geology is typical pre-Baetic Mountains, with limestone and dolomite outcrops alternating with marly intercalations that date back to the quaternary. According to the USDA Soil Taxonomy System, soils are Calcic Aridisols with loamy to sandy loam texture. Vegetation belongs to the *Querco cocciferae-Pino halepensis S.* series. Before the fire of 2012, the natural vegetation was mature Aleppo pine stands with a companion shrub layer which, in combination, formed a dense cover in all plots (Table 1). Aleppo pine covers much of the tree vegetation layers (tree, shrub and herb), and oak represents a large cover in the shrub layer (Peinado Lorca et al., 2008). These oaks form an intricate mass of thorny nanophanerophyte, e.g., kermes oak (*Quercus coccifera*), black hawthorn (*Rhamnus lycioides*), Italian buckthorn *(Rhamnus alaternus)*, grey asparagus (*Asparagus horridus*) and other inerms (*Pistacia lentiscus, Genista spartioides subsp. retamoides*). Esparto grass (*Stipa macrochloa*), also abundant in the area, were used from the 17^{th} century until halfway through the 20^{th} century as an economic driver because it is a fibre producer. These spartals were the main historic disturbance of forest stands in the area and favoured their growth. The progressive abandonment and the reforestation carried out by the public administration have shaped a forest landscape composed of spontaneous Aleppo pines, growing in shaded areas and watercourses. In the 1980s, the Aleppo pine was repopulated in accessible public lands with little soil along with thermophile scrublands in sunny spots (spartals and rosemary scrublands). Records of forest fires began in Spain in 1968. In the Sierra Donceles forest, two fires have taken place: a first fire in 1994, which was caused by lightning and affected 46 ha, and an arson fire in July

2012, which devastated roughly 6500 ha of Mediterranean maquis. It is the effects of this 2012 fire that are investigated in this study.

2.2. Experimental design and sampling

This study was conducted in a three km^2 catchment last affected by fire in July 2012. In autumn 2012, stabilisation treatments were carried out on hillslopes in the studied basin, and check dams were built at its outlet. The hillslope stabilisation treatment consisted of log erosion barriers (LEB) and contour-felled log debris (CFD). A LEB was built by felling burned trees that are laid on the ground along the slope contour (Napper, 2006). Each log was anchored in-place, avoiding any space between the log and soil surface to create a storage basin upstream of the LEB, where the water and sediment flows are trapped. Earthen berms were sometimes installed to reduce the share of water circumventing the log sides. In the study basin, the stabilisation treatment was operated at a mean density of 30 LEBs ha^{-1} with a mean length of 10 metres (for a linear density of 300 linear meters of logs per hectare). These densities were limited by the scarce availability of wood material, due to the unsuitable type of vegetation in the area (small-diameter and low-density trees). The CFD treatment consisted of branch and small felling burned trees, which were laid on the ground along the slope contour, as for LEB. In this case, logs were not anchored. The mean treatment density was 17 CFD ha^{-1} with a mean length of 50 m (corresponding to 850 linear m ha^{-1}) given the less compacted and concentrated material for building the CFD.

In October 2020, ten 20 x 20 m plots randomly distributed were set up in the burned and treated forest areas, five in the areas with CFD, and five other plots in the areas with LEB. Five additional plots were set up in the burned and unmanaged areas (hereinafter "burned and no action plots", "Bna"), and five plots were located in an unburned area inside the forest (UB plots), very close to the burned area. All plots were separated from each other around 200 meters (Fig. 1) to be considered totally independent. All the plots were located at a mean altitude of about 500 m a.s.l., at a slope of 30 to 45% and exposed to north (Table 1 and Fig. 1). Three soil composited samples (each of 600 g) were collected in each plot. Each composite sample consisted of six subsamples randomly collected in an individual plot, to be representative of the entire area. The samples were collected from the surface soil layer (0-10 cm) after litter removal, sieved (2-mm diameter) and kept at 4ºC until analyzed. Soil analyses were carried out within 15 days after sampling. Plot burn severity characterization was made using the normalized burn ratio index (NBR) calculated in the study area by Gómez-Sánchez et al. (2017). Information on the vegetation cover stoniness and depth of soils, and plant characteristics (cover and species composition) was derived using three 10 x 1-m transects in each treatment area (Table 2).

2.3. Soil analyses

2.3.1. Physico-chemical indicators

Soil pH and electrical conductivity (µS/cm) were determined in a 1:5 (w/v) aqueous solution. Soil organic matter (OM, % of dry soil) was measured using the potassium dichromate oxidation method (Nelson and Sommers, 1996).

2.3.2. Biochemical and microbiological indicators

As biochemical and microbial soil indicators, microbial biomass carbon (MBC, mg C kg^{-1}) was determined by the fumigation-extraction methods (Vance et al., 1987) and basal soil respiration (µg CO_2 $hour^{-1}$ g^{-1} soil) was measured in a multiple sensor respirometer (Micro-Oxymax, Columbus, OH, USA). With regard to the soil enzymatic activities, soil dehydrogenase activity (μg_{INTF} g^{-1} $hour^{-1}$ g^{-1} soil) was determined as the reduction of p-iodonitrotetrazolium chloride (INT) to piodonitrotetrazolium formazan by modifying the method reported by Von Mersi and Schinner, (1991). Urease activity ($\mu mol_{N\text{-}NH4+}$ $hour^{-1}$ g^{-1} soil) was measured according to the method of Tabatabai (1994), using urea as the substrate and borate buffer (at pH = 10) (Kandeler and Gerber, 1988). Acid phosphatase ($\mu mol_{p\text{-}NP}$ $hour^{-1}$ g^{-1} soil) and β-glucosidase ($\mu mol_{p\text{-}NP}$ $hour^{-1}$ g^{-1} soil) activities were determined according to Tabatabai and Bremner (1969) and Eivazi and Tabatabai (1977). Protease activity ($\mu mol_{p\text{-}NP}$ $hour^{-1}$ g^{-1} soil) was evaluated using the modified method of Ladd and Buttler (1972).

2.4. Statistical analysis

To determine whether there were any statistically significant differences in soil pH and electrical conductivity among groups treated with the hillslope stabilization techniques (i.e., Bna, CFD, LEB and UB), one-way analysis of variance (ANOVA) was performed. If there were significant treatment effects, Tukey's HSD (Honestly-significant-difference) test was performed to compare the differences between groups. Differences were considered significant at $p < 0.05$. To determine the treatment effects on soil functionality, we calculated an averaging metric (Jing et al., 2020) of soil multifunctionality through taking the mean of eight z-score standardized indictors of soil functionality. We first conducted one-way ANOVA and Tukey's HSD test for indicators of soil functionality and soil multifunctionality. We then conducted non-metric multidimensional scaling (NMDS) to visualize differences in soil multifunctionality using the Euclidean distance of the eight z-score standardized indicators of soil functionality. Analysis of variance using distance matrices was used to compare differences in soil multifunctionality among groups treated with the hillslope stabilization techniques. Finally, a correlation analysis was conducted to determine whether there were any significant bivariate associations among soil pH, electrical conductivity and eight indicators of soil functionality. Because there were only five samples per treatment, we only visualized the bivariate associations between soil organic matter content and soil enzymatic activities using their mean values and standard errors. All statistical analyses were carried out in R version 4.0.2 (R Development Core Team, 2020). Data cleaning and plotting were conducted using the tidyverse package. Tukey's HSD test was conducted using the multcomp package. NDMS and analysis of variance using distance matrices were conducted using the vegan package. Correlation matrix chart were created using the Performance Analytics package (R Development Core Team, 2020).

3. Results

Our result found significant differences among physico-chemical and microbiological soil properties at each experimental condition. In relation to physico-chemical soil properties, results showed that soil pH (8.3-8.6) and soil OM content (6.3-6.9%) were similar across all plots (Table 3). In addition, mean electrical conductivity was higher for CFD (147 µS/cm) than LEB (207 µS/cm), but only LEB was markedly different from the burned control (Table 3, Fig. 1 supplementary material). Regarding microbiological soil parameters, results showed that soil respiration was greater by ~2 µg CO_2 $hour^{-1}$ g^{-1} soil for CFD and LEB compared to unmanaged burnt plots; whereas, MBC (2260-2500 mg C kg^{-1}) was similar across all plots (Table 3, Fig. 2 supplementary material). Moreover, LEB plots had significantly higher dehydrogenase and urease soil enzymes activities compared to Bna, while CFD plots had significantly higher dehydrogenase and acid phosphatase activity compared to Bna (Table 3). Finally, we note that no significant differences were found between CFD and LEB for all surveyed soil enzymes. Based on microbiological soil properties, our results showed the lowest soil multifunctionality for the Bna plots, the highest for UB, and an intermediate value for both treatments, CFD and LEB (Table 3). This indicates that soil multifunctionality was enhanced by the treatments over unmanaged burnt slopes. Finally, CFD and LEB have high OM content, but low urease, acid phosphatase, protease, and β-glucosidase activities. By contrast, Bna has low OM content and low enzymatic activities, suggesting increasing in OM in CFD and LEB is related to low enzyme activity. There were clear differences in dehydrogenase activity among CFD, LEB and UB (Fig. 2).

Correlations among physico-chemical and microbiological soil properties (Table 4) show that electrical conductivity is inversely correlated with pH ($r = -0.75$, significantly at $p < 0.001$) and directly correlated with OM ($r = 0.50$, significantly at $p < 0.05$). Moreover, electrical conductivity and pH are also correlated with some enzymatic activities (e.g., electrical conductivity with protease activity, $r = -0.68$, $p < 0.001$, pH with PA, $r = 0.69$, $p < 0.001$, and with urease activity, $r = 0.72$, $p < 0.001$). Strong correlations are evident between almost all the enzymes, with the highest coefficients of correlations found between β-glucosidase and acid phosphatase activities ($r = 0.93$, $p < 0.001$) (Table 4). MBC was directly correlated to OM ($r = 0.55$, $p < 0.05$), while no significant correlations were found between soil respiration and the other analyzed indicators (Table 4).

The nonmetric multidimensional scaling (NMDS) statistical procedure significantly ($p = 0.001$; analysis of variance using distance matrices) grouped two of the soil treatments (CFD and LEB) in one cluster, depending on the physico-chemical properties and enzymatic activities of soils (Fig. 3). Two other distinct clusters can be identified in Bna and UB soils (Fig. 3). Finally, a soil multifunctionality metric—evaluated by combining all the indicators measuring the soil mcirobial biomass and microbial activities—was the highest in UB soils (0.70 ± 0.11 unitless) and the lowest in Bna plots (-0.83 ± 0.07). The soils affected by wildfire and then treated showed intermediate but very similar values of multifunctionality (0.07 ± 0.05) and (-0.07 ± 0.06) for CFD and LEB plots, respectively) (Fig. 4).

4. Discussion

In our study, a clear, mid-term, post-fire recovery in soil multifunctionality was detected 8 years after the implementation of LEB and CFD compared to unmanaged burned soils. We note that the observed LEB and CFD post-fire recovery in soil multifunctionality did not reach the level of the undisturbed (unburnt) forest soils. Since the experimental plots were located in sites subject to the same burn severity and with very similar climatic and geomorphological conditions, the changes in soil properties are likely to be attributed to the effects of hillslope stabilization techniques. These results generally agree with the scant past work. In fact, several studies have detected changes in the soil properties after fire and post-fire restoration (González-Pérez et al., 2004), such as increases in soil pH (Mataix-Solera et al., 2002; Ulery et al., 1993), diminished aggregate stability (DeBano, 2000), changes in the nutrient availability and water retention (Certini, 2005) and modifications of enzymatic activities (Lucas-Borja et al., 2020b; Mataix-Solera et al., 2009). Specifically, past work found wildfire significantly reduced pH (which was a short lived impact, in general) and increased the electrical conductivity of soils compared to the unburned soils, while leaving the OM content constant (Mataix-Solera et al., 2009). An increase in electrical conductivity is also in agreement with past literature, since this soil property can experience sudden increases immediately after fire (Mataix-Solera et al., 2009; Muñoz-Rojas et al., 2016). In our study, the LEB treatment significantly increased soil electrical conductivity. This increase may be attributed to the "barrier eff ect" of LEB, which due to the burning, accumulates ions, minerals, carbon and other nutrients from burned forest fuel, the former litter layer and the burned topsoil (Caon et al., 2014; Gómez-Sánchez et al., 2019).. Contrary to past work, our study found that both the post-fire CFD and LEB resulted in no change to soil pH. The decrease in soil pH after fire reported in past research, however, is slight and gradually returns to the original pre-fire values due to the washout eff ect (Lucas-Borja et al., 2020b; Mataix-Solera et al., 2009; Muñoz-Rojas et al., 2016). Overall, the direct effects of treatments on microbiological soil properties is one possible mechanism, which has been consistently reported in earlier studies, while the novel findings in this work are that treatment may indirectly influence microbiological soil properties through changes in soil electrical conductivity or pH.

Soil OM content is, arguably, one of the most important indicators of functionality among the soil physico-chemical properties, since OM enhances functions related to plant growth (e.g., water retention, nutrient storage and dynamics) (Muñoz-Rojas et al., 2016) while also supporting plant productivity, biodiversity and other ecosystem services (Gómez-Sánchez et al., 2019; Lucas-Borja et al., 2020a). The OM content of soils was affected by LEB and CFD treatments, yielding values that were higher than burned unmanaged soils—and even higher compared to the unburned sites (although not significant). This soil OM stabilization by LEB and CFD may be beneficial to vegetation recovery. The observed increases in SOM may be due to the release of burnt materials in the treated areas, enhanced by both the vegetal residues falling from the structures and their effectiveness in slowing down water drainage/flow while trapping and retaining sediment (Robichaud et al., 2008; Wohlgemuth et al., 2009) . The hydrological and sedimentological effects of vegetal residues are particularly noticeable in forests under semi-arid climatic conditions (Fernández et al., 2011; Gómez-Sánchez et al., 2019) but prone to runoff and erosion hazards, due to the high erosivity of rainfall concentrated in few events per year. In general, post-fire hillslope stabilization techniques similar to LEB and CFD can create a physical barrier against soil OM loss (Badía-Villas et al., 2014). Moreover, the wood and the plant residues used for CFD and LEB construction, respectively, modify the microclimatic conditions of soil and provide sources of OM due to its decomposition, and this enhances the biological activity of soil (Lucas- Borja et al., 2016; Robichaud et al., 2000).

The increase in soil OM recorded in LEB and CFD also appears to have improved the quantity and activity of microorganisms, as reflected by the increased MBC and soil respiration detected in the CFD- and LEB-treated soils (differences that are more substantial when compared to unburned soils). These differences were presumably due to the accumulation of biodegradable plant material (Lucas-Borja et al., 2016; Rodríguez et al., 2017). Increases in MBC and soil respiration were found also after post-fire restoration with straw mulch by Lucas-Borja et al. (2020) and with LEB and CFD (Lucas- Borja et al., 20210). Additionally, Goméz-Sanchez et al. (2019) detected significantly higher soil respiration in LEB-treated soils higher compared to the unburned soils, while the MBC was significantly higher in burned and CFD- or LEB-treated burned areas.

The increased quantity and activity of soil microorganisms can even last for some years after fire (Gómez-Sánchez et al., 2019; Lucas-Borja et al., 2020b), until mineralised materials are consumed (Muñoz-Rojas et al., 2016). This is in accordance with Badía et al. (2014), who stated that post-fire management actions can still be active some years after a wildfire on soils without plant cover. With regard to the enzymatic activity, the latter plays an important role in catalysing biological reactions (Lucas-Borja et al., 2020b; Mataix-Solera et al., 2009). In general, all the enzymatic activities monitored in this study are well correlated with each other. As expected (Lucas- Borja et al., 2021) the untreated burned soils showed lower values of the related indicators compared to the unburned plots or the soils that were subject to the treatments. This is a clear effect of wildfire, in which, due to the high soil temperature, a large amount of the enzymes are destroyed (Barreiro et al., 2010). Lucas-Borja et al. (2021) attributed the differences in enzymatic activities between unburned and untreated burned soils to the nutrient cycling, climate regulation, waste decomposition, wood production, and water regulation functions, which were lower in the soils subject to wildfire. Also Goméz-Sanchez et al. (2019) detected a different behaviour in the intracellular (dehydrogenase) and extracellular soil enzymes (β-glucosidase, urease and acid phosphatase) among burned (treated or not with LEB and CFD) and unburned soils, with the highest values of dehydrogenase activity in the burned plots. This difference may be explained by the fact that dehydrogenase is not active as extracellular enzymes in soil (Błońska et al., 2017; Lucas-Borja et al., 2020b).

Implementing hillslope stabilization techniques appears to help reduce enzyme content depletion due to wildfire—although soil enzymes did not recover to the pre-fire (unburned) conditions in this study, particularly for urease, acid phosphatase and β-glucosidase. This recovery may be attributed to two factors: (i) the materials that these techniques allow to accumulate (organic matter and nutrients) act as a barrier against washing downstream, thereby aiding in their own decomposition (Lucas-Borja et al., 2020b); and (ii) an increase in exchangeable cations (Rodríguez et al., 2017), which continues until mineralised materials have been consumed (Muñoz-Rojas et al., 2016). This result is supported by the positive correlations between the soil respiration and the soil OM content (Goméz-Sanchez et al., 2019). Also, Lucas-Borja et al. (2020) attributed the higher microbiological effects detected in burned and mulched soils compared to untreated plots to the accumulation and decomposition of organic matter (shown by higher ß-glucosidase) and nutrients (response of urease and acid-phosphatase activity) due to the application of vegetal residues biodegradable, as well as to energy released by soil microorganisms. These authors also observed a lack of variation in dehydrogenase activity in the soils with application of OM and suggested that this result was likely due to dehydrogenase activity lacking sensitivity to seasonality and site effects—rather than management practices (Lucas-Borja et al., 2020). In general, the enzymatic activities of soils treated with both LEB and CFD techniques were similar for this study. This is in accordance with Goméz-Sanchez et al. (2019), who reported similar trends in extracellular soil enzymes among LEB and CFD treatments, and with Lucas- Borja et al. (2021), who reported that the same post-fire management strategies do not statistically differ when comparing the managed soils (with LEB or CFD) with unburned soils. Some other studies conducted in Mediterranean areas reported a lower sensitivity of this enzymatic activity to management practices compared to season and site effects (Quilchano and Marañón, 2002). Both the variations measured for urease and β-glucosidase were similar between LEB and CFD (as also noticed by Goméz-Sanchez et al., 2019), which, however, remained significantly lower compared to the unburned soils. In particular, β-glucosidase has a very important role on degradation of organic compounds that facilitates soil enzyme activities (Lucas-Borja and Delgado-Baquerizo, 2019; Sardans et al., 2008)). The acid-phosphatase activity recovered better in LEB-treated soils, and this recovery may be explained by its comparatively stronger relationship with the timing of plant recovery, when roots become the main resource (Gómez-Sánchez et al., 2019; López-Poma and Bautista, 2014).

An important outcome of the study is that both the post-fire management techniques led to an increase in soil OM compared to the burned and not treated plots—with even higher values than in the pre-fire conditions (shown by comparison to the unburned soils). Simultaneous increases in the enzymatic activities observed in this study were not proportional to those recorded for soil OM. Moreover, while noticeable increases in some enzymatic activities were recorded with the OM content in unburned soils (e.g., protease, dehydrogenase and active phosphatase), the trends for one or both post-fire techniques were lower (e.g., LEB and CFD for protease, LEB for dehydrogenase or CFD for active phosphatase) or even declining (e.g., LEB for urease and active phosphatase). This means that the soil functionality may not depend only on the quantity of the OM applied to the soil, but rather on the quality of OM compounds supplied with the restoration techniques. Another important result of this study is the high correlation between the soil pH and extracellular enzymatic activities. This result is accordance with Sinsanbaugh et al. (2008), who stated that the enzymatic potential for hydrolyzing the labile components of soil OM is tied not only to substrate availability and the stoichiometry of microbial nutrient demand, but also to soil pH. The enzymatic potential for oxidizing the recalcitrant fractions of soil OM, which is an approximate control on soil OM accumulation, is most strongly related to soil pH (Sinsabaugh et al., 2008). Therefore, the soil pH, which is much easier to measure compared to the enzymatic activities, may be assumed as an immediate indicator of soil multifunctionality and therefore its quality, at least for rapid estimations.

5. Conclusions

This study confirms that soil multifunctionality (based on multiple enzymatic measurements) is depleted by wildfire compared to the unburned plots in a Mediterranean forest ecosystem. However, findings demonstrate that both of the evaluated post-fire hillslope stabilization techniques (contour felled debris and log erosion barriers) successfully limited the post-fire decay in soil functionality, although it was not restored to pre-fire levels. The effects of the two hillslope stabilization techniques on soil multifunctionality were similar and, thus, the working hypothesis that these hillslope stabilisation techniques enhance soil functionality in fire-affected areas can be confirmed. Although the burned and treated soils underwent increases in organic matter content after post-fire management, the increases in the enzymatic activities were not so high. This result suggests that soil functionality does not depend only on the quantity of the organic matter applied to the soil, but on the interaction of various effects produced by the restoration techniques on the studied parameters. Finally, the high correlation detected between the soil acidity and the enzymatic activities (except dehydrogenase) suggests adopting pH as a quick and easy indicator of soil functionality at least for rough estimations, since it appears to be a proxy of the enzymatic potential for oxidizing the recalcitrant fractions of soil organic material. Overall, the results of the study may contribute to the selection of effective post-fire management actions seeking to prevent degradation of soil functionality.

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Figures

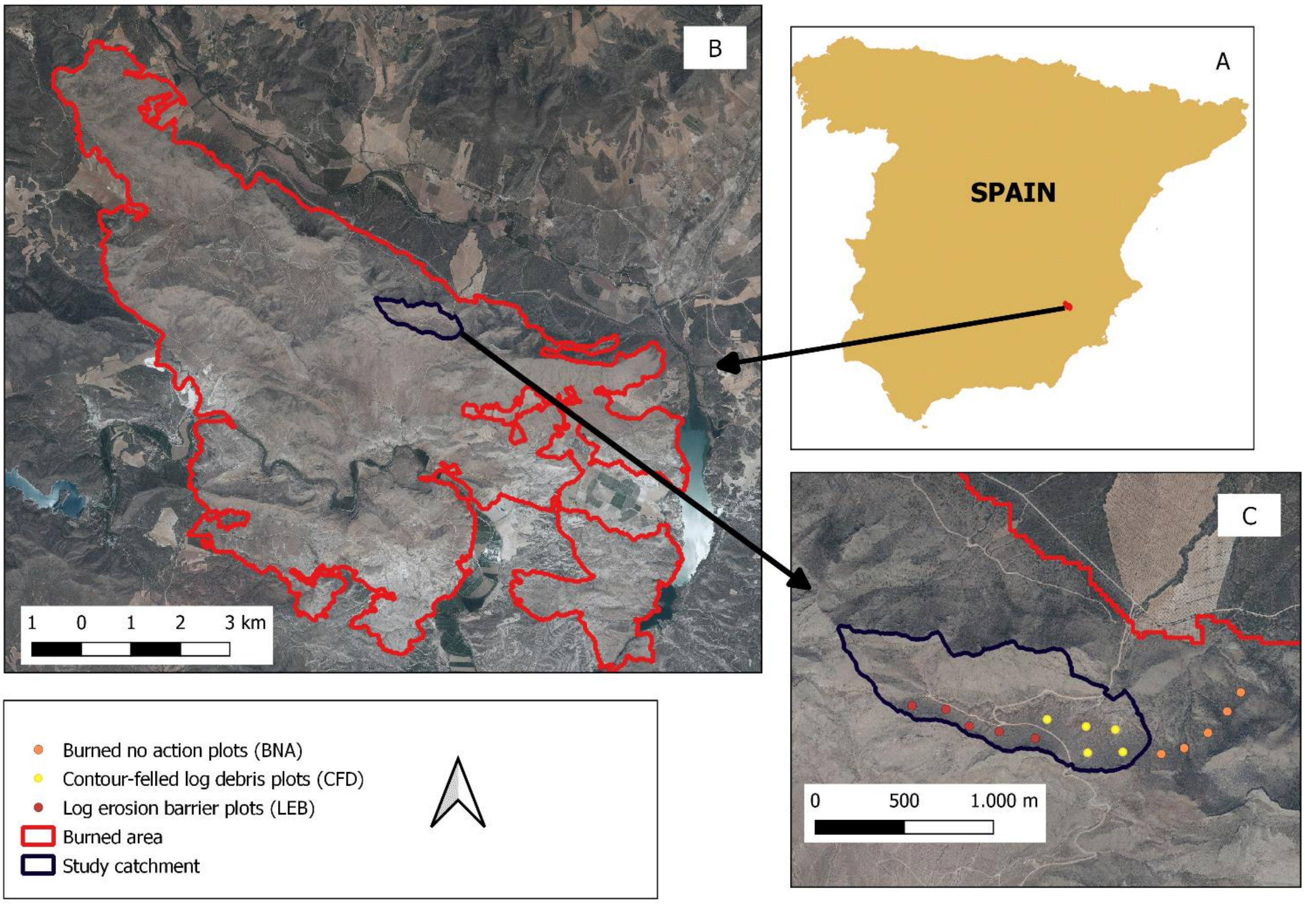

Figure 1. A) Location of the area affected by the July 2012 wildfire in Hellín (Albacete, Spain). B) Location of the study catchment in the burned area. C) Location of the plots within the burned area (Burned no action plots, Bna; Contour-felled log debris, CFD; Log erosion barrier plots, LEB).

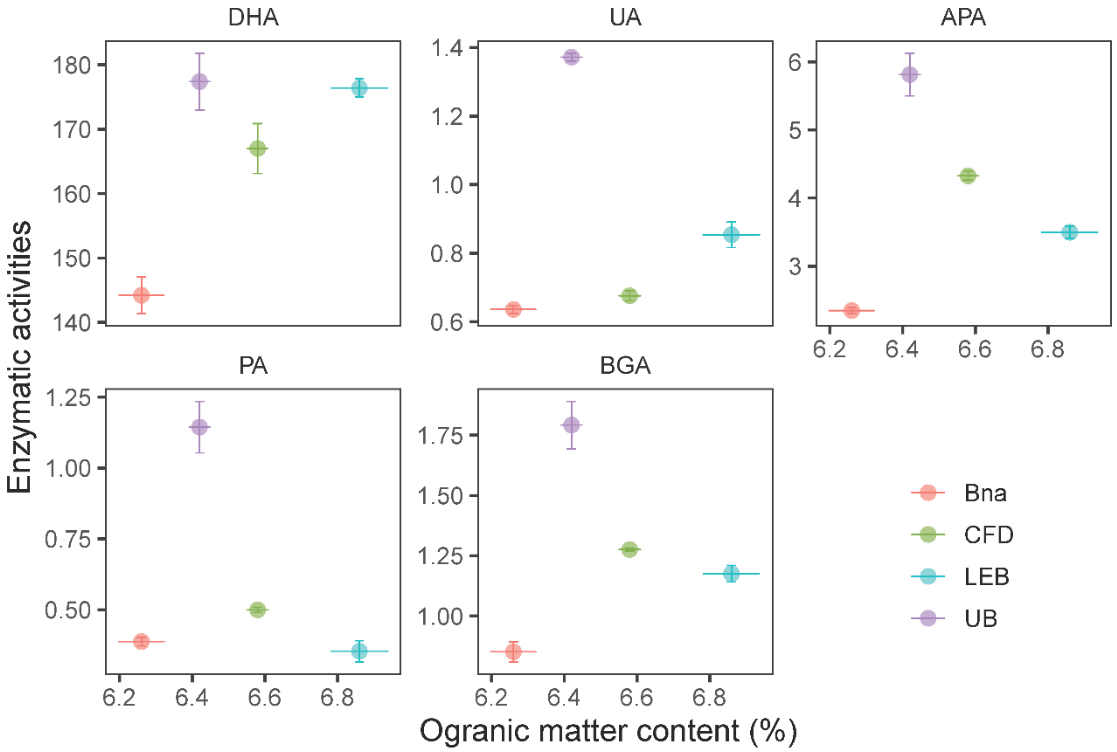

Figure 2. Bivariate associations between organic matter content and enzyme activity of plots in the studied plots affected by the wildfire of 2012 and treated with hillslope stabilization techniques in Sierra de Los Donceles (Castilla La Mancha, Spain). Points indicate the mean values (*n* = 5) of organic matter content and enzyme activity, and errors indicate the standard errors of organic matter content and enzyme activity, respectively. The units of soil enzyme activity are given in Table 3. Notes: UB = unburned; CFD = contour-felled log debris; LEB = log erosion barrier; Bna = burned and no action. DHA = dehydrogenase activity; UA = urease activity; APA = acid phosphatase activity; BGA = β-glucosidase activity; PA = protease activity

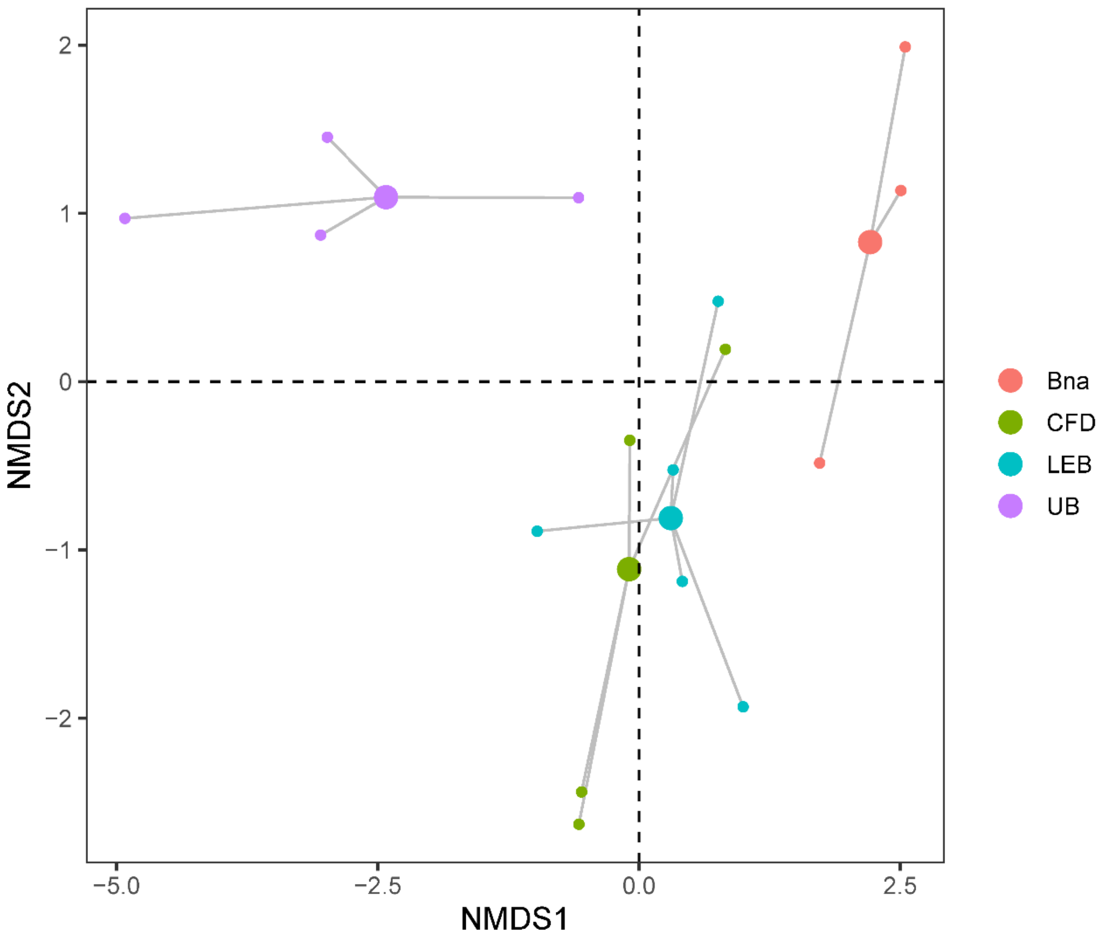

Figure 3. Biplot of physico-chemical properties and enzymatic activities of soil samples collected plots in the studied plots affected by the wildfire of 2012 and treated with hillslope stabilization techniques in Sierra de Los Donceles (Castilla La Mancha, Spain) using nonmetric multidimensional scaling (NMDS) routine. Legend: UB = unburned; CFD = contour-felled log debris; LEB = log erosion barrier; Bna = burned and no action.

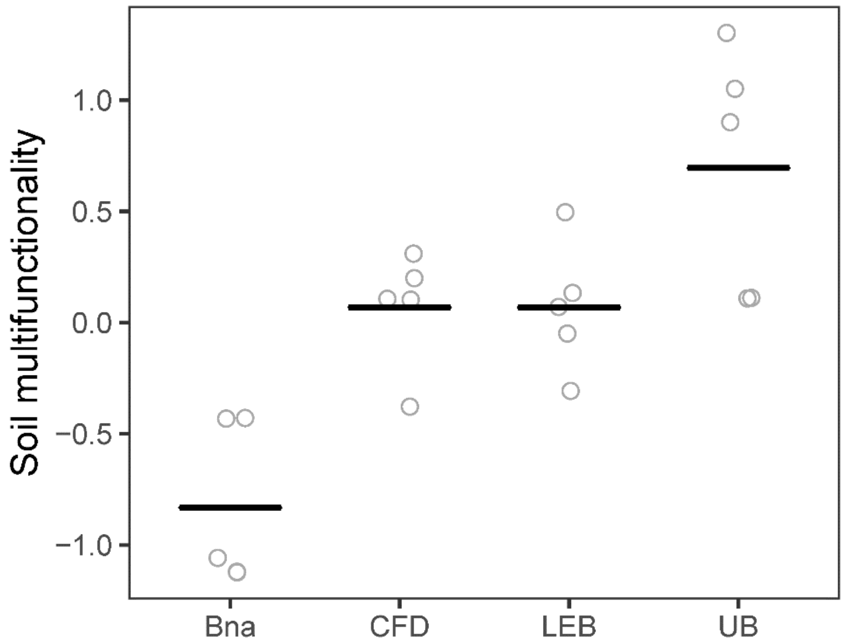

Figure 4. The soil multifunctionality evaluated in soil samples of plots in the studied plots affected by the wildfire of 2012 and treated with hillslope stabilization techniques in Sierra de Los Donceles (Castilla La Mancha, Spain). Crossbars indicate the mean values (n = 5) of soil multifunctionality and jittered points indicate the observed values of soil multifunctionality in the studied plots. Notes: UB = unburned; CFD = contour-felled log debris; LEB = log erosion barrier; Bna = burned and no action. Small hollow and large solid points represent the observed and mean values, respectively.

Tables

Table 1 - Main characteristics of the plots in the studied catchment affected by the wildfire of 2012 and treated with hillslope stabilization techniques in Sierra de Los Donceles (Castilla La Mancha, Spain).

Catchment characteristics	**Experimental condition**			
	Unburned	*Burned*		
		Treatment		
	UB	*Bna*	*LEB*	*CFD*
Area (ha)	2.2	1.1	2.2	2.2
Altitude (m.a.s.l)	450-500	500-550	450-500	500-550
Average slope (%)	32	47	32	44
Aspect	North	North	North	North
Lithology	Dolomites and Lias limestones			
Soil type	Calcic Aridisols			
Vegetation (before wildfire)	Western Mediterranean forest and scrubland. Tree layer: *Pinus halepensis;* Shrub layer: *Pistacia lentiscus, Quercus coccifera, Quercus ilex, Juniperus oxycedrus, Rosmarinus officinalis, Stippa tenaccisima, Thymus vulgaris.*			
Burned area (%)	0	100		
Burn severity (*)	-	Moderately High		

Notes: UB = unburned; CFD = contour-felled log debris; LEB = log erosion barrier; Bna = burned and no action; * fire severity classification according to Gómez-Sanchez et al 2019.

Table 2 – Vegetation cover, stoniness and depth of soils and plant characteristics of each plot in the studied catchment affected by the wildfire of 2012 and treated with hillslope stabilization techniques in Sierra de Los Donceles (Castilla La Mancha, Spain).

Soil condition and treatment	**Plot**	**Cover (%)**	**Stoniness (%)**	**Depth (cm)**	**Shrub and herbal vegetation**
Bna	1	75	70	15	*Cistus clusii, Pistacia lentiscus Anthyllis cytisoides, Rosmarinus officinalis, Stipa tenacissima, Brachypodium retusum*
	2	80	85	15	*Cistus albidus, Stipa tenacissima, Juniperus oxycedrus, Rosmarinus officinalis, Stipa tenacissima, Brachypodium retusum*
	3	85	70	10	*Rhamnus lycioides, Pistacia lentiscus, Pinus halepensis (seedlings), Brachypodium retusum*
	4	80	75	10	*Cistus albidus, Stipa tenacissima, Juniperus oxycedrus, Rosmarinus officinalis, Stipa tenacissima, Brachypodium retusum*
	5	85	70	10	*Rhamnus lycioides, Pistacia lentiscus, Pinus halepensis (seedlings), Brachypodium retusum*
CFD	6	85	75	10	*Cistus clusii, Brachypodium retusum, Pistacia lentiscus, Anthyllis cytisoides, Rosmarinus officinalis*
	7	80	80	15	*Cistus albidus, Juniperus oxycedrus, Rosmarinus officinalis, Pistacia lentiscus, Rhamnus lycioides, Anthyllis cytisoides, Rhamnus lycioides, Pistacia lentiscus*
	8	70	80	20	*Cistus albidus, Juniperus oxycedrus, Rosmarinus officinalis, Pistacia lentiscus, Rhamnus lycioides, Anthyllis cytisoides, Anthyllis cytisoides, Rosmarinus officinalis*
	9	80	80	15	*Cistus albidus, Juniperus oxycedrus, Rosmarinus officinalis, Pistacia lentiscus, Rhamnus lycioides, Anthyllis cytisoides, Rhamnus lycioides, Pistacia lentiscus*
	10	85	75	10	*Cistus clusii, Brachypodium retusum, Pistacia lentiscus, Anthyllis cytisoides, Rosmarinus officinalis*
LEB	11	95	45	15	*Rhamnus lycioides, Anthyllis cytisoides, Brachypodium retusum, Anthyllis cytisoides, Rosmarinus officinalis, Quercus coccifera, Rhamnus lycioides, Anthyllis cytisoides, Brachypodium retusum*
	12	100	50	15	*Anthyllis cytisoides, Brachypodium retusum, Anthyllis cytisoides, Rosmarinus officinalis, Quercus coccifera, Rhamnus lycioides, Anthyllis cytisoides, Brachypodium retusum*

	13	100	30	15	*Quercus coccifera, Rhamnus lycioides, Rosmarinus officinalis, Stipa tenacissima, Brachypodium retusum, Cistus albidus.*
	14	95	45	10	*Rhamnus lycioides, Anthyllis cytisoides, Brachypodium retusum, Anthyllis cytisoides, Rosmarinus officinalis, Quercus coccifera, Rhamnus lycioides, Anthyllis cytisoides, Brachypodium retusum*
	15	100	30	15	*Quercus coccifera, Rhamnus lycioides, Rosmarinus officinalis, Stipa tenacissima, Brachypodium retusum, Cistus albidus.*
UB	16	85	40	15	*Pinus halepensis, Rosmarinus officinalis, Juniperus oxycedrus, Quercus coccifera, Stipa tenacissima*
	17	100	40	20	*Pinus halepensis, Rosmarinus officinalis, Juniperus oxycedrus, Quercus coccifera, Stipa tenacissima*
	18	100	35	15	*Pinus halepensis, Rosmarinus officinalis, Juniperus oxycedrus, Quercus coccifera, Stipa tenacissima*
	19	95	40	15	*Pinus halepensis, Rosmarinus officinalis, Juniperus oxycedrus, Quercus coccifera, Stipa tenacissima*
	20	100	40	20	*Pinus halepensis, Rosmarinus officinalis, Juniperus oxycedrus, Quercus coccifera, Stipa tenacissima*

Notes: UB = unburned; CFD = contour-felled log debris; LEB = log erosion barrier; Bna = burned and no action.

Table 3 - Main physico-chemical and enzymatic activities of soil samples (mean ± standard deviation, n = 5) of plots in the surveyed catchment affected by the wildfire of 2012 and treated with hillslope stabilization techniques in Sierra de Los Donceles (Castilla La Mancha, Spain).

Soil properties	**Soil condition and treatment**			
	Bna	**CFD**	**LEB**	**UB**
pH	8.4 ± 0.01 b	8.3 ± 0.01 a	8.3 ± 0.02 ab	8.6 ± 0.01 c
EC (µS/cm)	146.4 ± 0.11 b	147.6 ± 0.3 b	207.4 ± 0.97 c	98.6 ± 0.11 a
OM (%)	6.3 ± 0.06 a	6.6 ± 0.03 ab	6.9 ± 0.08 b	6.4 ± 0.03 ab
MBC (mg C kg^{-1})	2262.4 ± 62.7 a	2402.4 ± 40.1a	2502.8 ± 14.2 a	2502.6 ± 20.1 a
BSR (μg_{CO2} $hour^{-1}$ g^{-1} soil)	14.5 ± 0.21a	17.3 ± 0.41b	15.4 ± 0.16 ab	15 ± 0.11 a
DHA (μg_{INTF} g^{-1} $hour^{-1}$ g^{-1} soil)	144.2 ± 2.82 a	167 ± 3.87 ab	176.4 ± 1.43 b	177.4 ± 4.41 b
UA ($\mu mol_{N\text{-}NH4+}$ $hour^{-1}$ g^{-1} soil)	0.6 ± 0.01 a	0.7 ± 0.01 ab	0.9 ± 0.04 b	1.4 ± 0.01 c
APA ($\mu mol_{p\text{-}NP}$ $hour^{-1}$ g^{-1} soil)	2.3 ± 0.04 a	4.3 ± 0.07 bc	3.5 ± 0.09 ab	5.8 ± 0.31 c
PA ($\mu mol_{p\text{-}NP}$ $hour^{-1}$ g^{-1} soil)	0.4 ± 0.02 a	0.5 ± 0.01 a	0.4 ± 0.04 a	1.1 ± 0.09 b
BGA ($\mu mol_{p\text{-}NP}$ $hour^{-1}$ g^{-1} soil)	0.9 ± 0.04 a	1.3 ± 0.01 a	1.2 ± 0.03 a	1.8 ± 0.1 b

Notes: UB = unburned; CFD = contour-felled log debris; LEB = log erosion barrier; Bna = burned and no action; EC = electrical conductivity; OM = organic matter; MBC = microbial biomass carbon; BSR = basal soil respiration; DHA = dehydrogenase activity; UA = urease activity; APA = acid phosphatase activity; PA = protease activity; BGA = β-glucosidase activity. Different letters indicate significant differences at $p < 0.05$ of the Tukey's HSD test.

Table 4 - Correlation matrix chart among the physico-chemical properties and enzymatic activities of soil samples collected plots in the studied plots affected by the wildfire of 2012 and treated with hillslope stabilization techniques in Sierra de Los Donceles (Castilla La Mancha, Spain).

	EC	**pH**	**OM**	**MBC**	**BSR**	**DHA**	**UA**	**APA**	**PA**	**BGA**
EC		**-0.75**	**0.50**	0.03	0.11	0.03	**-0.53**	**-0.51**	**-0.68**	**-0.47**
pH			-0.19	0.23	-0.37	0.02	**0.72**	**0.46**	**0.69**	**-0.47**
OM				**0.55**	**0.36**	0.29	0.01	0.05	-0.09	0.16
MBC					0.14	0.02	**0.40**	**0.43**	0.22	**0.56**
BSR						0.24	-0.19	0.24	-0.17	0.24
DHA							**0.39**	**0.63**	**0.55**	**0.51**
UA								0.67	**0.74**	**0.67**
APA									**0.79**	**0.93**
PA										**0.69**

Number in bold denotes the correlation coefficients with the significance level (* $p < 0.05$). EC = electrical conductivity; OM = organic matter; EC = electrical conductivity; MBC = microbial biomass carbon; BSR = basal soil respiration; DHA = dehydrogenase activity; UA = urease activity; APA = acid phosphatase activity; PA = protease activity; BGA = β-glucosidase activity.

DO

Changes in soil functionality eight years after fire and post-fire hillslope stabilisation in Mediterranean forest ecosystems

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