CSIRO PUBLISHING

SPECIAL ISSUE | RESEARCH PAPER
https://doi.org/10.1071/WF22091

International Journal of WILDLAND FIRE
International Association of Wildland Fire

# Burnt wood management enhances soil multifunctionality at the medium term after a large wildfire in north-west Spain

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**Received:** 8 June 2022
**Accepted:** 22 October 2022
**Published:** 11 November 2022

**Cite this:**
Fernández-Guisuraga JM *et al.* (2023)
*International Journal of Wildland Fire*
**32**(1), 99–110. doi:10.1071/WF22091



## ABSTRACT

**Background.** Mulching and burnt wood treatments are commonly applied to prevent the loss of soil quality and erosion, but their effect on soil multifunctionality remains unexplored. **Aims.** We filled this gap by assessing the medium-term (4 years) effects of these treatments on soil multifunctionality after a large wildfire in NW Spain. **Methods.** Straw mulching (SM) and cut plus lopping (CpL) treatments were applied in high-severity affected areas of heathland plant communities. CpL areas had been afforested with Scots pine 15 years before the fire. We considered four soil functions estimated in treated and burned control plots 4 years after fire: (1) carbon regulation; (2) water regulation; (3) soil fertility; and (4) nutrient cycling. The functions were integrated into a multifunctionality index and linear models were used to evaluate treatments effect. **Key results.** SM had no impact on individual functions and multifunctionality. Conversely, CpL with burnt Scots pine wood was able to sustain higher levels of multiple functions simultaneously than control areas. Consistent trade-offs between soil functions emerged in control areas for both treatments. **Conclusions.** Burnt wood could ensure long-lasting effects to promote soil multifunctionality in Mediterranean ecosystems. **Implications.** We recommend using a multifunctionality approach to avoid biases in treatment success.

**Keywords:** cut plus lopping, heathlands, high-severity, Mediterranean ecosystems, *Pinus sylvestris*, post-fire treatments, soil functions, straw mulching, woody debris.

## Introduction

Wildfires are a natural process in Mediterranean Basin terrestrial ecosystems (Pausas *et al.* 2008), but the frequency of extreme fire events of large extent and high severity is expected to increase (Fernández-Guisuraga *et al.* 2021*a*; Wagenbrenner *et al.* 2021). Fire regime shifts evidenced in forest ecosystems of this region have been attributed to anthropogenic climate warming (González-De Vega *et al.* 2016), which is exacerbating wildfire weather conditions (Vilà-Cabrera *et al.* 2018), but also to socio-economic factors such as land-use changes connected with rural abandonment (Moreira *et al.* 2020). These changes jointly promote the development of landscapes with high fuel continuity, which are prone to high-severity wildfires (Fernández-Guisuraga *et al.* 2021*b*).

In this context, the increase in fire severity affects not only the composition, structure and dynamics of vegetation communities (Fernández-Guisuraga *et al.* 2019), but also leads to major impacts on organic and mineral forest soils, including loss of soil quality, increased runoff or erosion (Vega *et al.* 2013; Moya *et al.* 2018; Fernández-García *et al.* 2021). These processes could be associated with the loss of important functions and services provided by forest ecosystems worldwide, including regulating services such as climate warming mitigation (Lasslop *et al.* 2019) or water regulation (Le Maitre *et al.* 2014), and supporting services like soil fertility (Duguy *et al.* 2007) or nutrient cycling (Thoresen *et al.* 2021). Remarkably, the loss of provision of these services may involve major negative impacts both for rural populations and for society as a whole (Pereira *et al.* 2021). In this sense, the scientific community and government administrations are increasingly concerned about evaluating and implementing measures that help mitigate the most adverse ecological effects of severe wildfires (Lucas-Borja *et al.* 2019).

Post-fire treatments for this purpose can fall into three categories: (1) long-term restoration; (2) burnt wood management strategies; and (3) emergency stabilisation measures (Robichaud *et al.* 2010). Long-term restoration treatments (e.g. vegetation afforestation) are implemented to assist and facilitate the recovery of native plant communities and habitats after a wildfire. These types of treatments are usually applied in areas degraded by recurrent wildfires that prevent the natural regeneration of vegetation (García Matallana *et al.* 2022). Among burnt wood management strategies, cut plus lopping treatment, where burnt trees are cut and felled, main branches being lopped off and cut wood left on the forest floor (Marañón-Jiménez *et al.* 2011), are usually applied to promote the natural recovery of the vegetation by climate amelioration (Taboada *et al.* 2018) and increase post-fire wildlife diversity (Lindenmayer and Noss 2006). In addition, coarse woody debris left on-site creating a dense mesh, assists in the protection of soil from runoff erosion in severely burned areas (Brown *et al.* 2003; Marañón-Jiménez and Castro 2013), and favours the long-term release of nutrients into the soil (Palviainen *et al.* 2010). Finally, emergency post-fire treatments (e.g. log or erosion barriers, straw mulching and woody shred mulching) have been developed focusing on stabilising the burnt area to prevent further additional damage to essential resources such as water supply systems or human infrastructures, or to critical habitats for protected species (Robichaud *et al.* 2010; Lucas-Borja *et al.* 2019). These measures need to be implemented as soon as possible after the fire (Vo and Kinoshita 2020), as they are usually highly effective in preventing soil erosion and loss of soil productivity by reducing raindrop impact and slowing down runoff (Prats *et al.* 2012; Fernández and Vega 2016). For these reasons, emergency stabilisation measures, and in particular the mulching treatment, are increasingly used by land managers (Robichaud *et al.* 2013*a*). However, due to its high cost, mulching is considered as a strategic treatment for priority areas burned at high severity (Bontrager *et al.* 2019).

Many studies have recently evaluated the effect of mulching and burnt wood treatments on post-fire soil chemical properties and carbon content (Gómez-Rey *et al.* 2013; Pierson *et al.* 2019), microbiological communities (Fontúrbel *et al.* 2012; Marañón-Jiménez and Castro 2013) and hydrological features (Prats *et al.* 2021), as well as on the composition and structural properties of plant communities (Duniway *et al.* 2015; Taboada *et al.* 2018; Jonas *et al.* 2019; García Matallana *et al.* 2022). Nevertheless, forest ecosystems provide a wide variety of functions and services (ecosystem multifunctionality *sensu* Garland *et al.* 2021). In this sense, ecosystem multifunctionality (EMF) could be considered as the ability of an ecosystem to supply multiple functions simultaneously, thus increasing the benefits that societies can obtain from ecosystems (Hölting *et al.* 2019; Liu *et al.* 2021). Complex trade-offs can emerge between ecosystem functions as a result of management practices (Bengtsson *et al.* 2019; Lucas-Borja *et al.* 2021). Therefore, the assessment of the effects of post-fire treatments on forest ecosystems should be conducted using an integrative approach (i.e. EMF or soil multifunctionality evaluation instead of single functions) so as not to obtain a biased perspective of the ecosystem response to treatment or restoration success (Lucas-Borja *et al.* 2021). Also, both the positive and negative effects of post-fire treatments may be of even greater magnitude when considering the overall ecosystem function (Maestre *et al.* 2012*a*; Byrnes *et al.* 2014; Fernández-Guisuraga *et al.* 2022). Nevertheless, to date, the influence of post-fire mulching and burnt wood treatments on EMF, and particularly on soil multifunctionality, remains little examined in fire-prone ecosystems in the medium term after fire. In this sense, Lucas-Borja *et al.* (2021) and Moghli *et al.* (2022*b*) demonstrated the effectiveness of erosion barriers and thinning/plantation actions for supporting multiple ecosystems functioning attributes on *Pinus halepensis* Mill. forests. However, only Lucas-Borja *et al.* (2020) assessed changes in multifunctionality in the short term after straw mulching application in the same ecosystems, demonstrating a positive outcome for soil functioning. Changes that mulching and coarse woody debris may trigger in the soil environment, including temperature and moisture (Devine and Harrington 2007; Mulumba and Lal 2008; Bontrager *et al.* 2019), decomposition rates (Palviainen *et al.* 2010) and microbial activity (Berryman *et al.* 2014), among others, support the use of an EMF approach for providing more integrated insights into the effectiveness and sustainability of such post-fire treatments.

We aimed to bridge these gaps by evaluating the medium-term (4 years) effects of two common soil stabilisation and burnt wood management strategies (straw mulching and cut plus lopping) on soil multifunctionality after a large wildfire in north-west Spain. We considered four key soil functions and their indicators: (1) carbon regulation; (2) water regulation; (3) soil fertility; and (4) nutrient cycling. Changes induced by post-fire treatments were compared with soil multifunctionality in adjacent burned control areas. We also analysed the effect of the treatments on the synergies and trade-offs between the considered soil functions. Specifically, we sought to answer the following questions: (1) Do post-fire treatments improve soil multifunctionality compared to untreated areas? and (2) Are there different synergies and trade-offs between functions for each treatment? We hypothesised that post-fire treatments would enhance soil multifunctionality as compared to untreated areas given the benefits of straw mulching and cut plus lopping measures for the soil environment immediately after fire (Robichaud *et al.* 2010; Marañón-Jiménez *et al.* 2013). We also hypothesised that different soil microclimatic conditions between treated and control areas (Robichaud *et al.* 2013*b*; Castro 2021) would trigger differential synergies and trade-offs between soil functions.

## Methods

### Study site and post-fire treatments

The study site is located in Cabrera mountain range (NW Spain), where a large mixed-severity wildfire burned 9940 ha of forests and shrub formations in August 2017 (Fig. 1). The burnt area was dominated by *Quercus pyrenaica* Willd. (Pyrenean oak) forests and *Pinus sylvestris* L. (Scots pine) afforestations (~3480 ha), different shrub formations dominated by *Genista hystrix* Lange (gorse), *Erica australis* L. (Spanish heath) and *Genista florida* L. (broom) (~5440 ha), and Mediterranean grasslands (~580 ha). The relatively extreme weather conditions on the fire alarm date (21 August 2017), with maximum temperatures of 35°C and 35% relative humidity, together with low precipitation during the seasons preceding the wildfire event (García-Llamas *et al.* 2020), facilitated fire spread and extreme burning conditions (37% of the surface burned at high severity; Fernández-Guisuraga *et al.* 2021*a*). Fire severity categories

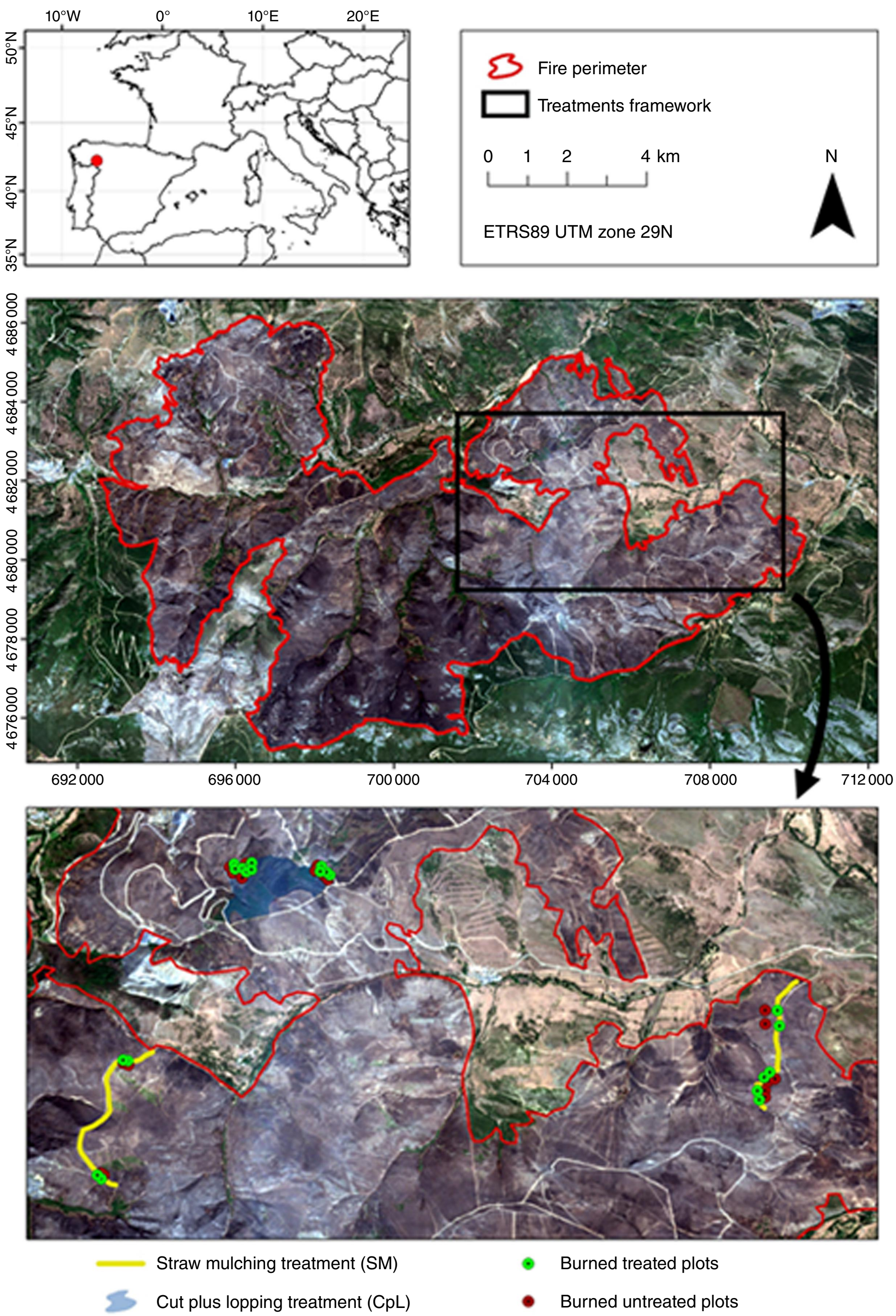


**Fig. 1.** Wildfire location within the Cabrera mountain range (NW Spain) and detailed view of the areas where post-fire treatments (straw mulching and cut plus lopping) were applied, as well as the location of treated and control burned field plots within those areas.

for the study site were defined using a dNBR (differenced Normalised Burn Ratio) and CBI (Composite Burn Index) thresholding approach from remote sensing and field data (Fernández-Guisuraga *et al.* 2021*a*). The climate in the region is Mediterranean with dry temperate summers, featuring 2 months of summer drought (Fernández-García *et al.* 2021). The site is characterised by an abrupt and rugged topography, with altitudes ranging between 836 and 1938 m above sea level. Soils are acidic (pH ≈ 5), originated over siliceous lithologies (slates, sandstones and quartzites), and classified as Lithic (LPq) and Distric (LPd) Leptosols, as well as Distric (CMd) and Humic (CMu) Cambisols (GEODE 2022; ITACyL 2022).

Two months after wildfire, the regional government began to implement two post-fire treatments aimed at protecting the soil and facilitating vegetation recovery in high-severity affected areas with medium-steep hill slopes (mean slope of 33.5%): (1) straw mulching (SM); and (2) cut plus lopping (CpL) (Fig. 1). SM was applied in strips from a helicopter in heathland plant communities. The mulch cover and depth reached in the strips was 90% and 5 cm, respectively. CpL was also applied in heathland plant communities, but in this case, the area had been afforested with Scots pine 15 years before the fire, reaching a density of 1000–1200 individuals/ha. All the burnt trees were cut by sawyers with chainsaws, the main branches being lopped off and all the wood left on the forest floor. The mesh of fine and coarse woody debris consisted exclusively of Scots pine logs and branches, with a mean cover of approximately 70%.

The vegetation species composition and structure in terms of vegetation mean height, cover and species richness of the post-fire heathland communities were analogous in SM and CpL treatment areas (field observation).

## Soil sampling and analyses

In summer 2018 (1 year after the fire), we randomly established a total of 40 plots (2 m × 2 m) in burned, treated areas: 10 plots in SM areas (heathland), 10 plots in CpL areas (heathland with pine afforestation), and 20 burned control plots in adjacent untreated areas (10 per treatment). All treated and untreated plots were located in high-severity affected areas. Plot locations had a north-northwest slope aspect and a slope of 20–30%.

At the medium term after fire (4 years; summer 2021), we measured several soil variables in the field plots as indicators closely associated with soil functions (Table 1). For this purpose, we collected four randomly selected soil samples within the 2 m × 2 m plots using an auger (7 cm diameter × 3 cm depth) and pooled them in a composite sample for each plot. Litter and woody debris were removed prior to sample collection. Soil samples were homogenised and sieved (< 2 mm), and divided into two fractions. One fraction was air-dried to analyse physical and chemical properties except ammonium (N–$NH_4^+$) and nitrate (N–$NO_3^-$). The other fraction was frozen at −18°C to determine N–$NH_4^+$ and N–$NO_3^-$, as well as microbial biomass and enzymatic activities. We measured mean weight diameter (MWD) to determine the average size of stable aggregates (Kemper and Rosenau 1986) and water drop penetration time (WDPT) was used to determine soil water repellency (WR) (Doerr 1998). Total organic carbon (TOC) was determined using a EuroVector EA3000 elemental analyser following the combustion method (Dumas 1831). Available phosphorous (P) was measured at a wavelength of 882 nm after digestion with $HClO_4$ (Olsen *et al.* 1954). N–$NH_4^+$ and N–$NO_3^-$ were extracted with 2M KCl at a 1:10 soil–extractant ratio (Keeney and Nelson 1982) and measured by distillation with an automatic micro-Kjeldahl analyser (Bremner and Mulvaney 1982). β-glucosidase (β-D-glucoside glucohydrolase) and acid phosphatase (phosphate-monoester phosphohydrolase) activities were analysed following the method of Tabatabai (1994), and urease (urea amidohydrolase) activity following Kandeler and Gerber (1988). Microbial biomass carbon (MBC) was determined by the fumigation-extraction method (Vance *et al.* 1987).

## Soil multifunctionality quantification

Each of the 10 soil indicators measured was assigned to one of the four considered soil functions (Table 1). Soil TOC, which corresponds to the main carbon pool in terrestrial ecosystems, and particularly in post-fire landscapes burned at high severity (Litton *et al.* 2003; Quintero-Gradilla *et al.* 2020), was measured as a proxy of carbon regulation function because of its implications on the global C balance and thus climate change (González-Pérez *et al.* 2004). Water regulation function was assessed using WR and MWD, these indicators being closely related to several processes

**Table 1.** Indicators of soil functions considered in this study.

| Soil function | Indicator | Unit |
|---|---|---|
| Carbon regulation | Total organic carbon (TOC) | % |
| Water regulation | Soil water repellency (WR) | s |
| | Soil mean weight diameter (MWD) | mm |
| Soil fertility | Ammonium ($NH_4^+$–N) | mg $kg^{-1}$ |
| | Nitrate ($NO_3^-$–N) | mg $kg^{-1}$ |
| | Available phosphorous (P) | mg $kg^{-1}$ |
| Nutrient cycling | β-glucosidase activity | $\mu mol_{p\text{-}NP}\, h^{-1}\, g^{-1}$ soil |
| | Urease activity | $\mu mol_{N\text{–}NH4+}\, h^{-1}\, g^{-1}$ soil |
| | Acid phosphatase activity | $\mu mol_{p\text{-}NP}\, h^{-1}\, g^{-1}$ soil |
| | Microbial biomass carbon (MBC) | mg C $kg^{-1}$ |

in fire-prone ecosystems, including surface runoff and soil erodibility (Goebel *et al.* 2011), primary production (Madsen *et al.* 2012), biogeochemical cycling and soil organic carbon recovery (Seaton *et al.* 2019; Rodriguez *et al.* 2021). The nutrient content in the soil ($N–NH_4^+$, $N–NO_3^-$ and available P) was used to estimate soil fertility function. Besides controlling numerous biogeochemical processes in forest ecosystems, $N–NH_4^+$ and $N–NO_3^-$ are the preferred nitrogen source for plants (Maestre *et al.* 2012*a*), and specifically, $N–NH_4^+$, together with glutamate and glutamine, for soil bacteria and fungi (Geisseler *et al.* 2010). Soil available P, along with nitrogen, commonly limits net primary production worldwide (Hou *et al.* 2020). Soil enzyme activities (i.e. β-glucosidase, acid phosphatase and urease) and MBC play an essential role in soil organic matter decomposition and carbon transfer between fast and slow soil pools (Sinsabaugh *et al.* 2008; Lange *et al.* 2015), and were therefore considered as a proxy of nutrient cycling function.

We considered that the higher the value of each raw soil functional indicator, the higher the level of the associated function (Maestre *et al.* 2012*a*; Fernández-Guisuraga *et al.* 2022), except for the WR variable, where large WDPT values are linked to hydrophobic soils and loss of soil quality and functionality worldwide (Seaton *et al.* 2019). Therefore, raw values of the WR indicator were reflected using the function $-f_i + \max(f_i)$, $f_i$ being the measures of indicator i, in this case, WR. Next, the maximum value for each indicator was defined as the average of the top-functioning 5% plots for each indicator (Delgado-Baquerizo *et al.* 2016) in order to reduce the chance of using an outlier value resulting from an analytical error or noise (Byrnes *et al.* 2014). With this in mind, each raw soil function indicator was standardised into a percentage of maximum performance for each plot (Delgado-Baquerizo *et al.* 2016). We then pooled the standardised indicators into the four considered soil functions (i.e. carbon regulation, water regulation, soil fertility and nutrient cycling), and soil multifunctionality was computed through an averaging approach of the individual functions (Maestre *et al.* 2012*a*). The standardisation by the highest observed function values and the averaging approach are among the most widely used methods in the literature because of their intuitive interpretation and straightforward applicability for estimating the capacity of an ecosystem to support several functions simultaneously (Maestre *et al.* 2012*b*; Byrnes *et al.* 2014; Fernández-Guisuraga *et al.* 2022).

### Statistical analyses

We explored the effect of each post-fire treatment (i.e. SM and CpL) on the set of soil functional indicators through a permutational multivariate analysis of variance (PERMANOVA) implemented with 1000 random permutations, and a principal component analysis (PCA). These analyses were conducted using the 'vegan' package (Oksanen *et al.* 2020) in R (R Core Team 2021).

Linear models were calibrated to evaluate whether there were statistically significant differences in the four soil functions and soil multifunctionality, between SM-CpL treated areas and burned control areas. Therefore, the dependent variables in the models were: (1) carbon regulation; (2) water regulation; (3) soil fertility; (4) nutrient cycling functions; and (5) soil multifunctionality. The predictor in the models was the treatment level (treated and control). Statistical significance was considered when *P*-values were lower than 0.05.

Finally, we disentangled the effect of SM and CpL post-fire treatments on the synergies and trade-offs between soil functions following the approach of Felipe-Lucia *et al.* (2018) and Moghli *et al.* (2022*a*). For this purpose, bivariate Pearson correlations between the soil functions, as well as soil multifunctionality, were evaluated in treated and control areas for each treatment, synergies and trade-offs being characterised by positive and negative correlations, respectively (Moghli *et al.* 2022*a*).

The analyses of post-fire treatment effects on soil multifunctionality (linear models) and function synergies/trade-offs (correlation analysis) were implemented in R.

## Results

Post-fire SM and CpL treatments showed contrasting effects on the pool of individual soil functional indicators at the medium term after fire. SM treatment in heathlands did not trigger significant effects on the functional indicators (PERMANOVA $F = 0.47$; $P = 0.51$). Indeed, soil samples from treated and control sites were clustered together in the PCA (cumulative explained variance by the first and second axes of 46.2%; Fig. 2*a*), with no treatment effect found in any of the PCA axes as supported by the lack of significance of the linear models calibrated from the projection of the samples on the axes ($P < 0.05$). Conversely, CpL treatment featured a significant association with the pool of soil functional indicators ($F = 6.46$; $P = 0.01$). Soil samples from treated and control areas were clearly segregated in the PCA (cumulative explained variance by the first and second axes of 55.3%; Fig. 2*b*). The treatment effect was found in the second PCA axis ($P < 0.01$). Soils from CpL areas were characterised by higher contents of TOC, P and urease enzyme activity, as well as by larger average size of stable aggregates than soils from untreated areas.

When analysing the behaviour of individual soil functions and soil multifunctionality within treatments (Fig. 3), an absence of a clear response mediated by SM was evidenced, in line with the pool of soil functional indicators. Although the values for most of the soil functions and soil multifunctionality tended to increase in SM areas with respect to control areas, the treatment effect was not significant in any of the cases (Fig. 3). Regarding CpL treatment, we detected only marginally significant differences ($P = 0.06$) for the carbon

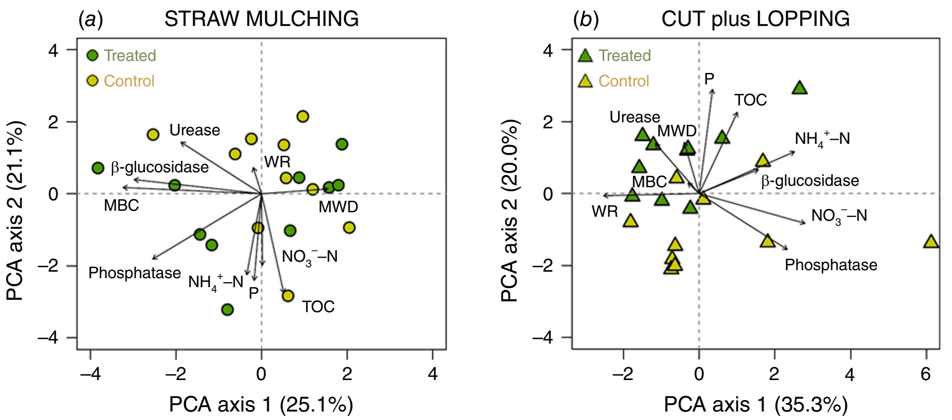


**Fig. 2.** Principal component analysis (PCA) biplot of the considered soil functional indicators for straw mulching (*a*) and cut plus lopping (*b*) treatments. Green and yellow symbols correspond to soil samples in treated and control areas, respectively. Variable codes correspond to those in Table 1.

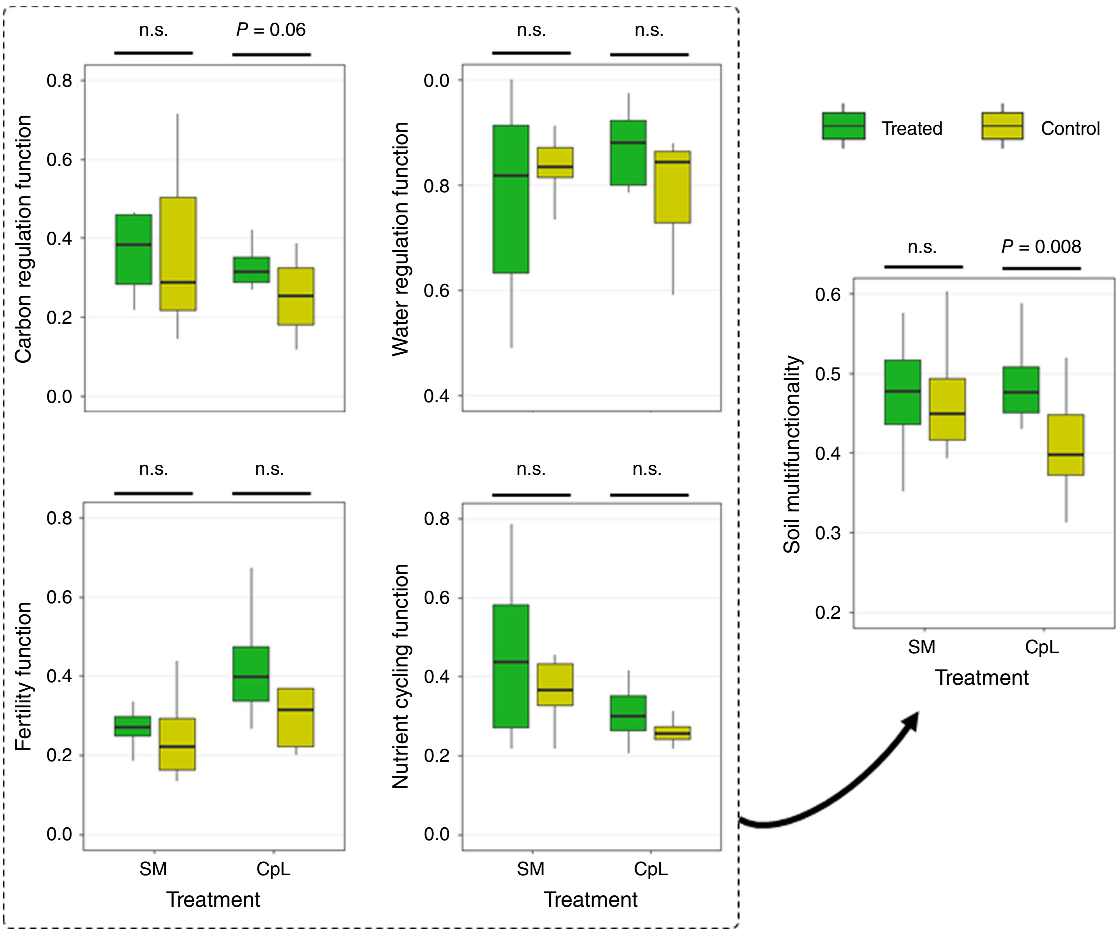


**Fig. 3.** Boxplots showing the relationship between soil functions/multifunctionality and straw mulching (SM) and cut plus lopping (CpL) treatments. We included the significance of treatment effect (n.s., not significantly different ($P$ > 0.05).

regulation function, even though several indicators linked to other soil functions had shown a clear increasing trend in CpL treated areas (Fig. 2). Notwithstanding, soil multifunctionality was significantly higher ($P = 0.008$) with CpL implementation (Fig. 3), and thus the ability of the soil to sustain higher levels of multiple functions simultaneously than untreated areas. We did not find individual soil functions performing differentially at excessive low or high values between CpL treated and control areas.

The patterns in synergies (positive correlations) and trade-offs (negative correlations) were consistent for SM and CpL treatments when comparing treated and control

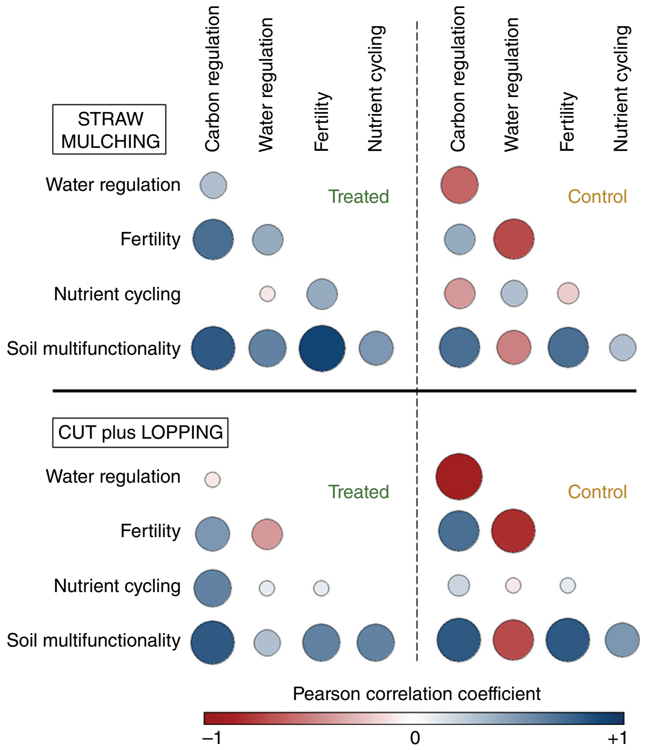


**Fig. 4.** Bivariate Pearson correlation coefficients denoting synergies and trade-offs between individual soil functions and multifunctionality for straw mulching and cut plus lopping treatments in treated and control areas.

areas (Fig. 4). The correlations between pairs of soil functions/multifunctionality varied from −0.92 to 0.84. Treated areas were characterised by strong synergies and the absence of substantial trade-offs between functions. In control areas we observed a decline in most of the synergies and several remarkable trade-offs emerged (between water regulation and both carbon regulation and soil fertility functions).

## Discussion

Severe stand-replacing wildfires in Mediterranean fire-prone landscapes might involve substantial impacts on individual soil functions (e.g. Borgogni *et al.* 2019; Fernández-García *et al.* 2020; Huerta *et al.* 2020) and plant community-level properties (e.g. Fernández-Guisuraga *et al.* 2019; Etchells *et al.* 2020), but also on ecosystem multifunctionality (Lucas-Borja *et al.* 2021). Therefore, improving knowledge of post-fire management effects on the ability of the soil to sustain multiple functions is essential for determining the overall effectiveness of these measures and preventing the most harmful ecological impacts of severe wildfires (Castro 2021). However, few insights into this topic are currently provided to guide adaptive management strategies in the context of changing fire regimes (Vilà-Cabrera *et al.* 2018; Lucas-Borja *et al.* 2020). This study represents a first attempt to assess whether straw mulching and cut plus lopping treatments could improve soil multifunctionality in the medium term after fire. Our results support the use of a soil multifunctionality approach instead of individual soil functions or soil functional indicators for several reasons: (1) to avoid biased assumptions on management success (Lucas-Borja *et al.* 2021); (2) to prevent the occurrence of changes in the magnitude of the overall post-fire treatment effect when considering multiple functions pooled together (Fernández-Guisuraga *et al.* 2022); and (3) to disentangle the synergies and trade-offs between soil functions evidenced in treated and untreated areas.

Contrary to our expectations, the application of straw mulch did not mediate a significant response in either individual soil functions (carbon regulation, water regulation, soil fertility and nutrient cycling) and soil multifunctionality at the medium term after fire, although their values tended to increase in heathland treated areas. The only study in the literature using a multifunctionality approach, and specifically in Mediterranean ecosystems (Lucas-Borja *et al.* 2020), found that straw mulching application significantly improved ecosystem functioning of *P. halepensis* forests in the short-term (1 year) after a stand-replacing wildfire. Their findings contrasted with previous research focusing on individual soil physicochemical and biological indicators under temperate climate conditions. These studies evidenced a limited effect of straw mulching on soil quality both in the short (Fontúrbel *et al.* 2012; Gómez-Rey *et al.* 2013; Fernández-Fernández *et al.* 2016; Pereira *et al.* 2018) and medium term (Gómez-Rey and González-Prieto 2014; Díaz-Raviña *et al.* 2018) after fire, probably attributed to the rapid recovery of the herb and shrub strata in the first post-fire periods above critical thresholds due to higher site productivity and plant species fitness (Fontúrbel *et al.* 2012; Díaz-Raviña *et al.* 2018).

The well-known effects of straw mulch post-fire treatments on: (1) prevention of soil erosion (e.g. Robichaud *et al.* 2013*a*, 2013*b*; Lombao *et al.* 2015) and thus losses of soil organic matter quality/quantity (Prats *et al.* 2016; De la Rosa *et al.* 2019); (2) soil respiration and microbial activity due to changes in soil microclimatic conditions (Barreiro *et al.* 2016); and (3) functional composition of the microbial communities (Berryman *et al.* 2014) could be responsible for the increase (although not significant) in most soil functions and soil multifunctionality evidenced here in heathland treated areas. The absence of a strong and significant effect on soil multifunctionality at the medium term after fire in this study might be associated with (1) the short-term decay and easy mobilisation of straw mulch by wind and overland flow remaining in place usually for less than 2 years (Robichaud *et al.* 2013*a*; Díaz-Raviña *et al.* 2018) together with (2) the sparse vegetation cover in the first post-fire years of heathlands burned at high severity in the site (Fernández-Guisuraga *et al.* 2021*b*).

The intricate mesh of fine and coarse pine woody debris in contact with the forest floor, resulting from the cut plus lopping treatment in burned heathlands with pre-fire Scots pine afforestation, significantly improved the ability of the soil to sustain higher levels of multiple functions simultaneously than adjacent burned and untreated areas, as we initially hypothesised. This behaviour resulted from the significant increase in soil carbon regulation function, together with the cumulative increments (although not significant) in the other individual functions in treated areas. These results confirmed that soil response to post-fire treatments is stronger when considering the overall soil function (Byrnes *et al.* 2014). Some criticism in the multifunctionality literature argued that overall ecosystem functioning cannot be expressed as the average of the constituent functions; i.e. increases or declines in some functions cannot be compensated by the opposite behaviour in other functions (Gamfeldt *et al.* 2008). However, we did not find individual soil functions performing differentially at excessive low or high values between treated and control areas, as supported by Maestre *et al.* (2012*a*) for using an averaging approach.

We are not aware of research evaluating the impact of post-fire burnt wood management strategies, and specifically cut plus lopping treatment, on overall soil multifunctionality, neither in the short nor in the medium term after the fire. Nevertheless, Marañón-Jiménez and Castro (2013) evidenced that Scots pine burnt wood constituted a large pool of nutrients that were strongly released through decomposition in the first 4 years after fire; and in the case of organic carbon, in the first 2 years. Enhanced nutrient release by decaying burnt wood, together with microclimate amelioration (Taboada *et al.* 2017, 2018), promote soil respiration and microbial activity (Marañón-Jiménez *et al.* 2011), which support an increase in soil multifunctionality in burnt wood treated areas. Moreover, the physical protection of the soil by the burnt wood mesh prevents erosion processes and the loss of soil carbon stocks with sediments (Prats *et al.* 2019), at a much lower cost and environmental impact than log or branch erosion barriers (Castro 2021). In addition, the much lower decay rate of burnt wood compared to straw or woody shred mulching may prompt long-term benefits on ecosystem functioning (Marañón-Jiménez *et al.* 2011; Robichaud *et al.* 2013*b*; Ferreira *et al.* 2015).

In spite of the contrasting effectiveness of straw mulching and cut plus lopping treatments on promoting soil multifunctionality, we identified the emergence of consistent trade-offs for both treatments between water regulation and both carbon regulation and soil fertility functions in treated areas with respect to control areas. Enhanced vegetation recovery in straw mulch treated areas (R. Tárrega pers. comm.) and the dense burnt wood mesh might prevent the impact of kinetic energy of raindrops on soil aggregate stability (Mataix-Solera *et al.* 2011; Thomaz 2017; Bai *et al.* 2020). The lack of soil physical protection in untreated areas may trigger aggregate breakdown and mobilisation in the finer fractions (Fox *et al.* 2007), decreasing aggregate-associated organic carbon pools and nutrients (Zhang *et al.* 2018), whereas total organic carbon and nutrient pools continue to increase as a consequence of litter and root inputs to the soil from recovering vegetation (Mataix-Solera *et al.* 2011; Alexis *et al.* 2012). Also, the absence of soil climate amelioration in untreated areas may turn the hydrophilic nature of certain organic compounds released by plant and microorganisms into hydrophobic, favouring soil water repellency conditions (Doerr and Thomas 2000; Stoof *et al.* 2011). According to Doerr *et al.* (2000), the small fraction of hydrophobic organic compounds responsible for soil water repellency is usually not proportional to the total organic matter inputs to the soil. However, the interpretation of the results concerning synergies and trade-offs of soil functions should be considered with caution, as they may be influenced by the relatively small sample size of the present study (Moghli *et al.* 2022*a*).

All together, the results of this study evidenced that burnt wood management strategies are a reliable approach in fire-prone Mediterranean heathlands for promoting high levels of multiple soil functions in the medium term after fire. In this study, the mesh of log and branches in the cut plus lopping measure proceeded from available young afforested Scots pine individuals in the heathland community before the fire, but this approach is also applied to mature forest communities (e.g. Marañón-Jiménez *et al.* 2011; Marañón-Jiménez and Castro 2013). Ultimately, burnt Scots pine wood could be delivered to open shrubland areas prone to high erosion from adjacent burned tree stands to establish a continuous or striped mesh of fine and coarse woody debris, ensuring a long-lasting treatment effect (Marañón-Jiménez *et al.* 2011) as evidenced in this study, at a much lower cost than straw helimulch application and with a lower environmental impact compared to other stabilisation treatments (Castro 2021). Burnt wood management strategies should be implemented in the early post-fire stages for improving vegetation recovery by enhanced microclimatic amelioration and nutrient supply (Marañón-Jiménez *et al.* 2013), while minimising the impact of cut and lopping operations on the regenerating plant communities (Castro 2021).

In relation to the limitations of the present study and future needs, the impact of straw mulching and burnt wood management strategies on post-fire erosion and sediment yields in the medium term after fire should be addressed. This approach would provide more integrated insights into the feedbacks of emergency rehabilitation techniques on soil multifunctionality (Lucas-Borja *et al.* 2019). Future studies on this topic should also consider soil microbiological indicators, such as the functional composition of microbial communities, which are crucial drivers of soil multifunctionality in burned areas (Lucas-Borja *et al.* 2020; Sáenz de Miera *et al.* 2020). In this sense, additional ecosystem functions and related variables such as litter decomposition, nutrient pools in above-ground biomass or ecosystem production, must be considered to expand the analysis to ecosystem multifunctionality (Garland *et al.* 2021), rather than soil multifunctionality. Finally, sampling more experimental plots would strengthen our conclusions regarding synergies and trade-offs of soil functions and the response of emergency post-fire treatments in a wider variety of environmental conditions, plant communities and fire severity scenarios.

## Conclusions

This novel study evaluated the effect of straw mulching and burnt wood treatments on the soil multifunctionality of heathland plant communities. Straw mulch did not trigger a significant response in any individual soil functions or soil multifunctionality. However, a mesh of fine and coarse Scots pine woody debris improved soil multifunctionality through cumulative increments in individual soil functions. These results support the use of soil multifunctionality instead of individual soil functional indicators for preventing biased assumptions on the success of management actions due to the larger overall soil functioning effect when pooling multiple functions together. Interestingly, both treatments promoted synergies between several soil functions, which were converted into trade-offs in untreated areas. Taking all results together, burnt wood management strategies could ensure longer-lasting effects to promote soil multifunctionality in Mediterranean fire-prone ecosystems as compared to straw mulch treatments and at a lower cost.

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**Data availability.** The data that support this study will be shared upon reasonable request to the corresponding author.

**Conflicts of interest.** The authors declare no conflicts of interest.

**Declaration of funding.** This study was financially supported by the Spanish Ministry of Economy and Competitiveness, and the European Regional Development Fund (ERDF), in the framework of the FIRESEVES (AGL2017-86075-C2-1-R) project; by the Regional Government of Castilla and León in the framework of the WUIFIRECYL (LE005P20) project; by the British Ecological Society in the framework of the SR22-100154 project, where José Manuel Fernández-Guisuraga is the Principal Investigator; and by the Portuguese Foundation for Science and Technology in the frame of project UIDB/04033/2020. José Manuel Fernández-Guisuraga was supported by a Ramón Areces Foundation postdoctoral fellowship.

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