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The Impacts of Post-Fire Straw Mulching and Salvage Logging on Soil Properties and Plant Diversity in a Mediterranean Burned Pine Forest

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Abstract: In the Mediterranean forests, wildfires and post-fire management actions may degrade soil properties and negatively impact vegetation characteristics. These effects may reduce soil functionality and result in loss of plant diversity. Although straw mulching and salvage logging are commonly carried out in burned forests, their impacts on respiration of forest soils as well as on species richness and evenness of forest plants have been little explored. To fill these gaps, this study has evaluated the soil respiration, different soil physico-chemical properties, as well as plant diversity in a forest of Castilla La Mancha (Central Eastern Spain), burned by a wildfire and then subjected alternatively to salvage logging or straw mulching or to both techniques. Compared to the unburned soils, immediately after the fire mulching and salvage logging alone increased (+146%) and reduced the soil respiration (−9%), respectively, the latter especially in combination with mulching. However, these differences decreased over time, and the mulched and non-logged areas always showed the maximum soil respiration. The post-fire treatments also significantly influenced the main physico-chemical properties of the experimental soils. No evident changes were found for the pH of the logged and mulched soils compared to the control. Mulching coupled with logging did not modify the OM increase due to fire, while the lowest increase was measured in the logged but non-mulched areas. Mulched and non-logged soils maintained high OM and TN one year after fire, but also in areas that were treated with logging (with or without mulching) these parameters were significantly higher compared to the unburned areas. Mulching increased the species richness and evenness, especially when itis carried out without logging, in comparison to the unburned areas. Logging without mulching did not exert negative impacts on plant biodiversity, whose species richness increased and evenness was unvaried compared to the burned and unburned areas. The results of this study can provide land managers easy to measure tools such as soil respiration and plant diversity, which can serve to assess and evaluate the effectiveness of management measures that are taken post-forest fire in order to conserve the delicate ecosystems of the Mediterranean forests.

Keywords: post-fire management; soil functionality; species richness; vegetation evenness; wildfire

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1. Introduction

Wildfire is a natural and essential agent that shapes vegetation dynamics in fire-prone forests [1]. However, fires with high severity heavily impacts several components of forest ecosystems (air, soil, water, fauna, and vegetation), including several ecosystem services [2,3]. Burning completely removes understory vegetation and often destroys the tree canopies, and this leaves the soil bare and thus exposed to erosion [4,5]. Moreover, several soil properties undergo heavy changes after heating at high temperatures, especially in the case of high-severity fires [6–8]. As such, wildfire is considered a primary driver of soil erosion and land degradation [9,10], especially in Mediterranean conditions. The Mediterranean soils are generally shallow and have little organic matter [11,12], and weather conditions of the semi-arid areas may be particularly adverse (heavy and flash storm events with high erosive power [13,14]. The effects of high-severity and large fires on ecosystem services in the Mediterranean areas must also properly considered [15,16].

In addition to wildfires, other negative factors can increase the erosion and degradation rates in Mediterranean forests. For instance, salvage logging after fire is mainly carried out to recover timber from burned forests, and secondarily to reduce fire recurrence and restore catchments (for instance, by creating contour-felled debris logs [17,18]). Salvage logging after wildfire is a controversial but commonplace practice, and its effects are quite scarcely investigated in Mediterranean areas [19,20]. However, the negative impacts of salvage logging are well known, since this forest operation may damage soil and belowground processes, and can increase runoff and erosion in burned catchments [21,22]. More specifically, it is true that salvage logging provides economic benefits, reduces fire susceptibility, and facilitates forest accessibility, but we must keep in mind its negative constraints, such as the increase in soil compaction and hydrological response, loss of habitat in the long-term, and a large downing of wood [23–25]. The literature has widely debated the pros and cons of salvage logging in burned areas, and the results of these studies are still contrasting. Moreover, some impacts of these forest operations have not been completely understood, such as the effects on some important soil properties or functionality, particularly in the Mediterranean ecosystems [10]. For instance, it is still not clear whether salvage logging after wildfire may affect the soil respiration of forest ecosystems in the short-term. Moreover, the effects on plant diversity in areas that are affected by wildfire and then subjected to logging are not completely understood. Data from several studies demonstrate that salvage logging affects the number of species and the composition of vegetal communities, which, as a consequence, negatively affects several taxonomic groups [20]. Caution must be paid to this practice in burned areas, in order to avoid loss of biodiversity in addition to the other negative impacts.

On another side, the need to control the heavy impacts of wildfires on the runoff and erosion rates in Mediterranean forests has enhanced the use of post-fire treatments [8,26,27]. Soil mulching is one of the most common post-fire techniques to reduce soil erosion in the short-term in wildfire-affected forests. The mulch material that is spread on the burned soils provides a vegetal cover that reduces raindrop impact, increases water infiltration, and slows down overland flow [28–30]. The mulching effectiveness at reducing runoff and erosion has been demonstrated by several studies in different environments that have been affected by fires with different severity (e.g., [10,28,31–38]. However, the literature reports examples of adverse effects of post-fire soil mulching. For instance, [39] demonstrated that straw mulching can reduce short-term infiltration in burned soils, while [40] reported a low effectiveness of straw mulching to reduce soil erosion after moderate precipitation rates. Fewer studies have evaluated the changes in soil properties after wildfire and mulch application. More specifically, while it is well known that soil mulching with vegetal residues (straw, woodchips, strands, and so on) is a source of organic material that van be easily incorporated into the soil, few studies have analyzed the influence of soil mulching on soil functionality using its properties as indicators. Moreover, little is known on the capacity of these post-fire management measures to help the recovery of plant diversity, since the effectiveness of mulching to conserve biodiversity in burned areas shows a high variability and is influenced by the wildfire severity and forest characteristics [41–43].

From the discussion above, the combination of salvage logging and soil mulching in forests that are burned by wildfires may have contrasting impacts, which may be sometime synergistic, but, in other conditions, may lead to increased degradation rates of fire-affected soils, with particular regard to soil functionality and plant diversity. The latter plays an important role on soil fertility and ecosystem health in delicate environments, such as the Mediterranean forests [44]. The variations in C/N, pH, texture, organic matter, and nutrient contents are meaningful indicators of soil functionality [25,45–48]. In particular, soil respiration strictly influences the forest productivity and soil fertility [49], and as such, this property is a key indicator of the health and quality of soil since it indicates the ability of soils to enhance plant growth [50–52].

Moreover, the plant diversity may also be affected by soil response to burning and post-fire treatments. For instance, [43] found in forests that were distributed across the Iberian Peninsula a limited influence of post-fire management techniques on plant diversity after wildfires. On the other hand, [53] demonstrated that mulching does not result in short-term negative impacts on the initial recruitment of vegetation in sub-humid areas. [54] indicated that the moisture that was retained by mulch may be beneficial for natural regeneration of pine species in environments with water shortage, while applications of deep mulch layers may hamper natural regeneration, resulting in a physical barrier to seed emergence.

Therefore, exploring the variability of essential soil properties and plant diversity in burned soils under combined operations of salvage logging and straw mulching may give land managers an insight about the ecological viability of these post-fire actions. In other words, more research is needed to better understand whether and to what extent the straw mulching, salvage logging and combinations of these operations may influence soil functionality and plant diversity, especially in the Mediterranean forests.

As mentioned above, while the literature has widely investigated the effects of salvage logging and straw mulching on several properties of soils or on vegetation cover in burned forests, very few studies have paid attention to soil functionality and vegetation diversity in burned and logged or mulched sites. Moreover, to the authors' best knowledge, no studies have explored the combined effects of these post-fire treatments on these ecosystem aspects. This leaves it unclear whether soil respiration and vegetation biodiversity are affected or not by these practices, and, therefore, no relevant indicators are available for forest managers.

To fill this gap, this study has evaluated the soil respiration and a significant dataset of soil properties as well as the most important indexes of plant diversity in a forest of Castilla La Mancha (Central Eastern Spain), that was burned by a wildfire and then subjected alternatively to salvage logging or straw mulching or to both techniques. We hypothesize that mulching exerts beneficial effects on those properties that are linked to soil functionality as well as forest biodiversity, while salvage logging may reduce these positive impacts.

2. Materials and Methods

2.1. Study Area

The study area is in the Sierra de las Quebradas forest Liétor, province of Albacete, Castilla-La Mancha region, Central Spain (geographical coordinates: 38°30′40.79″ N, 1°56′35.02″ W) (Figure 1). The elevation is between 520 and 770 m, and the aspect is W-SW. The area has a semiarid climate (BSk type, according to the Köppen classification [55]). The mean annual value of temperature is 16.6 °C, while the annual precipitation is on average 321 mm. According to the weather data that were collected between 1990 and 2014 (source: Spanish Meteorological Agency), the highest monthly precipitation is in October (44.5 mm) and the lowest rainfall is in May (39.6 mm). A hot and dry period (air relative humidity below 50%) occurs from June to September. According to the Soil Taxonomy system, the soils are classified as Inceptisols and Aridisols with a sandy-loam texture [56] and a depth lower than 30 cm. The vegetation consists of species of the *Quercus cocciferae-Pinus halepensis* S. series, with Aleppo pine as tree cover of and kermes oak as a shrub layer [57]. *Pinus halepensis* M. stands mainly compose the vegetation of the forest area. In the study site, the mean density of forest trees was about 500–650 trees/ha and their height was 7–14 m before the wildfire. The main shrubs and herbaceous species were *Rosmarinus officinalis* L., *Brachypodium retusum* (Pers.) Beauv., *Cistus clusii* Dunal, *Lavandula* *latifolia* Medik., *Thymus vulgaris* L., *Helichrysum stoechas* L., *Stipa tenacissima* L., *Quercus coccifera* L., and *Plantagoalbicans* L. Since the middle of the twentieth century, this area was progressively abandoned and reforested by the local public authorities, and this has shaped a forest landscape that is composed of natural Aleppo pines.

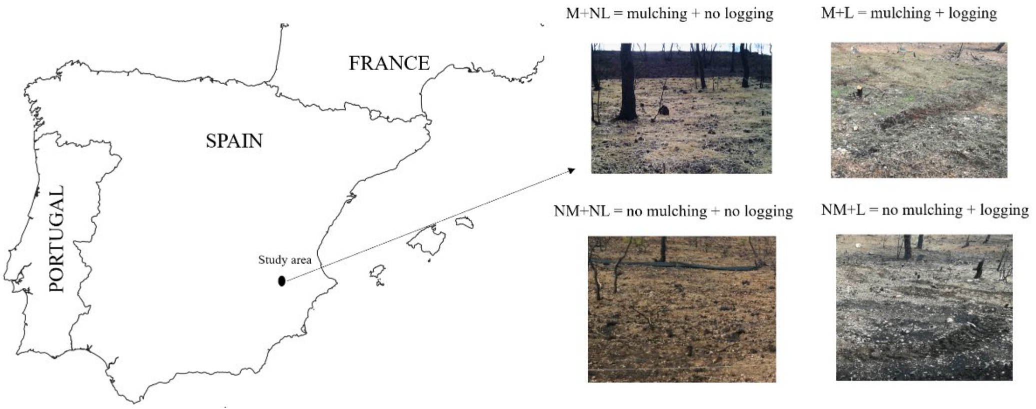


Figure 1. Geographical location of the study area (Sierra de las Quebradas forest, Castilla-La Mancha, Central-Eastern Spain.

2.2. Experimental Design

A large area (830 ha of forest land) in the Sierra de las Quebradas forest was burned by a wildfire in July 2016. On 26 September 2016, part of the burned area was treated with mulching. The mulch material consisted of barley (*Hordeum vulgare* L.) straw, which was cut in a farm that was close to the burned forest. The straw was manually applied on the plots at a rate of 0.2 kg m^{-2} (dry weight) and a depth of 3 cm. This dose was proposed by [58] in northern Spain to achieve a soil cover over 80%. The same quantity of straw is commonly and successfully used in croplands as anti-erosive action [59].

Salvage logging was conducted in a part of the burned area on 11 December 2016 using an agricultural adapted tractor with herringbone-tire pneumatic rubber agricultural wheels (tire size 18.4R30). The tractor was a 4-cylinder Landini DT9880, which is able to reach a rated power of 69.2 kW and a total weight of 4697 kg. The working speed ranged from 6.0 to 8.0 km/h. Trees were felt using mechanical chainsaws, and burned logs were then removed from the plots with the agricultural tractor in the same day.

Immediately after the wildfire, a site of about 2 ha and a tree cover of Aleppo pine was identified. In this site, the trees were affected by crown fire with a mortality of 100%. Here, sixteen rectangular experimental plots were randomly located. The plots, each covering 200 m^2 (20 m × 10 m)) were at a minimum reciprocal distance of 200 m. The plot distribution ensured their comparability in terms of slope and aspect. Soil burn severity, assessed according to [60,61], was always high, and this confirmed the plot comparability.

Of these 16 plots, four were mulched and logged (hereafter indicated as "M + L"), four were mulched and not logged ("M + NL"), four not mulched and logged ("NM + L"), and the remaining four plots were not logged and not mulched ("NM + NL"). Two additional plots with the same physiographic characteristics were installed in the unburned area, surrounding the burned forest, and considered as the control ("C"). Therefore, the experimental design consisted of five post-fire treatments (mulching + logging, non-mulching + logging, non-mulching + non-logging, mulching + non-logging, and a control).

2.3. Soil Sampling and Physico-Chemical Analysis

Soils of the 18 plots were sampled in November 2016 and September 2017, collecting two 600-g composite samples (one for each period) from each plot. The samples come from the same parent material. Before sample collection, the litter layer was removed. The composite samples consisted of six 100-g subsamples, that were randomly collected from the top 10 cm of surface soil in as many points in each plot, to capture the potential variability of soil conditions. Only the soil surface was sampled, since the wildfires effects on soil are confined to the surface layer, due to the fact that soil is a poor heat conductor. The soil subsamples were at a minimum reciprocal distance of 5 m, representing different areas of each plot. After collection, the samples were sieved (at 2 mm) and stored at 4 °C until the next day, when the main physical and chemical properties of the samples were analyzed.

Among the soil physical properties, the texture (contents of sand, silt, and clay) was analyzed according to the method of [62]. Regarding the soil chemical properties, the pH was determined in a 1:5 (*w*/*v*) aqueous solution by a multiparameter portable device (Hanna Instruments® model HI2040-02, Gipuzkoa, Spain). The organic matter content (OM) was measured by the potassium dichromate oxidation method [63]. The total nitrogen (TN) was determined using the Kjeldahl method [64]. The C/N ratio was obtained by dividing the organic carbon (calculated by multiplying the OM by 0.58) by the total nitrogen.

Moreover, as a further indicator of soil functionality, we measured soil respiration in each plot using a 6400-09 portable soil CO_2 flux chamber that was attached to an LI-COR 6400 (LI-COR Inc. Lincoln, NE, USA) using PVC soil collars (n = 3 per plot) that were inserted to a depth of 2 cm into the soil. The collars were placed at least 24 h before the R_s measurement (between 9:00 and 17:00 h), in order to limit soil disturbance. The soil temperature (ST) was measured using a thermocouple probe 6000-09TC, connected to the LI-COR 6400. The volumetric soil water content (SWC) was determined by a portable Moisture Probe MP406 (ICT International, Armidale, NSW, Australia). Both ST and SWC were measured in points surrounding the collars and simultaneously with R_s at 5 cm depth. The measurements were taken on four dates (November and December 2016, and May and September 2017).

2.4. Analysis of Plant Diversity

Plant diversity was measured in spring 2017, using three linear transects for each plot. The following diversity indexes were calculated:

1. The number of species (S), which measures the floristic richness, is the sum of the number of plant species that were recorded on the sampling lines in each plot, and the number of species that were detected by the floristic inventory in the whole plot, but did not intercept the transects;
2. The Shannon Index [65], which is related to the relative abundance of the different species in each plot (measured as interception length in cm, using one cm as minimum interception value).
3. The Pielou index [66], which is an index of species evenness, which indicates how the number of each species is close in a given environment.

The Shannon index (H) is given by the following formula:

$$H = -\sum_{i=1}^{S} p_i \ln p_i \tag{1}$$

where $p_i = \frac{n_i}{N}$ = frequency of "n_i" plants belonging to the species "i" compared to the total number of plants "N" in the transect. When all plant types are equally common, all $\mathrm{p_i}$ values equal 1/R, which gives a Shannon index equal to ln(S). When all plant individuals belong to one type, and the other types are very rare (even in the case of high numerosity), the Shannon index is approximately zero.

The Pielou index (J) can be calculated as:

$$J = \frac{H}{H_{\max}} \tag{2}$$

where H and H_{max} are the Shannon index and its maximum, respectively. J ranges between 0 and 1. A lower J expresses a low evenness in the communities between the species, that is the presence of a dominant species.

2.5. Statistical Analysis

The statistical differences in the physico-chemical properties and respiration of soil as well as plant diversity indexes were evaluated by the multivariate permutational analysis of variance (PERMANOVA) [67], using the soil condition (NL + NM, L + NM, NL + M, L + M, and C), and the sampling time (November 2016 and September 2017) as factors. PERMANOVA analyzes the simultaneous response of one variable to one or more factors in an experiment based on resemblance measures, using a permutation method. Before PERMANOVA, the soil properties were square root transformed; the resemblance matrix was built using Bray–Curtis distance for the abundance data that were found at each plot, respectively. The sums of squares type were Type III (partial) and the factors were fixed effects. The permutation method that was used was the unrestricted permutation of raw data and the number of permutations was 999. Then, a DISTLM function (distance-based linear modelling) was applied, to identify the relative importance of the soil properties and covers on soil respiration. For the DISTLM function, "marginal" tests of the relationship between the response variable (soil respiration) and an independent variable (a soil property) was carried out, to identify the independent variables that explained the variability in the soil samples. Then, "sequential" tests of individual variables were carried out, to evaluate if the addition of an individual variable significantly contributes to the explained variation of the response variable. Finally, distance-based redundancy analysis (dbRDA) was applied to soil respiration, to develop a regression model of soil respiration against two new response variables ("axis" 1 and "axis" 2), built on the soil properties and covers by the step-wise procedure. The AICc [68] criterion selected the best model.

For the statistical analyses, the software PRIMER V7® with the PERMANOVA add-on [67] and Statgraphics Centurion XVI® (StatPoint Technologies, Inc., Warrenton, VA, USA) were used. A significance level of 0.05 was used, unless otherwise indicated.

3. Results

3.1. Soil Respiration

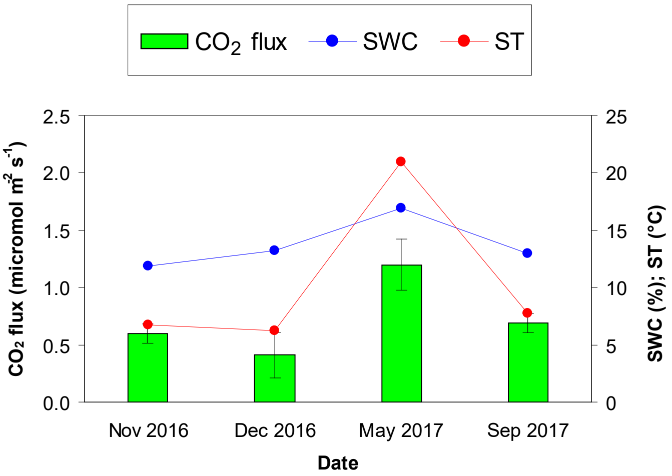
The results of the PERMANOVA show that the differences in the water content, temperature, and CO_2 flux among the studied soil conditions, and the sampling dates were always significant (Table 1).

Table 1. Results of the PERMANOVA that was applied to the soil water content, temperature, and CO_2 that were measured at two dates under five soil conditions in the experimental site (Liétor, Castilla La Mancha, Spain).

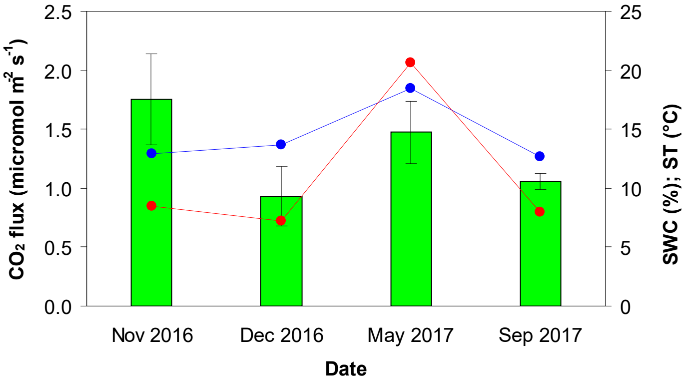
Source	Pseudo-F	P(perm)
	SWC	
Soil condition	8.44	**0.001**
Date	44.2	**0.001**
Soil condition × date	13.5	**0.001**
	ST	
Soil condition	31.2	**0.001**
Date	785	**0.001**
Soil condition × date	3.27	**0.002**
	CO_2 flux	
Soil condition	13.38	**0.001**
Date	15.93	**0.001**
Soil condition × date	3.36	**0.005**

Notes: SWC = soil water content; ST = soil temperature; bold letters indicate significant differences at $p < 0.05$.

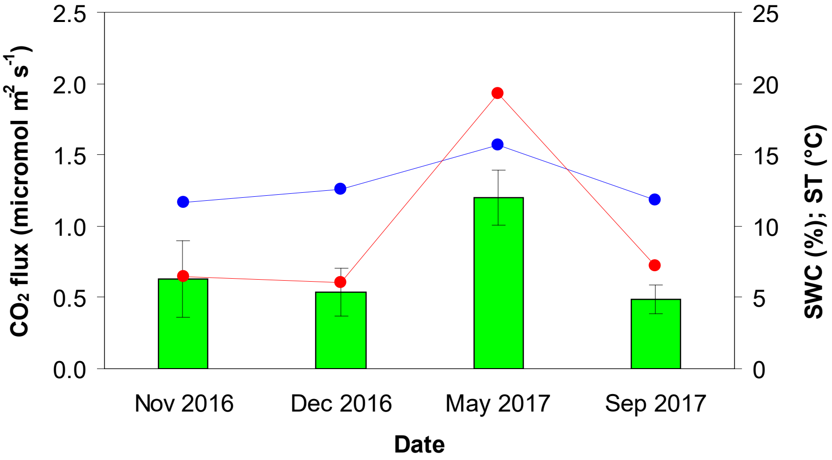
Immediately after the wildfire, the SWC and ST significantly decreased in the burned soils (minimum of 11.7 ± 0.24%, and 6.5 ± 0.5 °C, respectively, both in NM + L soils) in comparison to the control (unburned soils, SWC of 15.9 ± 0.6% and temp. of 14 ± 0 °C). The CO_2 fluxes decreased in the NM + L (0.63 ± 0.19 µmol m^{-2} s^{-1}), M + L (0.6 ± 0.06 µmol m^{-2} s^{-1}) and NM + NL (0.63 ± 0.11 µmol m^{-2} s^{-1}) soils, and increased in the other soil condition (M + NL, 1.75 ± 0.27 µmol m^{-2} s^{-1}), although these differences were not significant compared to the unburned plots (Table 1 and Figure 2).



(M + L)

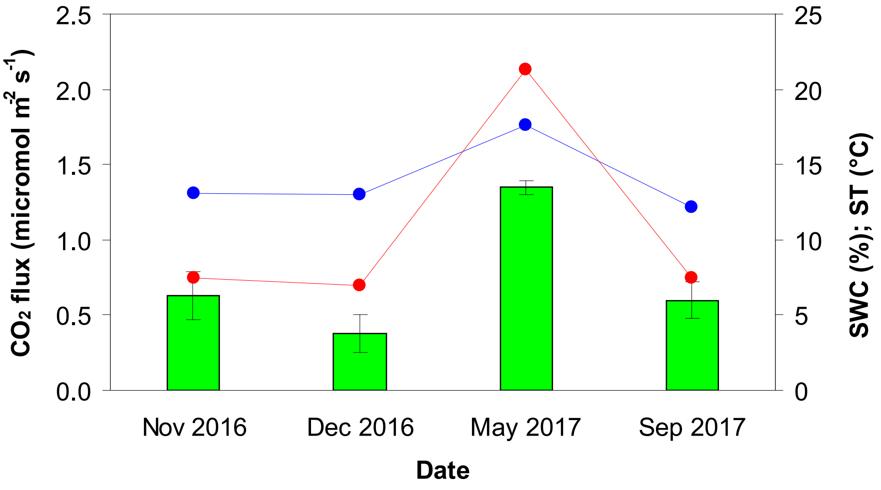


(M + NL)

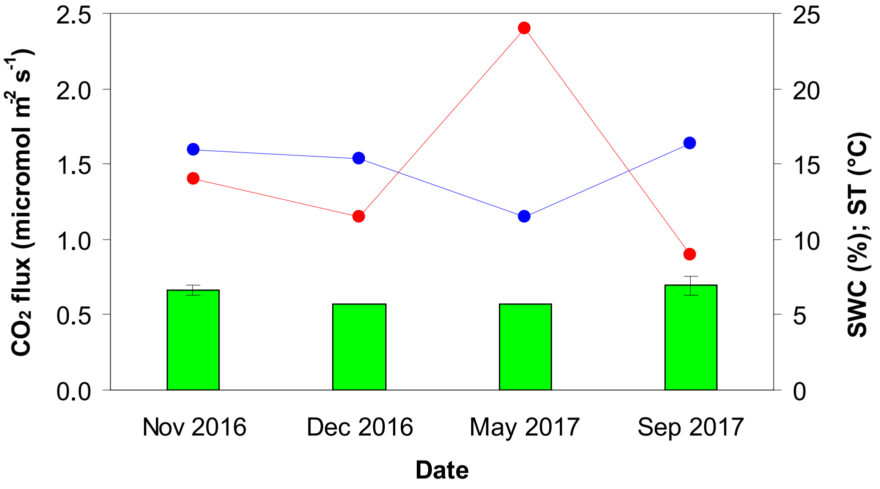


(NM + L)

Figure 2. *Cont.*



(NM + NL)



(C)

Figure 2. Soil respiration (CO_2 flux) that was measured at four dates under five soil conditions in the experimental site (Liétor, Castilla La Mancha, Spain). Notes: SWC = soil water content; ST = soil temperature; NM + L = non-mulched and logged; M + L = mulched and logged; M + NL = mulched and non-logged; NM + NL = non-mulched and non-logged; C = control (non-burned).

One year after the wildfire, both the SWC and ST were significantly lower in the burned soils compared to the control (minimum SWC and ST of 11.82 ± 0.11% and 7.25 ± 0.14 °C in NM + L plots against 16.4 ± 0.49% and 9 ± 0 °C). The CO_2 flux that was measured in the control soils (0.69 ± 0.06 μmol m^{-2} s^{-1}) was equal into that of the M + L plots, higher compared to the NM + L (0.49 ± 0.07 μmol m^{-2} s^{-1}) and NM + NL (0.59 ± 0.08 μmol m^{-2} s^{-1}), and lower compared to the M + NL areas (1.06 ± 0.04 μmol m^{-2} s^{-1}), but only the latter difference was significant (Table 1 and Figure 2).

Moreover, under some soil conditions (M + L, NM + L, and NM + NL), an increase in the temperature in the dry season (May 2017) led to a corresponding increase in CO_2 flux. However, no clear trends were detected between SWC or soil temperature in one side and the CO_2 flux on the other side ($r^2 < 0.27$).

3.2. Soil Physico-Chemical Properties

According to the results of the PERMANOVA, the differences in the soil physico-chemical properties among the studied soil conditions and sampling dates were always significant with few exceptions (differences in pH between soil conditions and dates, and their interaction, and in C/N between the date) (Table 2).

Table 2. Results of the PERMANOVA that was applied to the main soil parameters that were measured at two dates under five soil conditions in the experimental site (Liétor, Castilla La Mancha, Spain).

Source	Pseudo-F	P (perm)
	SaC	
Soil condition	13.1	**0.001**
Date	45.8	**0.001**
Soil condition × date	5.8	**0.003**
	SiC	
Soil condition	88.0	**0.001**
Date	135	**0.001**
Soil condition × date	5.70	**0.008**
	ClC	
Soil condition	475	**0.001**
Date	43.2	**0.001**
Soil condition × date	18.8	**0.001**
	pH	
Soil condition	2.51	0.054
Date	0.001	0.976
Soil condition × date	1.63	0.185
	OM	
Soil condition	47.6	**0.001**
Date	86.8	**0.001**
Soil condition × date	42.5	**0.001**
	TN	
Soil condition	69.0	**0.001**
Date	107	**0.001**
Soil condition × date	37.4	**0.001**
	C/N	
Soil condition	8.86	**0.001**
Date	6.34	0.027
Soil condition × date	17.9	**0.001**

Notes: SaC = sand content; SiC = silt content; ClC = clay content; OM = organic matter; TN = total nitrogen. Bold letters indicate significant differences at $p < 0.05$.

Immediately after the wildfire, the soil textural characteristics were significantly different for sand and clay. Higher contents of sand in M + L, M + NL, and NM + NL plots (with a maximum of 59.68 ± 1.09% in M + NL vs. 52.17 ± 0.59%) were detected in the unburned plots, while the contents of clay were lower in all soil conditions (minimum ClC in M + NL plots, 8.58 ± 0.00%, against 32.68 ± 0.00% in the control). In contrast, the silt content was basically unvaried with non-significant changes recorded in all plots (Table 2).

The pH always decreased in the burned plots (minimum of 8.44 ± 0.01 in NM + NL soils) compared to the unburned areas (8.54 ± 0.10), but the differences were not significant. Noticeable and significant increases were detected in the OM and TN contents of the burned soils (with a maximum of 19.36 ± 1.79% for OM and of 0.55 ± 0.01% both recorded in

M + L plots) compared to the unburned plots (2.11 ± 0.08% of OM and 0.09 ± 0.00% of TN). The OM and TN content of NM + L soils (4.75 ± 0.06% and 0.22 ± 0.00%, respectively) are exceptions, since these values are close (but equally significantly different) to the corresponding values that were measured in the control. The calculation of the C/N ratio based on the OM and TN contents of soils shows a significant decrease in the NM + L plots (12.59 ± 0.13), and a significant increase in the M +L and NM + NL soils (20.08 ± 1.22% and 21.45 ± 0.60%, respectively) compared to the unburned soils (14.29 ± 0.36%), whose value was similar to the C/N of M + NL plots (15.60 ± 0.61) (Table 2).

One year after the wildfire, while the changes in the sand content were low under all the soil conditions (with only slight increases compared to the control), the differences in the silt and clay contents were noticeable and significant. In more detail, the SiC increased from 19.14 ± 1% (control) up to a maximum of 42.01 ± 0.01% in the NM + L plots and the ClC decreased from 32.68 ± 0% (control) down to a minimum of 6.84 ± 0.09% again measured in the NM + L soils). Moreover, the differences in the soil texture among the burned soils were low (Table 2).

The pH was comparatively lower in the burned soils (minimum of 8.41 ± 0.01 in M + NL plots) compared to the control plots (8.64 ± 0.21) (Table 3). The OM and TN contents of the burned noticeably and significantly increased in the burned soils (maximum OM of 9.03 ± 0.15% and 0.32 ± 0.01% both recorded in the M + NL soils) compared to the unburned areas (2.19 ± 0.16% and 0.09 ± 0.01%, respectively) (Table 2). Due to these variations, the C/N ratio increased, although not significantly, in all soil conditions with a maximum calculated in the NM + L plots (17.17 ± 0.49) compared to the control value (13.92 ± 0.73) (Table 2).

Table 3. Main soil parameters that were measured at two dates under five soil conditions in the experimental site (Liétor, Castilla La Mancha, Spain).

Soil Parameter	**Soil Condition**									
	NM + L	**M + L**	**M + NL**	**NM + NL**	**C**	**NM + L**	**M + L**	**M + NL**	**NM + NL**	**C**
	November 2016					**September 2017**				
SaC (%)	52.14 ± 0.98 aA	58.52 ± 0.55 bA	59.68 ± 1.09 bA	57.46 ± 0.98 bA	48.17 ± 1 aA	51.14 ± 0.08 aA	51.17 ± 1.12 abB	52.17 ± 0.59 aB	50.19 ± 1.73 abB	48.17 ± 1 bA
SiC (%)	32.97 ± 0.30 aA	31.82 ± 0.99 aA	31.73 ± 1.09 aA	32.16 ± 1.59 aA	19.14 ± 1 bA	42.01 ± 0.01 aB	40.73 ± 0.46 bB	40 ± 2.05 bB	41.44 ± 1.17 abB	19.14 ± 1 cA
ClC (%)	14.88 ± 0.67 aA	9.64 ± 0.43 aA	8.58 ± 0.00 bA	9.65 ± 0.43 bA	32.68 ± 0 cA	6.84 ± 0.09 aB	8.09 ± 0.75 aA	7.82 ± 0.59 aA	8.36 ± 0.69 aA	32.68 ± 0 bA
pH	8.48 ± 0.01 aA	8.48 ± 0.01 aA	8.52 ± 0.00 bA	8.44 ± 0.01 aA	8.54 ± 0.10 abA	8.49 ± 0.03 aA	8.48 ± 0.03 aA	8.41 ± 0.01 aB	8.45 ± 0.02 aA	8.64 ± 0.21 aA
OM (%)	4.75 ± 0.06 aA	19.36 ± 1.79 bA	10.84 ± 0.86 cA	18.74 ± 0.96 bA	2.11 ± 0.08 dA	7.31 ± 0.23 aB	6.01 ± 0.45 bB	9.03 ± 0.15 cA	6.10 ± 0.30 bB	2.19 ± 0.16 dA
TN (%)	0.22 ± 0.00 aA	0.55 ± 0.01 bA	0.4 ± 0.01 cA	0.51 ± 0.04 bA	0.09 ± 0.00 dA	0.25 ± 0.00 aB	0.23 ± 0.00 bB	0.32 ± 0.01 cB	0.24 ± 0.01 abB	0.09 ± 0.01 dA
C/N	12.59 ± 0.13 aA	20.08 ± 1.22 bA	15.60 ± 0.61 cA	21.45 ± 0.60 bA	14.29 ± 0.36 cA	17.17 ± 0.49 aB	15.44 ± 1.09 abB	16.25 ± 0.76 abA	14.72 ± 0.65 bB	13.92 ± 0.73 bA

Notes: NM + L = non-mulched and logged; M + L = mulched and logged; M + NL = mulched and non-logged; NM + NL = non-mulched and non-logged; C = control (non-burned); SWC = soil water content; SaC = sand content; SiC = silt content; ClC = clay content; OM = organic matter; TN = total nitrogen. Lowercase and capital letters indicate significant differences among the soil conditions and sampling dates, respectively.

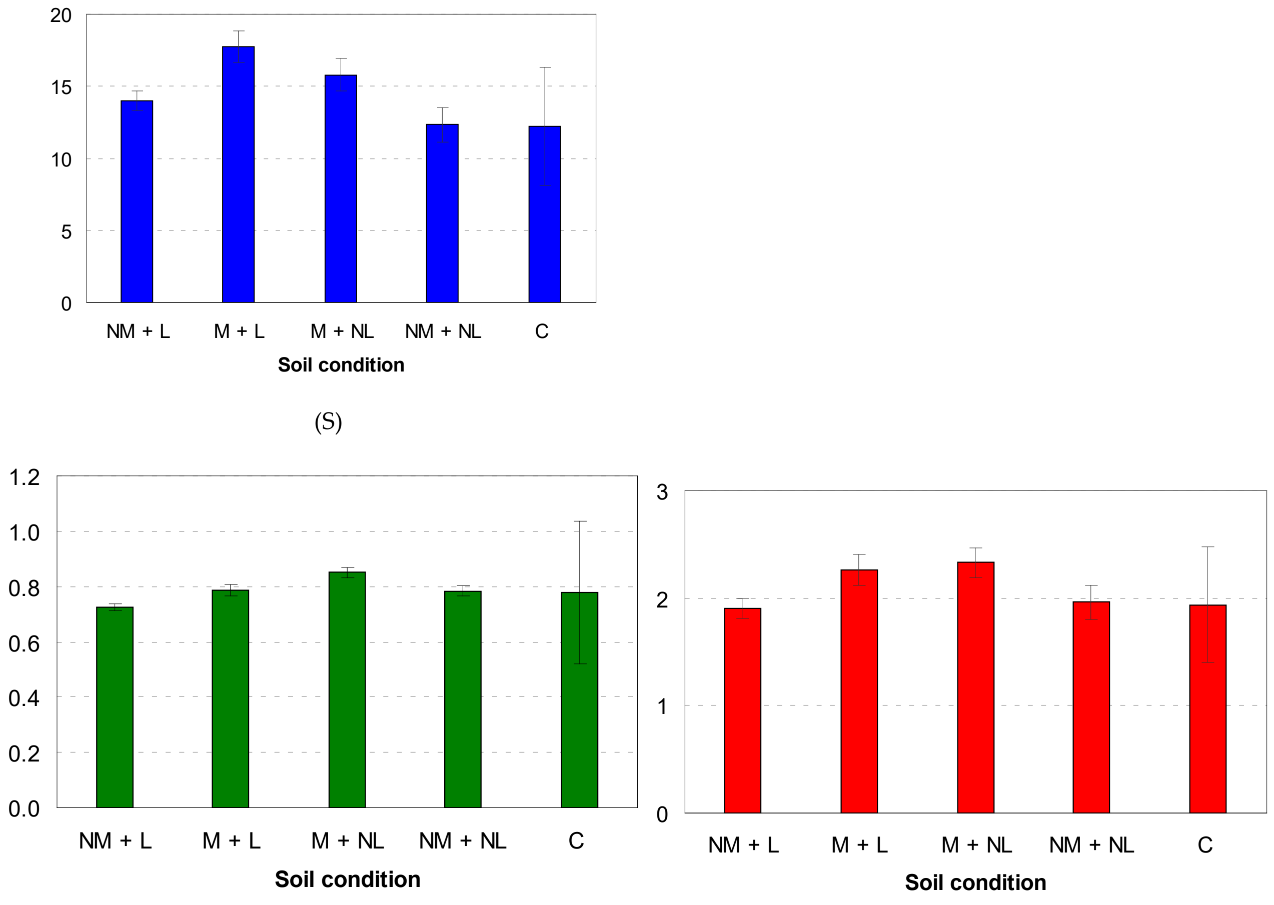
3.3. Plant Diversity

All plant diversity indexes were significantly different among the soil conditions (Table 4). In more detail, the mulched soils supported the highest species richness, especially when subjected to logging (S = 17.8 ± 1.13). The lowest S was detected in the unburned soils (12.2 ± 4.0), while intermediate values were measured in the non-mulched plots (12.3 ± 1.2, NM + NL, and 14 ± 0.7, NM + L). Similar trends were noticed for the Shannon (H) and Pielou (J) indexes, which were the highest in the mulched areas (H of 2.26 ± 0.1

and 2.33 ± 0.1, for M + L and M + NL, and J of 0.79 ± 0.02 and 0.85 ± 0.02, for M + L, respectively). In contrast, the lowest H and J values were detected in the NM + L plots (0.72 ± 0.01 and 1.90 ± 0.05, respectively), and these indexes were very close to the values that were detected in the control soils (H of 1.94 ± 0.65 and J of 0.78 ± 0.26) (Figure 3).

Table 4. Results of the PERMANOVA that was applied to the three indexes (S, species richness; J, Piélou; and H, Shannon) to measure the plant species diversity under five soil conditions (different post-fire treatment) in the experimental site (Liétor, Castilla La Mancha, Spain).

Source	Pseudo-F	P (perm)
	S	
Soil condition	7.475	0.002
	J	
Soil condition	5.077	0.004
	H	
Soil condition	6.3161	0.001



(S)

(J) (H)

Figure 3. Indexes (S; species richness; J, Piélou; and H, Shannon) to measure the plant species diversity under five post-fire treatments in the experimental site in spring 2017 (Liétor, Castilla La Mancha, Spain).

3.4. Data Processing with PERMANOVA Techniques

The marginal tests of distance-based linear modelling (DISTLM) showed that, of all soil properties that were evaluated in this study, SaC, and ST jointly influenced the CO_2

flux at a $p < 0.05$ (data not shown). The sequential tests demonstrated that the best distance linear model ($R^2 = 0.44$; AICs = 171) use SaC, ST, C/N, and OM for predicting the CO_2 flux (Table 5).

Table 5. Results of sequential tests of DISTLM (distance-based linear modelling) on soil samples that were collected under five soil conditions in the experimental site (Liétor, Castilla La Mancha, Spain).

Variable	Pseudo-F	*p*	Proportion	Cumulative	AICc
+ST	3.94	0.04	0.10	0.10	177
+SaC	7.23	0.01	0.19	0.29	174
+C/N	3.61	0.05	0.10	0.39	171
+OM	2.57	0.10	0.05	0.44	171

Notes: ST = soil temperature; SaC = sand content; OM = organic matter.

The variations (out of the fitted model and out of the total variation) that were reflected by the axes of dbRDA, axis one (dbRDA1) applied to CO_2 flux explained 96.7% of the fitted model and 42.7% of the total variation of the variables, while the axis two (dbRDA2) explained 3.3% of the fitted model and 1.42% of the total variation (Figure 4).

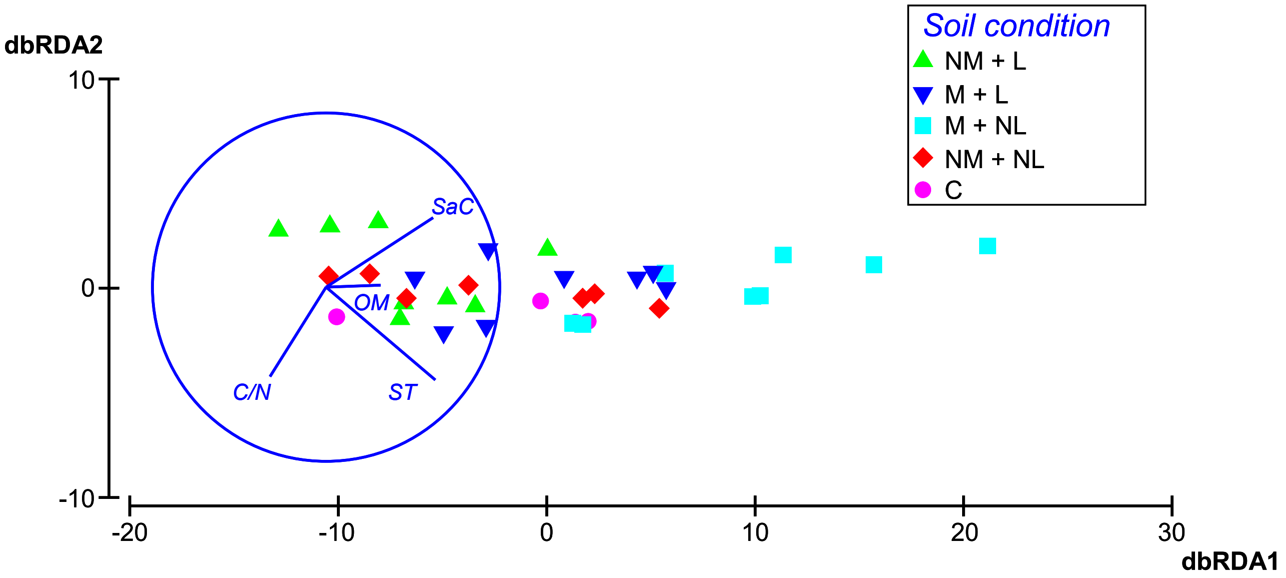


Figure 4. Results of dbRDA (distance-based redundancy analysis) of soil samples that were collected under five soil conditions in the experimental site (Liétor, Castilla La Mancha, Spain). Notes: NM + L = non-mulched and logged; M + L = mulched and logged; M + NL = mulched and non-logged; NM + NL = non-mulched and non-logged; C = control (non-burned); SaC = sand content; ST = soil temperature; OM = organic matter.

The RDA did not group the soils in evident clusters, except for the samples that were collected in the mulched and non-logged areas and those that were surveyed in the non-mulched and logged plots, which were associated to extreme values of ST and SaC (influencing the dbRDA1), higher for the M + NL plots and lower for the NM + L areas (Figure 4).

4. Discussion

The wildfire and post-fire treatments significantly altered some important properties of the burned soils, and these effects were different over time. Compared to the unburned areas, the mulched and non-logged soils supported a higher soil respiration (both immediately after the fire, +146%, and some months after, +55%). From the hydrological point of view, mulching is beneficial for soil protection in burned areas [69,70]. This shadows soil from rainfall erosivity, reduces the runoff amount and velocity thanks to the increased roughness and infiltration capacity, and could influence soil respiration. Moreover, mulching promotes water storage and interaction with nutrients, improving the soil structure and the organic matter content [29,71]. The application of mulch materials should maintain lower temperature and higher humidity in the topsoil, but this was not observed in our mulched plots, since these variables were lower compared to the unburned soils. This is in contrast to some studies that reported that high soil respiration can be due to increases in the temperature and water content levels of the topsoil or other microclimate features [72]. In our study, a seasonal effect of temperature on soil respiration was detected, and this supports the well-known sensitivity of soil respiration to temperature [73]. However, our results agree with the findings of [50], who suggested that higher soil respiration, regardless of the site condition (unburned or burned), is generally enhanced by higher temperatures and water availability. A possible reason for the increase in soil respiration in the burned and mulched areas may be the differences in carbon cycling, resulting in ash and litter incorporation, and microbial decomposition [74,75]. Moreover, according to [50], it may be possible that the relationships between the soil respiration on one side, and the soil temperature and water content on the other side varied due to the vegetation types in each soil condition, leading to different trends that can not be explained by the variability or soil respiration with these environmental variables. Overall, the presence of the mulch material helped to reduce the significant effects that were exerted by wildfires on soil respiration rates by reducing vegetation cover and the albedo on the soil surface [50,76,77]. The higher soil respiration that was detected in mulched areas in this study agrees with the results of other experiences. For instance, in fire-affected ecosystems of Western Australia, [50] there were larger measured rates of soil respiration in the burned areas compared to the unburned control sites (from 0.44 to 3.65 μmolm^{-2}-s^{-1} and from 0.24 to 3.19 μmolm^{-2} s^{-1} in the burned and control sites, respectively), although these differences strongly depend on the type of vegetation cover and time that has elapsed from fire. Other authors have demonstrated increased respiration due to the microbial decomposition of organic matter following fire [76,78], although fire is known to reduce the soil respiration from the activity of root and rhizosphere organisms due to root mortality [77].

In contrast to mulching, salvage logging reduced the soil respiration (−63% compared to the mulched and non-logged plots, and −9.1% compared to the unburned areas), and this effect was even more noticeable in the soils that were logged and treated with mulching (−90.9%) immediately after the fire. However, the differences in soil respiration among the five conditions decreased over time, but the mulched and non-logged areas always showed the maximum value (+54.5% compared to the unburned areas). Also, [44] detected differences in soil respiration between burned and logged and burned and not logged plots from pine stands of Central Eastern Spain.

Mulching and logging, and their combinations also significantly influenced the main physico-chemical properties of the experimental soils. Regarding the soil texture, one year after the wildfire, the most noticeable changes were the increases in the silt content and the decreases in the clay content compared to both the unburned areas and the values that were detected immediately after the wildfire.

Previous studies have demonstrated changes in soil texture after wildfires, which were attributed to reductions in aggregate stability and organic matter content (e.g., [9,79]. In this regard, in the same environments as our study, [44] found clearly different soil textures between unburned soils on one side, and burned plots (logged or not). In another experiment, [25] detected decreased clay and increased silt contents in burned and non-mulched soils together with an increase of silt and a decrease of sand in burned and mulched areas. However, both the latter and our studies used lightweight machinery during logging operations, which may have resulted in low ground pressure, and thus limited changes in soil texture. It is important to highlight that the monitoring of fire-induced changes in soil structure is an essential task for land managers, since a decrease in the soil finer fraction may expose the burned and untreated soils to more erosion compared to the unburned areas.

The wildfire reduced the pH, but not significantly. However, this effect may be mainly due to the natural variability of this parameter resulting from rainfall leaching and other soil processes, also considering that the pH in the unburned areas underwent a noticeable variation. Due to this variability, it is hard to disentangle whether the treatments were effective or not at exerting effects on the soil pH. According to the literature, soil pH increases after burning (e.g., [9,80], but both these properties progressively return to the pre-fire values due to leaching [7,81]. Regarding the post-fire treatments, the low variability of pH in mulched and/or logged sites may be ascribed to the good buffering capacity of the soil. Although specific analysis of related soil parameters would be needed (e.g., on active limestone and carbonate contents, which contrast the pH variations in the soil), this is indirectly confirmed by the low sensitivity of pH to burning (which should exert a heavier effect on soil compared to post-fire treatments) that was detected in this study. In a study by [44] that was carried out in a burned pine stand of Central Eastern Spain, the soil pH was slightly affected by fire and post-fire logging. In burned forests of Southern Italy, [81] found significant reductions in pH of soils that were treated with fern mulching immediately after the fire, but the pH values were not restored after one year compared to the unburned areas. The authors concluded that mulching was not successful to limit the changes in these soil properties, although it should bear in mind the low severity of the fire.

The influence of the wildfire and treatments on the organic matter and nitrogen of soil was noticeable and significant. Compared to the control, the fire immediately increased both these parameters (on average +787% for OM and +494% for TN in NM + NL plots). In contrast, the literature shows that high-intensity fires cause a decrease in the organic carbon content of soil [79], which is generally due to combustion, mineralization, volatilization, and solubilization [82,83]. Presumably, the soil temperature should not be so high to determine total combustion of OM in our study [84–86]. Some research supports this explanation, since increases in the organic carbon content in burned areas compared to the unburned sites have been recorded also for low- to moderate-intensity fires, such as the prescribed fires [87]. Another possible reason for the OM increase of our experiment may be the addition of partially pyrolyzed plant residues [82,88], the incorporation of ash into the soil [81], and the forest floor decomposition [89]. Overall, the OM content is one of the most important quality indicators among the physico-chemical properties of soil, considering its influence on plant growth and other soil processes, such as water retention, nutrient exchange, and soil structure [50,79]. In our study, while mulching coupled with logging did not modify the OM increase (+817% for OM and + 540% for TN in M + L plots), the absence of logging (M + NL plots) reduced this increase to 413% for OM and 362% for TN. The lowest increase was measured in the logged but non-mulched areas, +125% for OM and 154% for TN compared to the unburned plots.

The variability that was recorded for the organic matter and nitrogen contents of soil decreased over time. Mulching alone was able to maintain increased OM (by 311%) and TN (by 252%) one year after fire compared to the unburned plots, and these increases were the highest among the evaluated soil conditions. However, also in the other burned areas (treated with mulching and/or logging or untreated), these parameters were significantly higher (over +174% for OM and +145% for TN). It is worth noting that the beneficial effects on the OM and TN contents of soils were also noticed in the plots that were subjected to logging and non-mulching (+233% for OM and +168% for TN compared to the unburned soils). Also, [44] did not find different increases in the organic matter in soils that were subjected to logging in burned pine forests of Central-Eastern Spain. The authors also detected a higher TN content in the burned plots (logged or non-logged, which did not show significant differences) compared to the unburned areas. In the same environment, [25] reported higher OM content after soil mulching with straw, while this soil property was significantly lower in unburned, and burned but non-mulched sites. Moreover, these authors demonstrated significant increases in TN content after wildfire, with or without the mulching treatment.

In our study, the variability of OM and N among the five soil conditions generally led to significant increases in the C/N ratio in the mulched and logged as well as the untreated soils compared to the unburned soils. [44] found similar C/N ratios in burned pine stands of Central Eastern Spain subject to wildfire and logging, indicating low activity and velocity of disintegration for OM as well as a low level of N mineralization regardless of burning and logging. In the experiments by [25], carried out in the same pine stand, simultaneous changes in OM and TN noticeably reduced the C/N ratio only in the non-mulched areas in the short-term after the wildfire, because the C/N is associated to OM decomposition and N mineralization [90]. After one year, the experimental soils did not show significant differences in the C/N ratio, except mulched plots, where a slight increase was noticed. Other studies have shown that, in burned pine forests, after the initial C/N reduction due to fire, due to the accumulation of recalcitrant N and volatilization of C compounds immediately after fire [91], the C/N ratio gradually restored its pre-fire values [92].

Among the evaluated physico-chemical properties, the sand and organic matter contents, temperature, electrical conductivity, and C/N ratio of soils were found to be the best predictors of soil respiration, although the DistLM model did not show an exceptionally high prediction capacity. Moreover, the RDA revealed that the wildfire and post-fire treatments, although exerting significant changes in many soil physico-chemical parameters do not clearly discriminate unburned from burned soils (treated or not with mulching and logging). Mulching without logging is the only exception, since the scatterplot showed that the variations in the OM content (and secondarily in the other soil parameters that were evidenced by the DistLM models) are able to play significant effects on soil respiration compared to the other soil conditions.

While burning did not alter the plant diversity compared to the unburned areas, mulching was effective at increasing species richness and evenness in the burned areas, especially when it was carried out without logging. We found on average six more species in the M + NL plots compared to the burned (NM + NL plots) and unburned areas, and also the indexes of species evenness and abundance were significantly higher. The effects of mulching on plant diversity may be due to the better edaphic conditions that the presence of a cover layer exerts on post-fire recruitment of new plants, especially in semi-arid areas (for instance, thanks to sunlight interception), where the water shortage is a limiting factor towards plant growth [10]. Our results are in agreement with the findings of [43], who reported increases in species richness and diversity after wildfires and post-fire mulching in forests of *Pinus halepensis* and *Pinus pinaster*, and shrublands of the Iberian Peninsula. In other environments, [93,94] reported increases in species richness, but no differences in species diversity as a response to mulching. Logging without mulching did not exert negative impacts on plant biodiversity, which was even increased compared to the burned and unburned plots in terms of species richness or unvaried in terms of species evenness. In semi-arid habitats of *Pinus halepensis* Mill. after salvage logging, [95] reported lower plant diversity, while burning did not result in significant differences in species richness. More in general, a meta-analysis by [20] on the impacts of salvage logging on biodiversity demonstrated that this practice significantly decreases the numbers of many species, and alters the community composition.

5. Conclusions

This study has evaluated the soil respiration and a significant dataset of soil properties as well as the plant diversity in a forest of Castilla La Mancha (Central Eastern Spain), that was burned by a wildfire and then subjected alternatively to salvage logging or straw mulching or to both techniques.

With regard to the changes in the physico-chemical properties of soil, compared to the unburned areas, immediately after the fire mulching and salvage logging alone increased soil respiration, especially in combination with mulching. However, these differences decreased over time, and the mulched and non-logged areas always showed the maximum soil respiration. The post-fire treatments also significantly influenced the main physico-chemical properties of the experimental soils. One year after fire, increases in the silt and decreases in the clay contents compared to both the unburned areas were detected. While no evident changes were found in the pH of the logged and mulched soils, compared to the control, mulching coupled with logging did not modify the OM increase due to fire, while the lowest increase was measured in the logged but non-mulched areas. Mulched and non-logged soils maintained high OM and TN one year after fire, but also in areas that were treated with logging (with or without mulching) these parameters were significantly higher compared to the unburned areas.

Concerning the effects of the post-fire treatments on plant diversity, compared to the unburned areas, mulching increased the species richness and evenness, especially when it was carried out without logging. Logging without mulching did not exert negative impacts on plant biodiversity, whose species richness increased, and evenness was unvaried compared to burned and unburned areas.

These results confirm our hypotheses that mulching exerts beneficial effects on soil functionality and plant diversity and demonstrates that these effects are enduring over time. Moreover, the other hypothesis that salvage logging may reduce these positive impacts should be rejected, since this operation did not significantly affect species richness and evenness. However, caution must be paid to soil respiration, which may result in sudden decreases in areas that are subject to mulching and logging immediately after the wildfire.

In spite of these results, some research issues are still open. For instance, the monitoring of the wildfire effects on soil functionality and plant diversity should be extended over time, covering at least 8–10 years from the fire and treatments. Moreover, since scarce literature in general exists about these essential ecosystem features as affected by post-fire management, there is the need for more knowledge about the effects of other common restoration actions at the hillslope scale, such as log erosion barriers, contour felled log debris, soil preparation, etc.

Overall, the study provides a contribution to the knowledge of the effectiveness of post-fire management on soil properties and plant diversity. The knowledge of the associated changes are essential for land managers in order to identify the level of these effects and plan possible control actions against soil degradation in delicate ecosystems such as the Mediterranean forests.

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