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Mid-Term Changes in Soil Properties after Wildfire, Straw Mulching and Salvage Logging in *Pinus halepensis* Mill. Forests

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Abstract: The hydrological effects of straw mulching and salvage logging have been widely experimented in the Mediterranean forests affected by wildfires. In contrast, knowledge about the impacts of these post-fire management techniques on the physico-chemical properties of burned soils is poor, especially many years after the fire. In particular, no studies have evaluated the soil changes after the combinations of soil mulching and salvage logging after wildfires in Mediterranean forests. To fill this gap, this study explores the effects of straw mulching and salvage logging, applied individually or in combination to a burnt forest of *Pinus halepensis* Mill. of central-eastern Spain, on the physico-chemical properties of soil six years after a wildfire. Both the post-fire techniques significantly altered the organic matter, phosphorous, and carbonate contents of the burned soils as well as their C/N (carbon/nitrogen) ratio, while the texture and other chemical properties (pH, electrical conductivity, total nitrogen, potassium, cations/anions, and active limestone) of the soils were not significantly affected by these post-fire treatments. Organic matter (OM) and phosphorous (P) contents increased by 57% and 69%, respectively, in mulched soils in comparison to the burned but untreated plots. In logged soils, the OM increased by 27%, while P decreased by 17%. Salvage logging after straw mulching increased OM, albeit less than under the individual soil treatments (+13%), but noticeably reduced P (−39%). The C/N ratio practically underwent the same variation (+15–20%) after the combination of the two treatments. The principal component analysis and the agglomerative hierarchical cluster analysis applied to the soil properties measured in the plots under the individual and combined management show that the effects of salvage logging on soil properties appear to be more impactful compared to straw mulching.

Keywords: post-fire management; organic matter; nutrients; high-severity fires; Mediterranean forests

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1. Introduction

Wildfire is a key driver of hydrological and ecological processes in forest ecosystems [1,2]. This influence becomes heavy in Mediterranean forests [3,4], since in these ecosystems, soils are shallow and show low aggregate stability [5], and the semi-arid climate is very sensitive to future changes [6].

One of the most severe effects of wildfires is the change in several soil properties due to heating [7,8]. The contents of organic matter, nutrients, and ions may noticeably be altered in soils after high-intensity fires such as wildfires [9,10]. These changes modify the hydrological response of soils to rainstorms, with induced soil water repellency and reduced water infiltration [11–13], resulting in higher surface runoff and soil erosion compared to the unburnt areas [5,14]. For instance, ref. [15] has shown that, immediately after a wildfire, surface runoff and erosion rates noticeably increase, but straw mulching is effective in limiting these increases in pine forests of central-eastern Spain. The short-term effectiveness of soil mulching with forest residues at reducing post-fire runoff and erosion has been demonstrated in pine and eucalypt forests in north-central Portugal [16]. Moreover, ref. [17] have reported the good efficacy of bark strands and straw mulching applied in a heathland of north-western Spain for erosion control and vegetation recovery. Additionally, the microbial communities are affected by the post-fire soil changes [4,10,18] with consequent modification in organic matter and nutrient cycling [19].

Every year, local administrations make great efforts to limit the risk of wildfire, adopting diverse prevention strategies with varying effectiveness. To limit these changes in burnt forest soils and protect soil from degradation in wildfire-affected areas, forest managers apply post-fire management techniques, whose suitability and effectiveness depend on many factors (soil, weather patterns, and fire severity) [20,21]. Among these post-fire actions, mulching is by far the most cost-effective action, since the mulch cover can control soil hydrology from burnt forests [15,22] and accelerate plant regeneration after fires [23–25]. Often, soil mulching after a wildfire is combined with salvage logging, which recovers timber from burnt forests [26], and secondarily reduces the wildfire risk (for instance, by creating contour-felled debris logs, removing flammable dead fuels, and altering fuel trajectories [27–29]). Generally speaking, soil mulching has beneficial effects on burnt forests, since this technique is particularly effective to counteract soil erosion (e.g., [17,30–32]). However, some impacts of soil mulching can be negative: for instance, the mulch material can be displaced by the wind, leaving some forest areas bare and accumulating in other sites with consequent constraints for vegetation regeneration [33,34]. Furthermore, some examples of the low effectiveness of mulching against erosion control are reported in the literature (e.g., [35–37]). Additionally, salvage logging may have negative effects on burnt and treated soils. For instance, the heavy machinery that drags the trunks over the burnt soil exerts high pressure on skid tracks which compacts the forest soils [38,39]. This compaction on one side disturbs forest vegetation by decreasing regeneration [40] and on the other side reduces water infiltration [41–43] with consequent increases in surface runoff and soil loss [43,44].

Despite the ample and eminent literature in recent decades (e.g., [43–49]), the contrasting effects of post-fire mulching and salvage logging require more investigation, especially in Mediterranean forests where these impacts have been poorly studied [49,50]. Some open research questions that are still open are the effects of these post-fire management actions on the changes in the physico-chemical properties of the soil. The effects of fire on these properties have been investigated by a plethora of studies carried out in different environmental conditions. In contrast, the studies that have evaluated the post-fire changes in soil chemistry in soils affected by wildfires and subjected to post-fire treatments are much fewer, especially in the Mediterranean ecosystems [51] and after much time from the fire. More specifically, while it is well known that soil mulching with vegetal residues (straw, woodchips, strands, and so on) can act as a new source of organic material to be incorporated into the soil, few studies have analysed the influence of soil mulching on those properties in the midterm. Furthermore, it is still not clear how much salvage logging after wildfires may affect the soil's physico-chemical properties of forest ecosystems many years after its application. Finally, to the authors' best knowledge, no studies have evaluated the soil changes after combinations of soil mulching and salvage logging after wildfires in Mediterranean forests. In other words, there is no certainty whether these combined impacts are synergistic (with improvements in the quality of wildfire-affected sites) or, in contrast, can increase the degradation of burnt forest soils, especially at a distant time from the fire.

To fill this gap, this study investigates the effects of post-fire straw mulching and salvage logging, applied individually or in combination, on the physico-chemical properties of soil in a burnt forest of *Pinus halepensis* Mill. of central-eastern Spain six years after the fire. The research questions will investigate (i) which soil properties are more affected by changes due to the post-fire management techniques, (ii) and whether straw mulching and salvage logging are able to discriminate the treated soils in comparison to the unburned sites in terms of their main properties. This study should support the tasks of land managers towards the conservation of the Mediterranean forest ecosystems against the negative impacts of high-severity fires.

2. Materials and Methods

2.1. Study Area

The study site was selected 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 site elevation ranges between 520 and 770 m, and its aspect is W-SW. The forest is located in the meso-Mediterranean bioclimatic belt [52], whose climate is a semi-arid BSk type according to the Köppen classification [53]. According to the weather data collected between 1990 and 2014 (source: Spanish Meteorological Agency), the mean annual temperature is 16.6 °C, and the mean annual precipitation is 321 mm. The maximum monthly rainfall is 44.5 mm (October) and the minimum is 39.6 mm (May). From June to September, the weather is hot and dry with a relative air humidity lower than 50%. According to the soil taxonomy classification, soils are Inceptisols and Aridisols with a sandy-loam texture [54] and a depth that is lower than 30 cm. Vegetation consists of a tree cover of Aleppo pine (*Pinus halepensis* Mill.) and a shrub layer of kermes oak (*Quercus cocciferae*) [55]. In the study site, the mean density of the forest was about 500–650 trees/ha, and its height was in the range of 7 to 14 m before the wildfire. *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. are the main shrubs and herbaceous species.

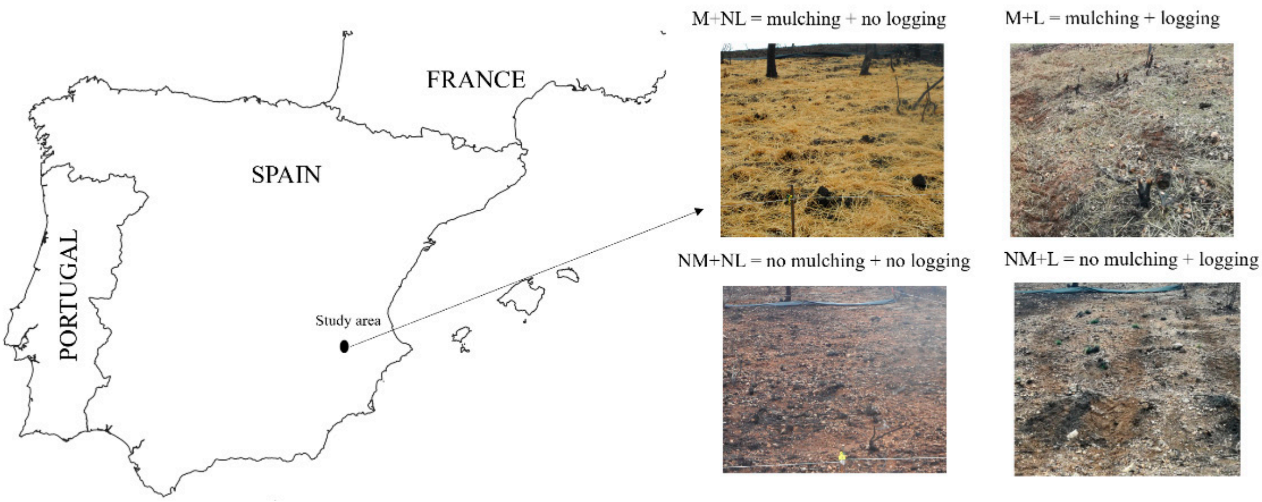


Figure 1. Geographical location of the study area (Sierra de las Quebradas forest, Castilla-La Mancha, central-eastern Spain). Mulching and logging operations.

In July 2016, over 800 ha of land in the Sierra de las Quebradas forest was burned by a wildfire. Mulching was applied to part of the burnt area on 26 September 2016, spreading barley (*Hordeum vulgare* L.) straw, which was cut in a close farm, at a rate of 0.2 kg/m^2 (dry weight) and a depth of 3 cm. This dose was proposed by [56] to achieve a soil cover of over 80% in northern Spain.

Salvage logging was carried out in a part of the burnt area partially overlying the mulched area on 11 December 2016. An agricultural adapted tractor with herringbone-tyre pneumatic rubber agricultural wheels (tyre size 18.4R30) was used at a working speed between 6 and 8 km/h. The tractor was a 4-cylinder Landini DT9880 with a rated power of 69.2 kW and a total weight of approx. 4700 kg. Trees were cut with mechanical chainsaws, and burnt logs were removed on the same day (Figure 1).

2.2. Experimental Design

Immediately after the wildfire, a site of about 2 ha totally covered by Aleppo pine and affected by crown fire (tree mortality of 100%) was selected (Figure 1). The plant density in this forest was 500–650 trees/ha. The plant height and diameter were 7–14 m and 25–35 cm, respectively [15,19,57].

Sixteen plots with a rectangular shape (10 m × 10 m) and an area of 100 m^2 were randomly located in this burnt site at a reciprocal distance higher than 200 m. Plots were distributed by selecting certain site characteristics, slopes, and aspects to ensure comparability. Using the methodology proposed by [58,59], soil burn severity was high in all plots.

Of the 16 plots, 4 were mulched and logged (hereafter indicated as "M + L"), 4 were mulched and not logged ("M + NL"), 4 logged and not mulched ("NM + L"), and the remaining 4 plots were not logged and not mulched ("NM + NL"). Therefore, the experimental design consisted of four soil conditions (mulching + logging, non-mulching + logging, non-mulching + non-logging, and mulching + non-logging).

2.3. Soil Sampling and Physico-Chemical Analysis

A composite sample of 600 g was collected at a depth of 10 cm from the soil of each of the 16 plots in June 2022, 6 years after the wildfire. Each sample was made up of six 100-g sub-samples collected in as many randomly selected points (reciprocal distance over 5 m), to capture the potential variability of soil conditions within the plots. Before sampling, the litter layer was removed. After collection, each soil sample was passed through a 2 mm sieve and stored at 4 °C. The day after collection, the following physico-chemical properties of each soil sample were analysed. Among the physical properties, the soil texture (contents of sand, silt, and clay) was analysed according to the method of [60]. Regarding the chemical properties, pH and electrical conductivity (EC) were determined in distilled water at a soil:solution ratio of 1:2.5 by a multiparameter portable device (Hanna Instruments® model HI2040-02, Gipuzkoa, Spain). Organic matter content (OM) was measured by the potassium dichromate oxidation method [61]. Total nitrogen (TN) was determined using Kjeldhal's method as modified by [62]. Total nitrogen (TN) was determined using the Kjeldahl method [63]. Although this method measures organic and ammonia nitrogen, the low presence of nitrites (unstable forms of nitrogen, since these compounds are easily oxidised to nitrates) and nitrates (generally leached into the deeper layers of soil), their concentrations should be very low in the topsoil, and therefore negligible. Moreover, this does not alter the differences in nitrogen among the different land conditions and fire severities investigated in this study. The C/N ratio was obtained by dividing the organic carbon (calculated by multiplying the OM by 0.58) by the total nitrogen. Available nitrate nitrogen ($N\text{-}NO_3$) was measured by the method described by Keeney and Nelson [64]. The contents of total phosphorous (TP) and cations (potassium, K^+, calcium, Ca^{2+}, and magnesium, Mg^{2+}) were determined by ICP spectrometry after nitric-perchloric acid digestion [65]. Chloride (Cl^-) content was determined following the procedures reported in [66]. Sulphates ($SO_4{}^{2-}$) were measured according to the methods by [67]. Carbonates ($CO_3{}^-$) and calcium carbonate contents of limestone ($CaCO_3{}^-$) were analysed using the methods from [68] and [69], respectively.

2.4. Statistical Analyses

A one-way ANOVA was applied to the physico-chemical properties of the soil samples (considered as dependent or response variables) to evaluate the statistical significance of the differences among the four treatments (M + L, NM + L, M + NL, and NM + NL). The pairwise comparison by LSD test (at $p < 0.05$) was also used. In order to satisfy the assumptions of equality of variance and normal distribution, the data were square root-transformed when necessary. The statistical analysis was carried out using XLSTAT release 19.1 software.

3. Results

The soil texture was similar among the four soil conditions, and the differences in the contents of sand, silt, and clay were not significant (F < 0.212, $p > 0.084$). On average, the experimental soils contained 39.4 ± 1.7% of sand, 39.7 ± 1.4% of silt, and 21 ± 1.1% of clay (Figure 2a).

The differences in pH and EC were also not significant (F = 2.463, $p = 0.113$ for pH, and F = 0.716, $p = 0.561$ for EC). The pH was higher in M + L plots (8.2 ± 0.01) and lower in M + NL soils (8.05 ± 0.06), while the EC was in the range 0.49 ± 0.01 mmhos/cm (M + L plots) to 0.56 ± 0.02 (NM + NL soils) (Figure 2b).

Soil OM was significantly different among the soil treatments, as shown by the ANOVA results (F = 5.623, $p = 0.012$). The highest OM content was measured in the M + NL soils (9.85 ± 0.40%), while the lowest value was found in NM + NL plots (6.29 ± 1.14%) (Figure 2c). In contrast, no significant differences in the TN content were noticed, with the M + NL (0.31 ± 0.01%) and M + L and NM + NL (0.23 ± 0.025% for both) soils showing the maximum and minimum values, respectively (Figure 2d). Given the significant changes in the OM content of soils, the differences in the C/N were also significant (F = 4.012, $p = 0.034$). As noticed for OM, the lowest ratio was measured in NM + NL soils (15.6 ± 0.84), while the maximum was noticed in M + NL plots (18.3 ± 0.53) (Figure 2c).

The nitrate content did not follow the TN gradient among the different soil treatments, but the differences were not significant (F = 1.249, $p = 0.336$); however, the differences in the mean values were noticeable (from 0.06 ± 0.06 ppm, NM + L plots, to 5.71 ± 4.55 ppm, NM + NL soils) (Figure 2d).

While the differences in K content among the four treatments were not significant, F = 1.785, $p = 0.204$ (with this parameter being in the range 0.80 ± 0.06 meq/100 g, NM + L plots, to 1.06 ± 0.03 meq/100 g, M + NL soils), significant changes in soil P were detected (F = 3.593, $p = 0.046$). In more detail, the M + NL soils showed the maximum value (14 ± 1.27 ppm), while the lowest P was measured in the M + L soils (5.04 ± 1.05 ppm) (Figure 2e).

No differences in cation contents were revealed by the ANOVA (F > 0.274, $p > 0.245$). More specifically, the M + NL soils showed the highest Ca^{2+} (58.9 ± 0.52 meq/100 g) and Mg^{2+} (6.42 ± 0.34 meq/100 g) contents, while the lowest values of these parameters were measured in the M + L plots (55.1 ± 1.01 and 5.16 ± 0.85 meq/100 g, respectively). The minimum Na^{+} content was found in NM + L and M + L (0.04 ± 0.01 meq/100 g) plots, while the NM + NL soils showed the highest value (0.06 ± 0.02 meq/100 g) (Figure 2f).

Additionally, for anion contents of the soil, no significant differences were detected among the four treatments (F = 1.812, $p = 0.199$ for Cl^{-}, and F = 1.695, $p = 0.221$ for SO_4^{2-}). The lowest values for these parameters (25.7 ± 4.11 ppm for Cl^{-} and 17.5 ± 0.93 meq/100 g for SO_4^{2-}) were measured in the M + L soils, while the M + NL (44.7 ± 1.53 ppm for Cl^{-}) and NM + L (31.9 ± 6.37 meq/100 g for SO_4^{2-}) plots showed the minimum contents (Figure 2g).

The differences in soil carbonates were significant among the four treatments (F = 9.063, $p = 0.002$), but not for active limestone (F = 2.455, $p = 0.113$). The NM + NL soils showed the highest content of CO_3^{2-} (80.5 ± 2.75%) and AL (11.7 ± 0.80%), while these soil parameters were the lowest in M + L (69.6 ± 0.95%, CO_3^{2-}) and NM + L (9.71 ± 0.34%, AL) plots (Figure 3).

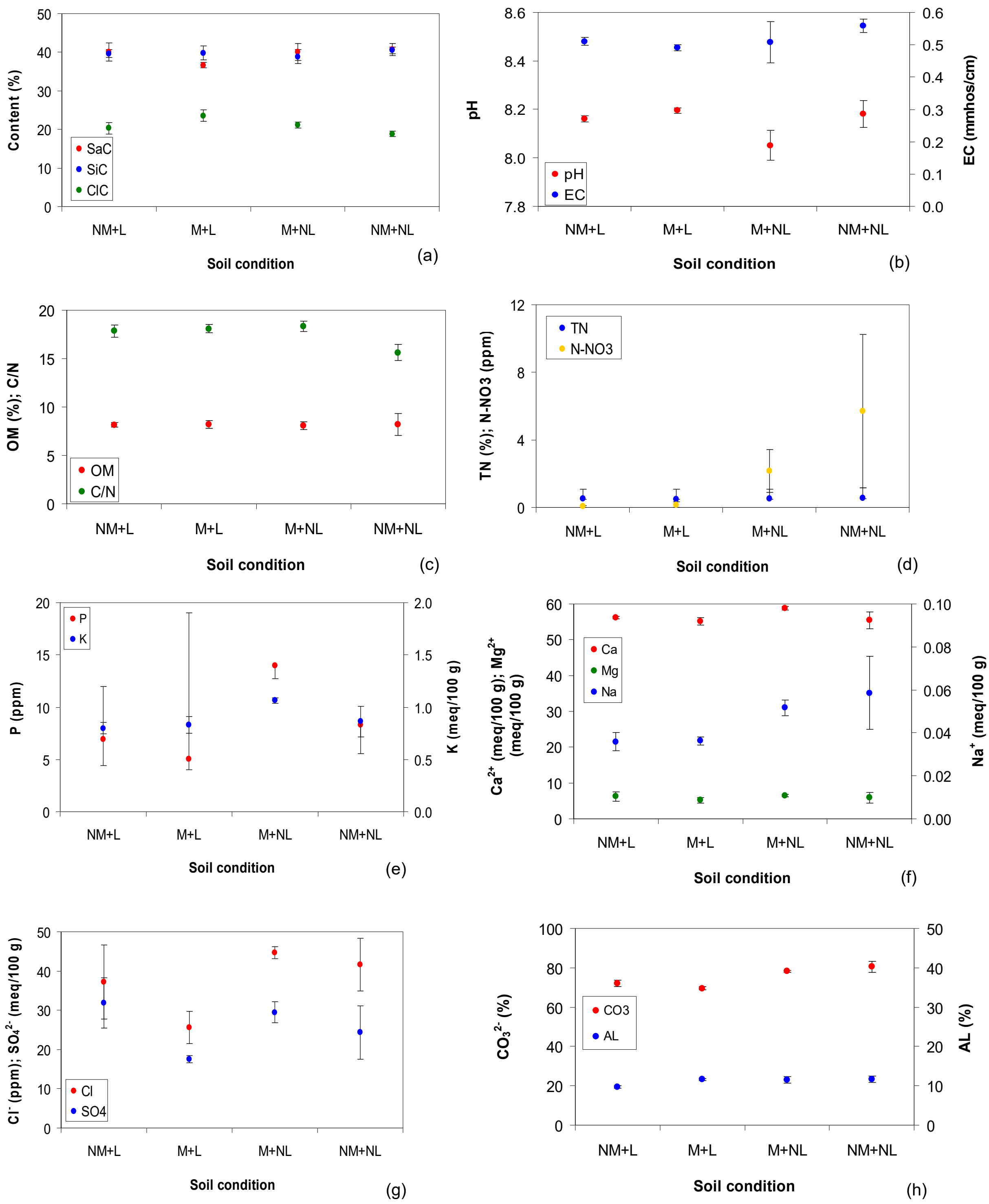
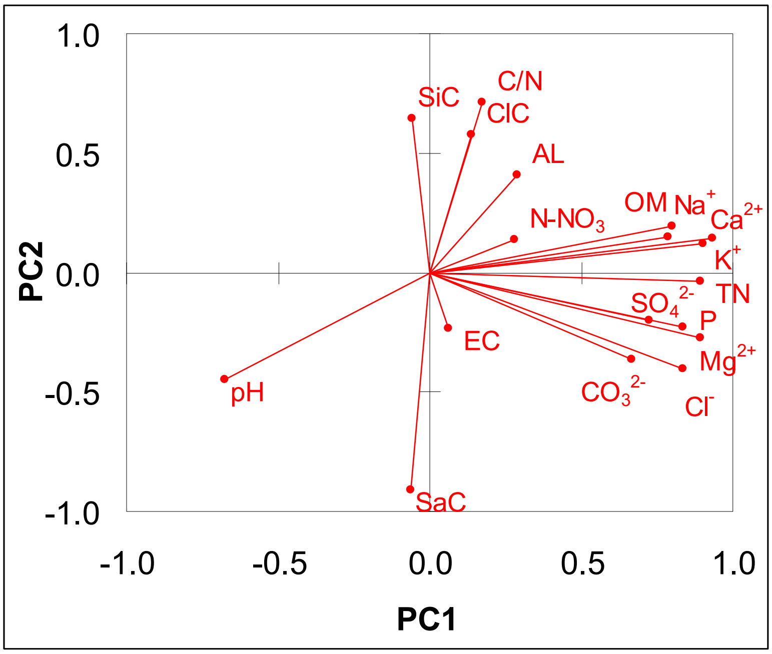
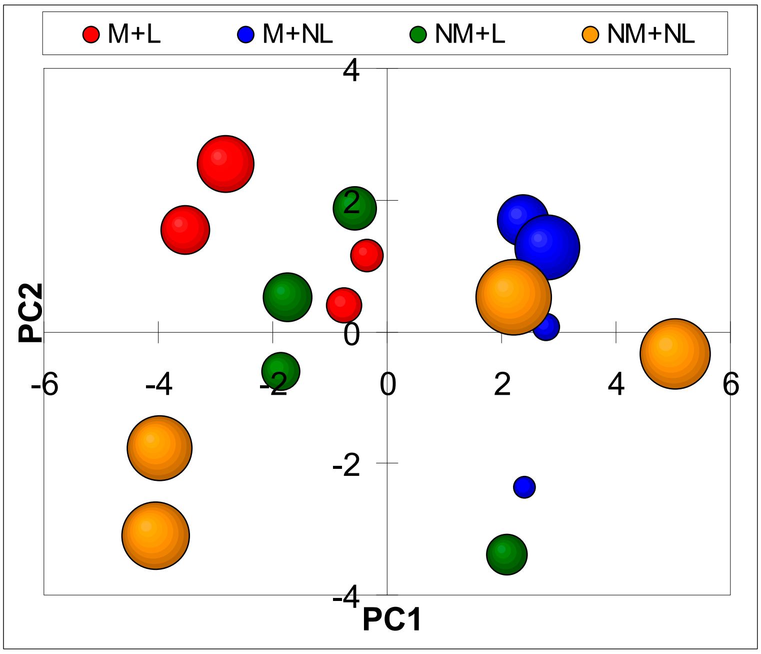


Figure 2. Main chemical properties of soils (mean ± standard error) supporting growth of *Pinus halepensis* Mill. in plots subjected to four treatments in Sierra de Los Donceles forest (Liétor, Castilla La Mancha, Spain). Legend: M + L = mulching + logging; NM + L = no mulching + logging; NM + NL = no mulching + no logging; M + NL = mulching + no logging; (**a**) SaC = sand content; SiC = silt content; ClC = Clay content; (**b**) EC = electrical conductivity; pH; (**c**) OM = organic matter; C/N = Carbon to nitrogen ratio; (**d**) TN = total nitrogen; N-NO_3 = nitric nitrogen; (**e**) P = phosphorous; K^+ = potassium; (**f**) Na^+ = sodium; Ca^{2+} = calcium; Mg^{2+} = magnesium; (**g**) Cl^- = chloride; SO_4^{2-} = sulphates; (**h**) CO_3^{2-} = carbonates; AL = active limestone.



(**a**)



(**b**)

Figure 3. Loadings of the original variables (main chemical properties of soils) (**a**), and their scores on the first two Principal Components (PC1 and PC2) provided by PCA, applied to observations of the growth of *Pinus halepensis* Mill. in plots subjected to four treatments in the Sierra de Los Donceles forest (Liétor, Castilla La Mancha, Spain). In chart (**b**), the area of circles is proportional to the values of PC3. Legend: M + L = mulching + logging; NM + L = no mulching + logging; NM + NL = no mulching + no logging; M + NL = mulching + no logging; SaC = sand content; SiC = silt content; ClC = Clay content; EC = electrical conductivity; OM = organic matter; C = carbon; TN = total nitrogen; N-NO_3 = nitric nitrogen; P = phosphorous; K^+ = potassium; Na^+ = sodium; Ca^{2+} = calcium; Mg^{2+} = magnesium; Cl^- = chloride; $SO_4{}^{2-}$ = sulphates; $CO_3{}^{2-}$ = carbonates; AL = active limestone.

PCA provided three principal components, which together explain 72.9% of the variance of the original variables. The first two components individually explain 42.2% and 17.1%, respectively, of this variance.

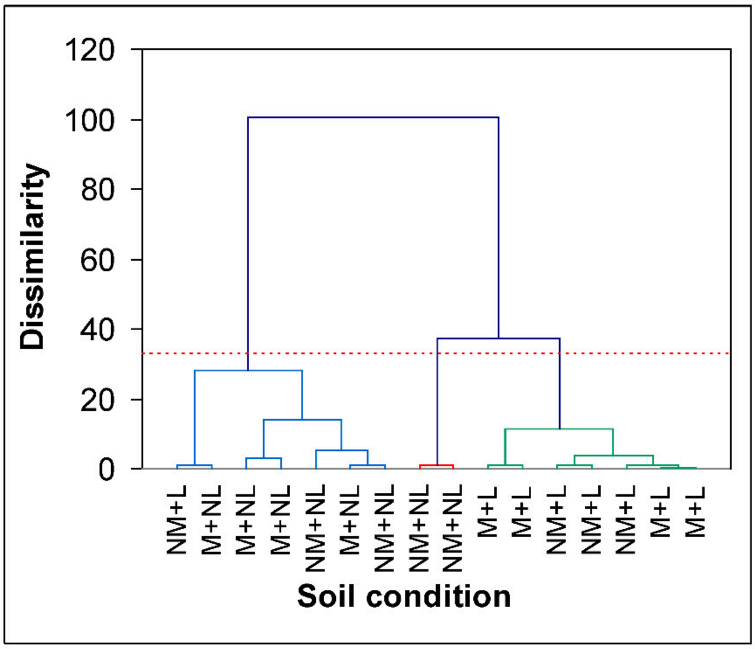
In more detail, the majority of soil properties—all cations and anions, OM and nutrients, and pH—had higher loadings (>0.45) on PC1, while the soil texture (loading over 0.33) and C/N ratio (0.51) had higher loadings on the second PC. EC and N-NO_3 influenced the third with loadings of 0.25 and 0.34, respectively. These loadings are always positive, except those of pH on PC1 and SaC on PC2 (Table 1 and Figure 3).

Table 1. Factor loadings of the original variables (main chemical properties of soils) on the first three Principal Components (PC1, PC2, and PC3) provided by PCA, applied to observations of the growth of *Pinus halepensis* Mill. in plots subjected to four treatments in the Sierra de Los Donceles forest (Liétor, Castilla La Mancha, Spain). Legend: SaC = sand content; SiC = silt content; ClC = Clay content; EC = electrical conductivity; OM = organic matter; C = carbon; TN = total nitrogen; N-NO_3 = nitric nitrogen; P = phosphorous; K^+ = potassium; Na^+ = sodium; Ca^{2+} = calcium; Mg^{2+} = magnesium; Cl^- = chloride; SO_4^{2-} = sulphates; CO_3^{2-} = carbonates; AL = active limestone.

	Principal Component		
	PC1	**PC2**	**PC3**
SaC	−0.062	**−0.910**	−0.117
SiC	−0.059	**0.646**	0.616
ClC	0.140	**0.575**	−0.445
pH	**−0.675**	−0.448	−0.144
EC	0.063	−0.236	**0.501**
OM	**0.799**	0.195	−0.398
TN	**0.894**	−0.037	−0.304
C/N	0.175	**0.713**	−0.402
N-NO_3	0.282	0.139	**0.585**
P	**0.894**	−0.271	−0.145
K^+	**0.903**	0.122	−0.112
Na^+	**0.786**	0.151	0.536
Ca^{2+}	**0.933**	0.145	−0.203
Mg^{2+}	**0.835**	−0.226	−0.135
Cl^-	**0.836**	−0.403	0.151
SO_4^{2-}	**0.726**	−0.198	0.000
CO_3^{2-}	**0.669**	−0.366	0.453
AL	0.291	0.406	0.482

Note: Values in bold correspond for each variable to the factor for which the loading is the largest.

The PCA coupled with AHCA allowed the soil samples to be clustered according to the post-fire treatments. More specifically, three clusters of soil samples were evident. More specifically, all M + L and M + NL soil samples were grouped in two separate clusters (no. 1 and 2). Almost all the NM + L samples fall in cluster no. 1, except one that was included in cluster no. 2. The NM + NL samples were partly in this cluster and partly in a third cluster (Figure 4).



Cluster	1	2	3
	NM + L	NM + L	NM + NL
	NM + L	M + NL	NM + NL
	NM + L	M + NL	
Plots	M + L	M + NL	
	M + L	M + NL	
	M + L	NM + NL	
	M + L	NM + NL	

Figure 4. Dendrogram of the original variables (main chemical properties of soils) and cluster compositions provided by the Agglomerative Hierarchical Cluster Analysis (AHCA) applied to observations of the growth of *Pinus halepensis* Mill. in plots subjected to four treatments in the Sierra de Los Donceles forest (Liétor, Castilla La Mancha, Spain); the *y*-axis of the dendrogram reports the similarity level, while the red dotted line reports the clustering level. Legend: M + L = mulching + logging; NM + L = no mulching + logging; NM + NL = no mulching + no logging; M + NL = mulching + no logging.

4. Discussion

4.1. Effects of Straw Mulching

Abundant literature has shown the effectiveness of straw mulching in limiting the negative impacts of wildfire on surface runoff and erosion in Mediterranean forests [17,32,36]. The mulch material is incorporated over time, and this influences the physico-chemical properties of the treated soils. This study has shown that the effects of this post-fire management technique are different from the analysed properties. In more detail, mulching did not alter the soil texture or many chemical properties, such as the pH, EC, TN, K, and ions, since the measurements performed in the M + NL plots were not significantly different compared to the NM + NL soils. In contrast, mulching increased the OM and P contents of soils by 57% and 69%. Quite surprisingly, the TN content was not affected by the treatment. The increases in OM and an important nutrient, such as phosphorous, are beneficial for the overall soil quality, considering their influence on plant growth and other soil processes such as water retention, nutrient exchange, and soil structure [70,71]. Moreover, the supply of OM with mulch material did not affect the concentration of carbonates, which was similar to the untreated plots. These increases in OM agree with the results of other authors who have investigated the changes in soil properties after straw mulching. For instance, refs. [19,31] reported higher OM content after soil mulching with straw compared to non-mulched sites, although these investigations were carried out in the short term. OM increases in burned and mulched soils were also reported by [72] two years after the wildfire and treatment with logging residues. Mulching supplies organic residues that decompose into the soil early [73,74] and promotes interaction with the nutrients, improving the soil structure and the organic matter content [30,74]. Moreover, the straw supplied with mulching would most likely exhibit nitrogen immobilisation, mainly from the lower concentrations of recalcitrant carbon compounds, which are more easily decomposed [75]. The non-significant influence of straw mulching on soil TN is quite surprising, since an increase in OM in the soil is often linked to similar accumulation in TN and other nutrients, due to mulch incorporation and decomposition [74]. However, after burning, a part of organic nitrogen decreases due to volatilisation [10,76,77] when soil temperatures exceed 200 °C [78]. It may be possible that the nitrogen supply deriving from the OM decomposition due to mulch material incorporation was balanced by the losses of volatilisation, resulting in non-significant variations in TN compared to the untreated soils. However, the literature shows that the effects of forest fires on soil nitrogen are contradictory and are hard to understand [9]. In line with this study, in the same environment, ref. [19] also found non-significant differences in TN content in burned plots (logged or non-logged), while, in another experiment, these authors demonstrated significant increases in TN content after wildfires, with or without the mulching treatment. The noticeable changes in OM dynamics played an evident and significant effect on the C/N ratio, which increased in M + NL sites compared to the NM + NL plots by over 15%. This ratio is in close linkage with OM decomposition and N mineralisation [79]. Other studies have shown that, in burned pine forests, after the initial C/N drop caused by fire and owing to recalcitrant N accumulation and volatilisation of C compounds immediately after the fire [80], the C/N ratio gradually recovers its pre-fire values [81].

4.2. Effects of Salvage Logging

Salvage logging did not affect almost all soil properties in comparison to the non-treated soils. Despite the pressure of the machinery exerted on the soils, no significant changes in soil texture were evident, and the same was noticed for the other chemical properties. However, as pointed out for straw mulching, an increase in OM (+27%) and a decrease in P (−17%) contents were measured in the NM + L soils compared to the NM + NL plots, although these variations were not significant, and the same was noticed for C/N (+14%). The residual dead wood can be provided nutrients during decomposition and it can also have retained organic matter [82]. Only a significant decrease in carbonate concentration (−10%) was measured compared to the untreated soils. These results indicate that this post-fire management practice did not significantly alter the soil properties, and, therefore, no negative impacts on quality may lead to the degradation of forest soils. These impacts may be possible at first sight, since the soil compaction due to machinery, especially on skid tracks, may reduce the oxygen entry into the surface soils, with consequent alteration of the carbon and nutrient cycling on burned forests. Our results are in line with other experiences about the effects of post-fire management on forest soils, carried out in the same or similar environments. For instance, ref. [83] did not find significant increases in the OM content of soils subjected to logging in the burned pine forests of central-eastern Spain.

4.3. Effects of Straw Mulching and Salvage Logging

It is interesting to evaluate the changes in the above-mentioned physico-chemical properties of soils subjected to both straw mulching and salvage logging, in order to establish whether the significant effects separately exerted by each technique are additive or not in the case of the combined application of both. In this regard, the increase in OM measured in M + L plots (+13%) was much lower compared to M + NL and NM + L soils, while the change in phosphorous soil (−39%) was a negative effect, which was even more impactful compared to the soils subjected to salvage logging alone. In contrast, the C/N ratio was practically not affected by the variability of OM and TN (+16% compared to NM + NL plots). These results highlight that each soil property shows its own sensitivity to post-fire management techniques and that the combination of straw mulching and salvage logging may be detrimental for soil quality in some cases. In [83], the authors found increases in OM content after wildfire and salvage logging but in the short term. The authors ascribed these increases to the accumulation of ash, which contains carbon and other nutrients from burned forest fuel [3,78]. In [84], the authors reported reductions in OM and TN four years after salvage logging in wildfire-affected areas, and the same was observed by [85] in the same observation period. Other studies have highlighted decreases in OM [46,86] and TN [46] in burned and logged soils in two-year monitoring studies. The medium-term reduction in OM content was attributed to the incorporation of burned material in the deep soil, the plant uptake due to regeneration, and to the disturbance due to heavy machinery in post-fire management [84,86,87]. In contrast, in our study, the amount of burned material removed was high and the weight of logging machinery was low, and these may be the reason for the slight but significant increase in OM detected in the experiment. The joint analysis of the studied soil properties using the techniques of multivariate statistics confirms that the effects of salvage logging after straw mulching did not sharply discriminate the soils subjected to the individual post-management techniques or their combination. In other words, it is true that straw mulching and salvage logging alter some important chemical properties of burned soils, such as OM and P. However, according to the AHCA coupled to PCA, the overlapping of these clusters is noticeable. It is worth noticing that the effects of salvage logging on soil properties appear to be more impactful compared to straw mulching. This statement can be demonstrated by the fact that, in the soil of mulched sites, the samples collected in logged (M + L) and non-logged (M + NL) plots fall in two separate clusters without overlay. This discrimination can be also observed for non-mulched sites, albeit with a lower level. Under this soil condition, five of the eight soil samples collected in burned areas without any mulching treatment (three in NM + L soils and two in NM + NL) are grouped in separate clusters, while three samples show a similarity among physico-chemical soil properties since these samples are clustered together.

5. Conclusions

The study has demonstrated that six years after a wildfire in a pine forest of central-eastern Spain, organic matter, phosphorous, and carbonate contents of the burned soils as well as their C/N ratio are the soil properties that are more affected by post-fire straw mulching and salvage logging. In contrast, the texture and other chemical properties (pH, electrical conductivity, total nitrogen, potassium, cations/anions, and active limestone) of the soils are less influenced by these post-fire management techniques.

PCA and AHCA applied to the soil samples collected under the individual and combined management quantitatively showed that the effects of salvage logging after straw mulching did not sharply discriminate the soils subjected to the individual post-management techniques or their combination.

Overall, these results highlight that each soil property shows its own sensitivity to post-fire management techniques and that the combination of straw mulching and salvage logging may be detrimental to soil quality in some cases.

This means that forest managers should be aware of the soil changes exerted by each post-fire management technique, carrying out a proper control of significant indicators of soil quality, in order to reduce soil degradation due to wildfires and the possible adverse effects of post-fire management.

Overall, although this study contributes to the knowledge of the effects of two common post-fire management techniques in Mediterranean forest soils, we think that this investigation is not exhaustive, since the monitoring of the soil properties affected by wildfire and post-fire management techniques should be extended over time until the end of the so-called "windows of disturbance", which may also last several years or even one decade. Moreover, some research issues are still open, such as the influence of post-fire management on hillslopes with different morphological characteristics (e.g., slope and aspect, which can significantly drive some soil processes), and on key properties, such as those related to soil functionality (e.g., enzymatic activities, microbial communities, and water availability), which noticeably weigh on the conservation of these delicate ecosystems against the negative impacts of high-severity fires.

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