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Short-term effects of post-fire mulching with straw and wood chips on soil properties in semi-arid forests

Manuel Esteban Lucas Borja[1] and Demetrio Antonio Zema[2,*]

[1] *Department of Agroforestry Technology, Science and Genetics, School of Advanced Agricultural and Forestry Engineering, Campus Universitario s/n, Castilla La Mancha University, E-02071 Albacete, Spain*

[2] *Department AGRARIA, "Mediterranea" University of Reggio Calabria, Località Feo di Vito, I-89122 Reggio Calabria, Italy*

* Corresponding author, dzema@unirc.it

Abstract

Few studies have compared the variability of the soil properties after using mulches of different types in semi-arid forests. To fill this gap, this investigation has evaluated the changes in physico-chemical soil properties in a semi-arid forest of Central Eastern Spain, where straw and wood chips (of pine species) were distributed on the soil as mulch cover three months after a wildfire. Soil have been sampled under burned and untreated, and burned and mulched plots at three and nine months after the treatments. The data was processed using the Principal Component Analysis (PCA) and Analytical Hierarchical Cluster Analysis (AHCA). Mulching with straw or wood chips did not play significant effects on the texture and chemical properties of burned but untreated sites few months after the treatment. In contrast, significant changes may be expected over time in organic matter, some nutrients and many ions. No significant differences were detected in all soil properties between the two mulches. These low changes were confirmed by PCA coupled with AHCA, which did not show a clear discrimination among the three soil conditions. However, a noticeable and significant variability of many of these properties over time is evident. This study shows that mulching does not result in degradation of soil properties in the short-term after a wildfire and post-fire treatments, and thus helps land managers to protect the semi-arid forest ecosystems against the negative impacts of high-severity fires.

Keywords: post-fire management; high-severity fire; Aridisols; erosion; vegetal residues incorporation; soil degradation.

1. Introduction

The effects of wildfires are particularly severe in the semi-arid forests (Shakesby 2011; Wagenbrenner et al. 2021), due to specific characteristics of climate (hot and dry seasons that increase the fire risk in these areas) and the intrinsic properties of soils (generally shallow and poor in organic matter and nutrients) (Cantón et al. 2011). The severe impacts of wildfires on Mediterranean forests result in increased losses of soil and biodiversity compared to other environments (Lindenmayer and Noss 2006; Moody et al. 2013). These impacts, which are associated to the removal of vegetation and changes in many physico-chemical properties of soils, generate new sources of physico-chemical and biological inputs into the soil system in the form of charcoal, organic distillates, metal oxides and plant litter (Garrido-Ruiz et al. 2022). After a high-severity fire, the vegetation almost totally burns, leaving the soil bare and thus exposed to surface runoff and erosion (Shakesby and Doerr 2006; Bodí et al. 2012). Ash is released with modifications in ion contents of the soil after rainfall leaching (Zavala et al. 2009; Pereira et al. 2018). Severe heating causes hydrophobicity, except in areas burned by wildfires with very low or extremely high severity (Pereira et al. 2018). This alters the contents of organic matter and nutrients (Certini 2005; Zavala et al. 2014) and causes changes in bulk density, porosity, aggregate stability and texture (Carrión-Paladines et al. 2022). The recovery of the pre-fire conditions of burned forest may require several years and, in case of very high burn severity, some decades (Certini 2005).

To accelerate the vegetation restoration and recovery of pre-fire soil properties in severely-burned sites, forest managers adopt targeted management actions both on hillslopes and in channels draining the fire-affected catchments (Robichaud et al. 2010). Mulching, one of the most common hillslope-scale actions in burned forests (Fernández and Vega 2016), is carried out by applying vegetation residues to protect the burned soil from the erosion and to favour plant regrowth (Prats et al. 2012; Prosdocimi et al. 2016). However, some studies have reported adverse effects of post-fire soil mulching. For instance, Lucas-Borja et al. (2018) have demonstrated that mulching can decrease infiltration in burned soils. Fernández-Fernández et al. (2016) have shown that straw application cannot be effective at reducing soil erosion after moderate precipitations. (Fernández et al. 2012) have demonstrated that mulching coupled with seeding do not significantly increase soil cover or affect runoff and infiltration. This means that the mulching impacts on soils depend on the environmental conditions of each site.

The effects of mulching on the hydrological, physico-chemical and biological properties of soils in burned forests have been widely investigated (Alcañiz et al. 2018; Girona-García et al. 2021).

However, many studies report contrasting impacts of both fire and post-fire management on the changes in soil properties (Fernández and Vega 2016; Lucas-Borja et al. 2018; Carra et al. 2021). Furthermore, these effects have been less studied in relation to the different mulch materials (straw, forest residues, chemical products). The majority of studies have focused on the use of agricultural straw, which is the most common mulch material in burned forests, showing in general beneficial effects on both soil hydrology and functionality (Hernández et al. 1997; Zavala et al. 2009). It is well known that straw residues applied with mulching are a source of organic material to be incorporated into the soil, increasing the contents of organic matter and nutrients (Prosdocimi et al. 2016). However, straw can be displaced by wind, leaving the burned soils bare in some areas, and accumulating in other sites with obstacles to seedling recruitment (Robichaud et al. 2020; Carrà et al. 2021). Forest residues (e.g., pruning, wood chips, strands) are viable but less experimented alternatives to straw mulching, and few studies have explored the impacts of these materials on soil properties.

On this regard, the effects of different vegetal residues applied to burned soils with mulching may be noticeably different, due to their quality, application rates and dimensions (Prosdocimi et al. 2016; Díaz et al. 2022). For instance, the impacts of straw and woody chips should not be the same, since the soil cover, chemical composition and size of these mulches are different. Straw and woodchip application differently modify the soil properties (Díaz et al., 2022). Both mulches alter the contents of organic matter and nutrients, microbial biomass carbon, respiration, enzymatic activities of burned soils (Entry and Emmingham 1998; Bastida et al. 2008), but the magnitudes of these soil alterations are differentiated between the vegetal residues. This depends on the amounts and quality of nutrients and organic matter as well as contents in mineral elements supplied with wood chips or straw to treat soils, and these amounts and quality are variable due to the different decomposition rates to the differential lignin and moisture contents of the mulch materials.

To the authors' best knowledge, no studies are available about the changes in the main chemical properties of burned soils after post-fire mulching with wood chips in comparison to the most widely used straw. A quantitative evaluation of the different soil response to the application of these mulches is essential, in order to measure the effectiveness of these vegetal residues on soil properties with the eventual impacts on its quality and response to any disturbance. This an important research issue, since the impacts of mulching in fire-affected soils may be variable, depending on the fire, soil, vegetation and weather characteristics as well as mulch characteristics (Moody et al. 2013), and this variability requires targeted investigations in specific environments. Due to the number and complexity of impacts of fire and post-fire management on soils, very little guidance is currently available to plan possible countermeasures against soil degradation.

To fill this gap, this study has evaluated the short-term changes in the main physico-chemical properties of forest soils burned by a wildfire and then mulched with straw or wood chips in comparison to burned but untreated soils under semi-arid conditions. To this aim, a case study of a pine forest of Central Eastern Spain has been analysed, where the treatments were implemented three months after the wildfire and the soil changes were monitored three and nine months after mulching. The specific research questions to which this investigation aims at replying are the following: (i) Which soil properties undergo changes after mulching in wildfire-affected areas immediately after treatments and over time compared to untreated areas? (ii) Are these differences significantly dependent on the applied mulch material? The evaluation of the effects of these vegetal materials for mulching should give forest managers indications about the more advisable technique for soil conservation in burned areas under semi-arid conditions.

2. Materials and methods

2.1. Study area

The study area is the Sierra de Los Donceles forest (municipality of Liétor, province of Albacete, region of Castilla-La Mancha, Spain, 38º30’41” N; 1º56’35” W) at an elevation between 520 and 770 m above the mean sea level (Figure 1). The climate is typically semi-arid Mediterranean (BSk type, according to the Köppen classification (Kottek et al. 2006). The mean annual values of temperature and precipitation are equal to 16.6 °C and 321 mm, respectively, from the last 20 years of weather data collected at the meteorological station of Hellín, about 20 km far from Liétor (historical records of the Spanish Meteorological Agency, AEMET). Soils are Calcic Aridisols (Nachtergaele 2001; Department 2014), and their texture is sandy loamy. The studied forest area is exposed to north-west, and its slope is between 15 and 25%.

The dominant overstorey vegetation consists of a tree layer of natural and reforested (about 60-70 years ago) Aleppo pine (*Pinus halepensis* Mill.) and a shrub layer of kermes oak (*Quercus cocciferae*) (Peinado et al. 2008). Before the wildfire, the stand density and tree height were in the range 500 - 650 trees/ha and 7 - 14 m, respectively. The understory vegetation consists of *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 *Plantago albicans* L.

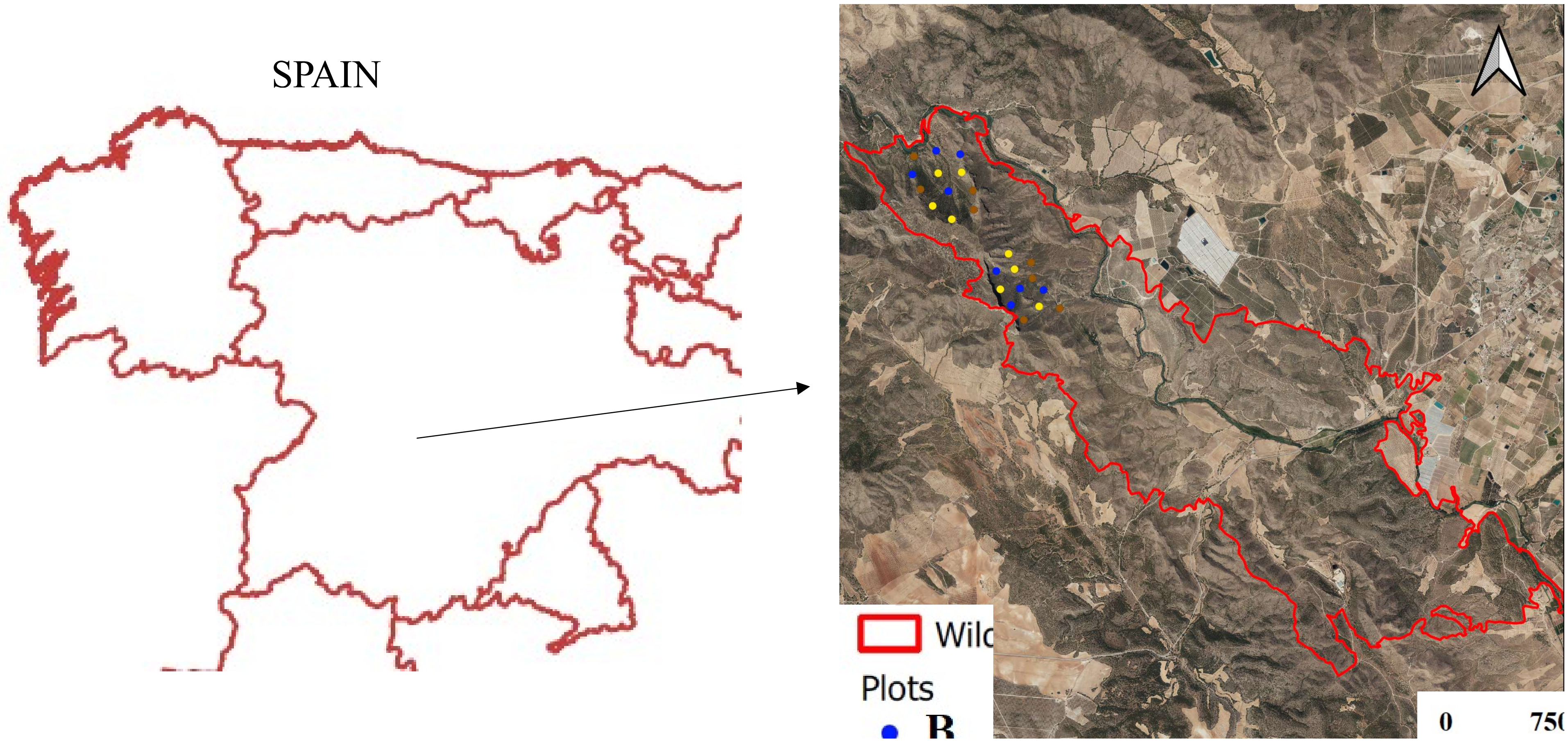


Figure 1 – Geographical location of the study area and location of the 24 experimental plots (Liétor, Castilla La Mancha, Central Eastern Spain).

In July 2021, a wildfire burned about 2500 ha in the studied forest (Figure 1). This fire first burned both ground vegetation and litter as well as tree crowns. Its soil burn severity can be considered as “high”, according to the classification proposed by (Vega et al. 2013), based on some visual indicators to identify the burn severity of soils affected by fires (Parson et al. 2010). In order to limit the expected increases in surface runoff and erosion after the fire, the Forest Service of the Castilla La Mancha Region immediately applied mulches of wheat straw and wood chips to the soils of the burned forest area as post-fire management actions.

2.2. Experimental design

One week after the wildfire, a study area of 700 ha was selected, including both unburned and burned forest soils (the latter affected by crown fire with 100% tree mortality). In this burned area, the Forest Service of Castilla La Mancha region selected sites for mulching with straw or wood chips, with a profile slope between 30.1 ± 3.9% and 48.1 ± 4.7%. The soils of plots were homogenous in term of texture (sandy loam).

In the northern part of the study area, 24 plots (each one being 20-m long x 20-m large, covering 400 m^2) were identified and delimited with red and black ribbon. The minimum reciprocal distance among plots was approximately 250 metres (Figure 1), to avoid pseudo-replication (that is, not statistically independent observations or correlations of measurements in time or space). The 24 experimental plots were different for soil conditions regarding burning and post-fire treatment. Eight plots were burned but not treated, while 16 other plots were mulched in late October 2021 (3 months after the wildfire) with straw (8 plots) or wood chips (8 plots) (Figure 1). The main characteristics of the mulch materials were the following: (i) wood cheap (mean values): species: pine; dose of 0.3 kg/m^2; length: 3-10 cm; width: 2-4 cm; thickness: 1-2 cm; density: 500-550 kg/m^3; (ii) straw (mean values): source: wheat; dose of 2 kg/m^2; length: 5-25 cm; width: 0.25-1.0 cm; thickness: 0.1-0.7 cm; density: 80-100 kg/m^3. These application doses are those suggested by the forest services of the Iberian Peninsula, and widely used in literature (e.g., Girona-García et al. 2021; Kim et al. 2008; Lucas-Borja et al. 2019). Some studies have demonstrated that the values of the soil properties, as modified by mulching, are different with changes in material characteristics, such as dose, length and diameter (e.g., (Rahma et al. 2017; Wang et al. 2022a, b).

During the monitoring campaign (July 2021-July 2022), a total rainfall of 413 mm was observed, and 236 events with depth up to 43.4 mm (March 2022) and maximum 30-minute intensity of 58 mm/h were recorded.

The experimental design consisted of three soil conditions (burned and untreated soil, burned soil mulched with straw, and burned soil mulched with wood chips) × two sampling dates (three and six months after treatment) × eight replicated plots, totalling 24 plots and 48 soil surveys. Since the specific aim of the study was the evaluation of changes in soil properties under burned conditions (i.e., between untreated and treated soils, with one of the two mulch materials), unburned soils were not deliberately analyzed in this study. Hereafter, the three soil conditions will be indicated as "B" for burned soils ("control"), "M(WC)" for soils mulched with wood chips, and "M(WS)" for plots treated with straw mulch. Moreover, the two survey dates will be referred as "three months after treatment" (indicated as "3MAT") and "nine months after treatment" ("9MAT").

2.3. Soil sampling

Soils in each of the 24 plots were sampled at 3MAT (January 2022, 6 months after the wildfire and 3 after post-fire treatments) and 9MAT (July 2022, at 12 and 9 months from fire and mulching, respectively). The first survey date is representative of soil conditions that establish few months after the treatment, when the soil is inevitably disturbed by mulching operations and weather conditions between the material distribution and survey dates (although the decomposition level of the mulch distributed over ground should be low). The soil samples were collected at the same date, in order to achieve the same soil conditions among the burned and untreated plots as well as the sites burned and mulched with the two mulch materials.

Forty-eight samples of 600 g, two samples per plot at each survey date, were collected from the top 10 cm of surface soil. This depth was chosen, due to the high severity of wildfire, which should have released a high heat on the surface layer of the burned soils. The high temperatures of soil, although not directly measured, may have extended to a noticeably deep soil layer (8-10 cm). Moreover, the need to identify the possible leaching effects on the chemical compounds released by mulch materials suggested increasing the sampling depth up to -10 cm. This aim requires exploring not only the soil surface, but also the subsurface layer, in which presumably the compounds that previously accumulated on soil surface may migrate due to infiltration. Each soil sample was made up of six 100-g sub-samples from randomly selected points (at a reciprocal distance higher than 5 m), in order to capture the potential variability of soil conditions within each plot. The litter layer was removed from the soil surface before sampling. Each sample was brought to laboratory, passed through a 2-mm sieve and then stored at 4 °C prior of the subsequent analyses in the following day.

2.4. Analysis of soil properties

The following soil physico-chemical properties were determined on the collected samples:

- texture (contents of sand, silt and clay), according to the method of Guitian Ojea and Carballas (1976);
- pH and electrical conductivity (EC), determined in distilled water, at a soil:solution ratio of 1:2.5 by a multiparameter portable device (Hanna Instruments® model HI2040-02, Gipuzkoa, Spain);
- organic matter content (OM), by the potassium dichromate oxidation method (Nelson and Sommers 1996);
- total nitrogen (TN), using Kjeldhal's method as modified by Mulvaney and Bremner (1978);
- available nitrate nitrogen (N-NO_3), following Keeney and Nelson (Page et al. 1982);
- total phosphorous (TP) and cations (potassium, K^+, calcium, Ca^{2+}, and magnesium, Mg^{2+}), by ICP spectrometry after nitric-perchloric acid digestion;
- chloride (Cl^-), following the procedures reported in Brito et al. (2004);
- sulphates (SO_4^{2-}), according to the methods by Severiche and González (2012);
- carbonates (CO_3^-) and active limestone, using the methods by Ulmer et al. (1992).

The C/N ratio was obtained by dividing the organic carbon (calculated by multiplying the OM by 0.58, (Guo and Gifford 2002; Brady et al. 2008) by TN.

The Kjeldahl method measures organic and ammonia nitrogen. Due 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, as also demonstrated by the results of this study (see below). Therefore, this method is feasible to determine TN.

2.5. Statistical analysis

A 2-way ANOVA was applied to the soil properties (dependent or response variables), in order to evaluate the statistical significance of the differences among soil conditions and survey dates (independent variables or factors), and their interactions. The equality of variance and normal distribution are assumptions of the statistical tests; these assumptions were evaluated by normality tests or were square root-transformed, when necessary. The differences in each soil property among factors were evaluated using the pairwise comparison by Tukey's test (at $p < 0.05$).

Following this, a Principal Component Analysis (PCA) was applied, in order to identify the existence of representative derivative variables (Principal Components, PCs) (Lee Rodgers and Nicewander 1988) and simplify the analysis of the large number of soil properties and conditions, losing as little information as possible. In this study, PCA was carried out by standardising the original variables (expressed by different measuring units) and using Pearson's method to compute the correlation matrix. The first two PCs, explaining at least at least a percentage of 70% of the original variance, were retained.

Finally, the observations were grouped in clusters using Agglomerative Hierarchical Cluster Analysis (AHCA), a distribution-free ordination technique to group samples with similar characteristics by considering an original group of variables. As similarity-dissimilarity measure the Euclidean distance was used (Zema et al. 2015).

The statistical analysis was carried out using the XLSTAT software (release 2019, Addinsoft, Paris, France).

3. RESULTS

According to the two-way ANOVA, soil texture was significantly different over time, but not among the three soil conditions or for the interaction between these factors (Table 1). By averaging the contents among the three conditions, the experimental soils showed contents of sand of 52 ± 3.07% at 3MAT and of 34.1 ± 5.41% at 9MAT, of silt of 30.6 ± 1.56% at 3MAT and of 42.7 ± 3.47% at 9MAT, and of clay of 17.3 ± 1.92% at 3MAT and of 24.1 ± 11.6% at 9MAT (Figure 2).

Table 1 – Results of two-way ANOVA applied to physico-chemical properties of soils collected under three conditions (burned, B, mulched with wood chips, M(WC), and mulched with wheat straw, M(WS)) and two survey dates (at 3MAT and 9MAT) in Liétor (Castilla La Mancha, Central Eastern Spain).

Factor	**Degrees of freedom**	**Sum of squares**	**Mean squares**	**F**	**Pr > F**
	SaC				
Soil condition	2	975	488	1.664	0.202
Time	1	3848	3848	13.13	**0.001**
Soil condition x time	2	964	482	1.644	0.205
	SiC				
Soil condition	2	503	251	2.413	0.102
Time	1	1750	1750	16.80	**<0.0001**
Soil condition x time	2	438	219	2.103	0.135
	ClC				
Soil condition	2	110	54.9	0.545	0.584
Time	1	559	559	5.539	**0.023**
Soil condition x time	2	115	57.6	0.571	0.569
	pH				
Soil condition	2	0.020	0.010	0.665	0.520
Time	1	4.392	4.392	287	< **0.0001**
Soil condition x time	2	0.024	0.012	0.798	0.457
	EC				
Soil condition	2	0.016	0.008	1.233	0.302
Time	1	1.089	1.089	172	< **0.0001**
Soil condition x time	2	0.029	0.014	2.256	0.117
	OM				
Soil condition	2	29.600	14.800	3.078	0.057
Time	1	36.512	36.512	7.592	**0.009**
Soil condition x time	2	10.688	5.344	1.111	0.339
	TN				

Soil condition	2	0.030	0.015	2.731	0.077
Time	1	0.045	0.045	8.359	**0.006**
Soil condition x time	2	0.013	0.007	1.233	0.302
	C/N				
Soil condition	2	175	87.5	2.776	0.074
Time	1	589	589	18.68	**< 0.0001**
Soil condition x time	2	160	80.2	2.546	0.090
	$N\text{-}NO_3$				
Soil condition	2	367	183	1.531	0.228
Time	1	165	165	1.379	0.247
Soil condition x time	2	73.1	36.6	0.305	0.739
	TP				
Soil condition	2	225	113	1.669	0.201
Time	1	123	123	1.826	0.184
Soil condition x time	2	41.1	20.6	0.304	0.739
	K				
Soil condition	2	3.106	1.553	5.939	**0.005**
Time	1	1.510	1.510	5.775	**0.021**
Soil condition x time	2	0.552	0.276	1.055	0.357
	Na^+				
Soil condition	2	0.036	0.018	7.148	**0.002**
Time	1	0.014	0.014	5.559	**0.023**
Soil condition x time	2	0.006	0.003	1.213	0.308
	Ca^{2+}				
Soil condition	2	1484	742	5.314	**0.009**
Time	1	3815	3815	27.31	**< 0.0001**
Soil condition x time	2	1063	532	3.806	**0.030**
	Mg^{2+}				
Soil condition	2	85.7	42.8	6.857	**0.003**
Time	1	55.1	55.1	8.813	**0.005**
Soil condition x time	2	14.5	7.2	1.159	0.324
	Cl^-				

Soil condition	2	1455	727	5.300	**0.009**
Time	1	2618	2618	19.079	**< 0.0001**
Soil condition x time	2	850	425	3.098	0.056
	SO^{2-}_4				
Soil condition	2	479	239	9.012	**0.001**
Time	1	138	138	5.208	**0.028**
Soil condition x time	2	35.7	17.9	0.672	0.516
	CO^{2-}_3				
Soil condition	2	291	146	0.449	0.641
Time	1	1222	1222	3.764	0.059
Soil condition x time	2	299	150	0.461	0.634
	AL				
Soil condition	2	198	99.0	1.825	0.174
Time	1	368	368	6.796	**0.013**
Soil condition x time	2	90.4	45.2	0.834	0.441

Notes: SaC = sand content; SiC = silt content; ClC = clay content; EC = electrical conductivity; OM = organic matter; TN = total nitrogen; C = carbon; N = nitrogen; TP = total phosphorous; K = potassium; Na^+ = sodium; Ca^{2+} = calcium; Mg^{2+} = magnesium; Cl^- = chloride; SO_4^{2-} = sulphates; CO_3^{2-} = carbonates; AL = active limestone. Bold characters highlight significant differences at $p < 0.05$.

The two-way ANOVA revealed that most of the analysed chemical parameters of burned soil did not show significant differences among the soil conditions. In contrast, the differences were significant over time for most of the soil properties. In more detail, while the $N\text{-}NO_3$, TP and CO_3^{2-} contents were not significantly different among both the soil conditions and survey dates, these factors and their interaction made the differences significant only for the Ca^{2+} content. The contents of K, Na^+, Ca^{2+}, Mg^{2+}, Cl^- and SO_4^{2-} were instead significantly different among both the soil conditions and over time (Table 1).

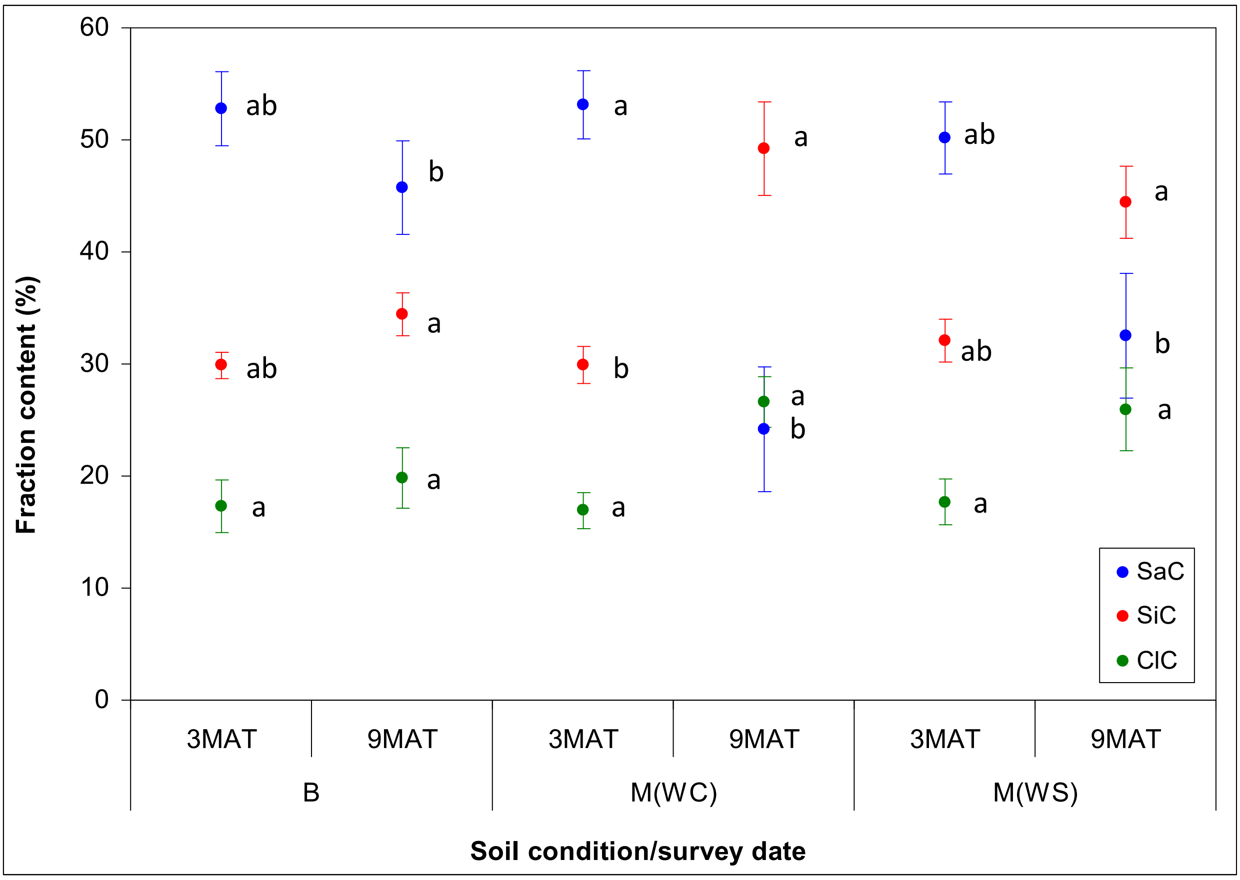
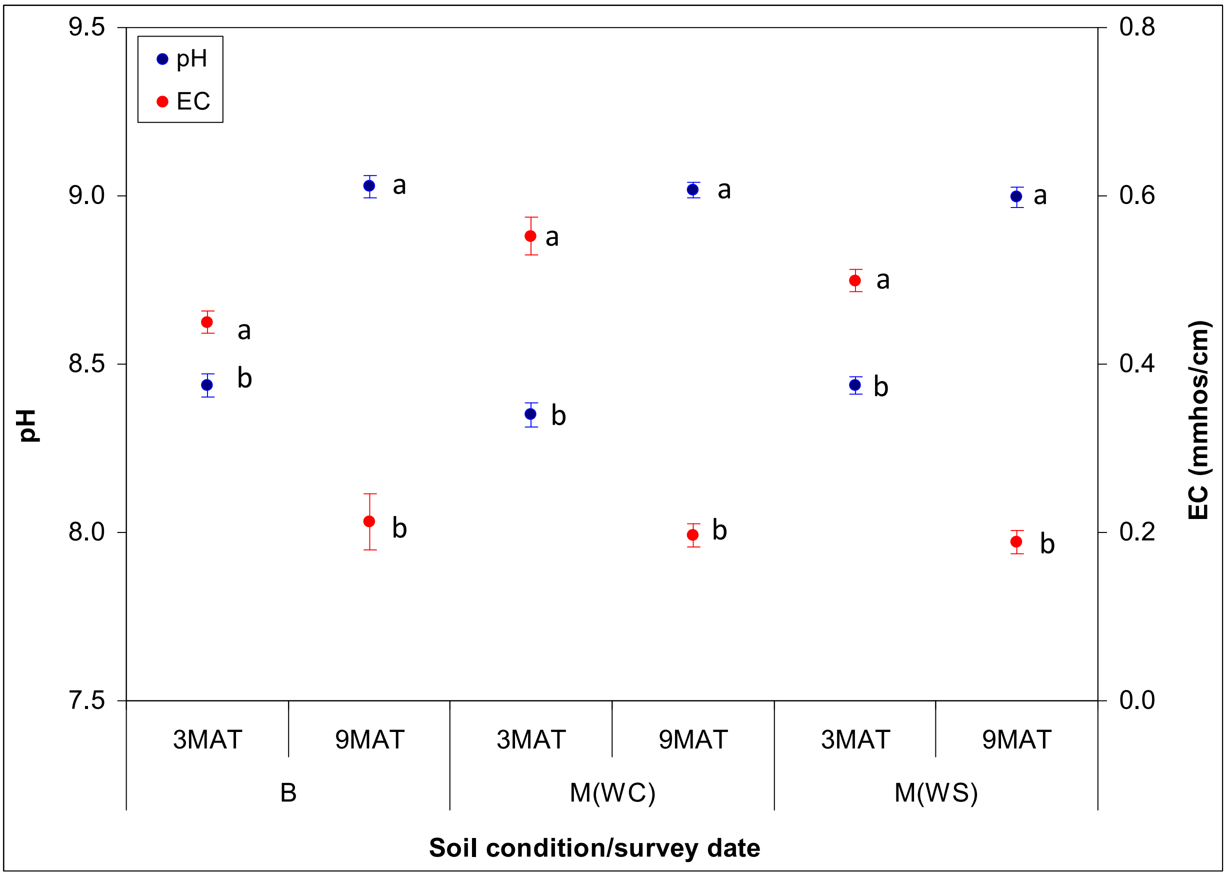
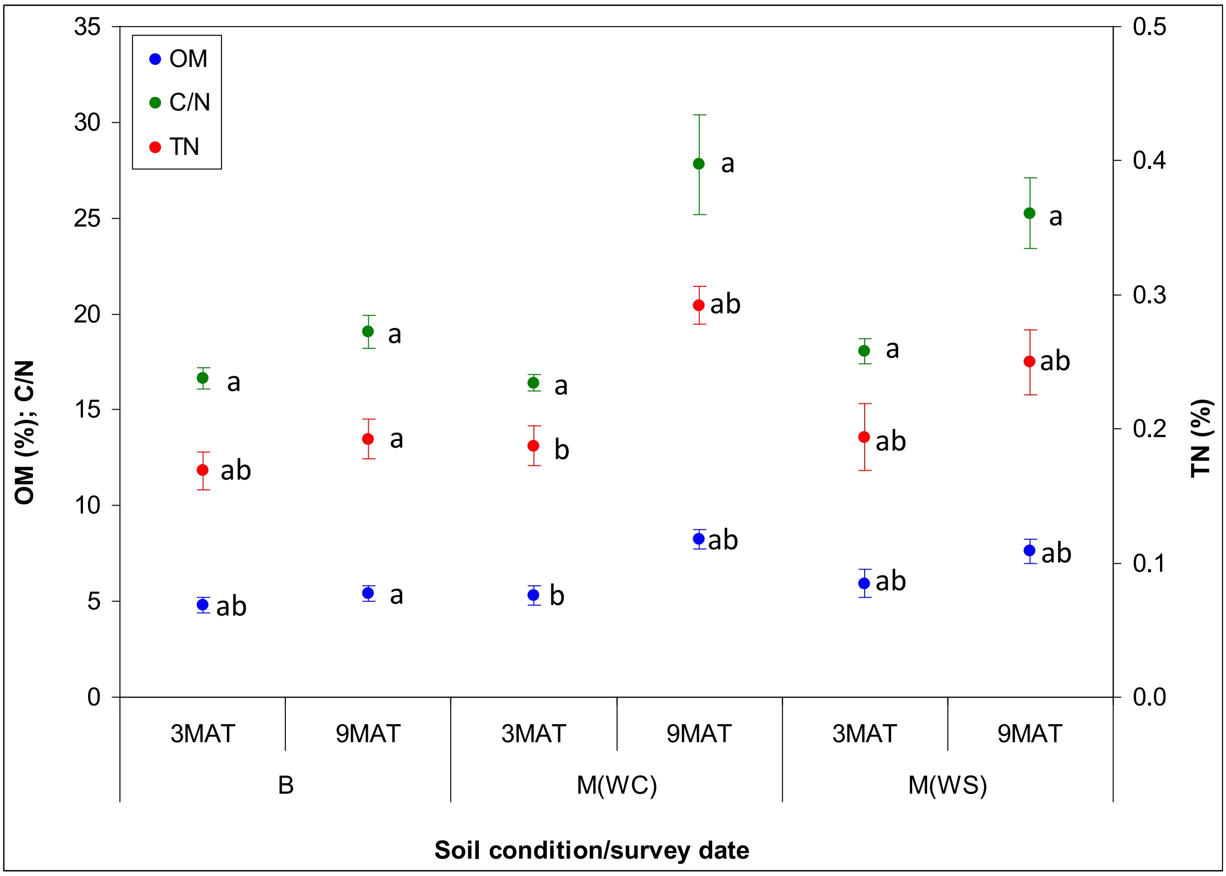
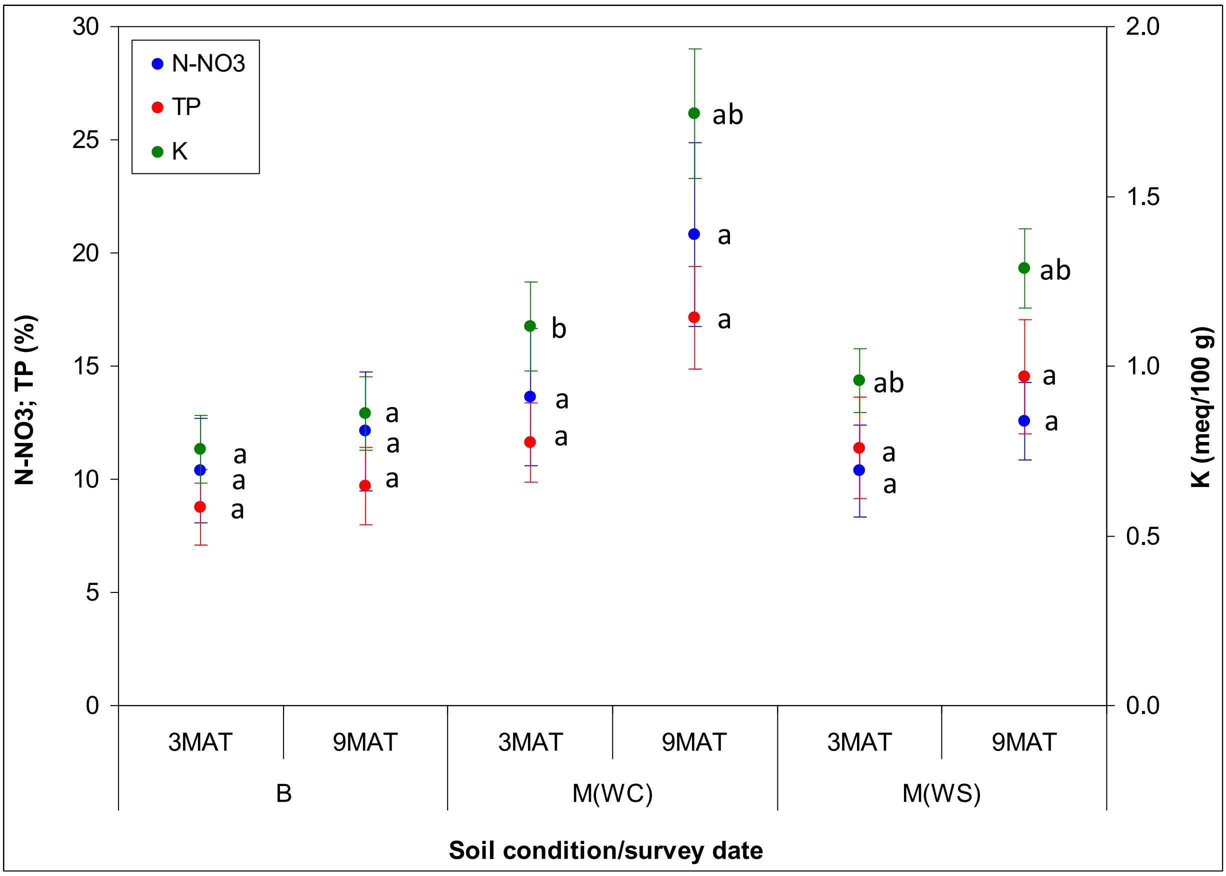


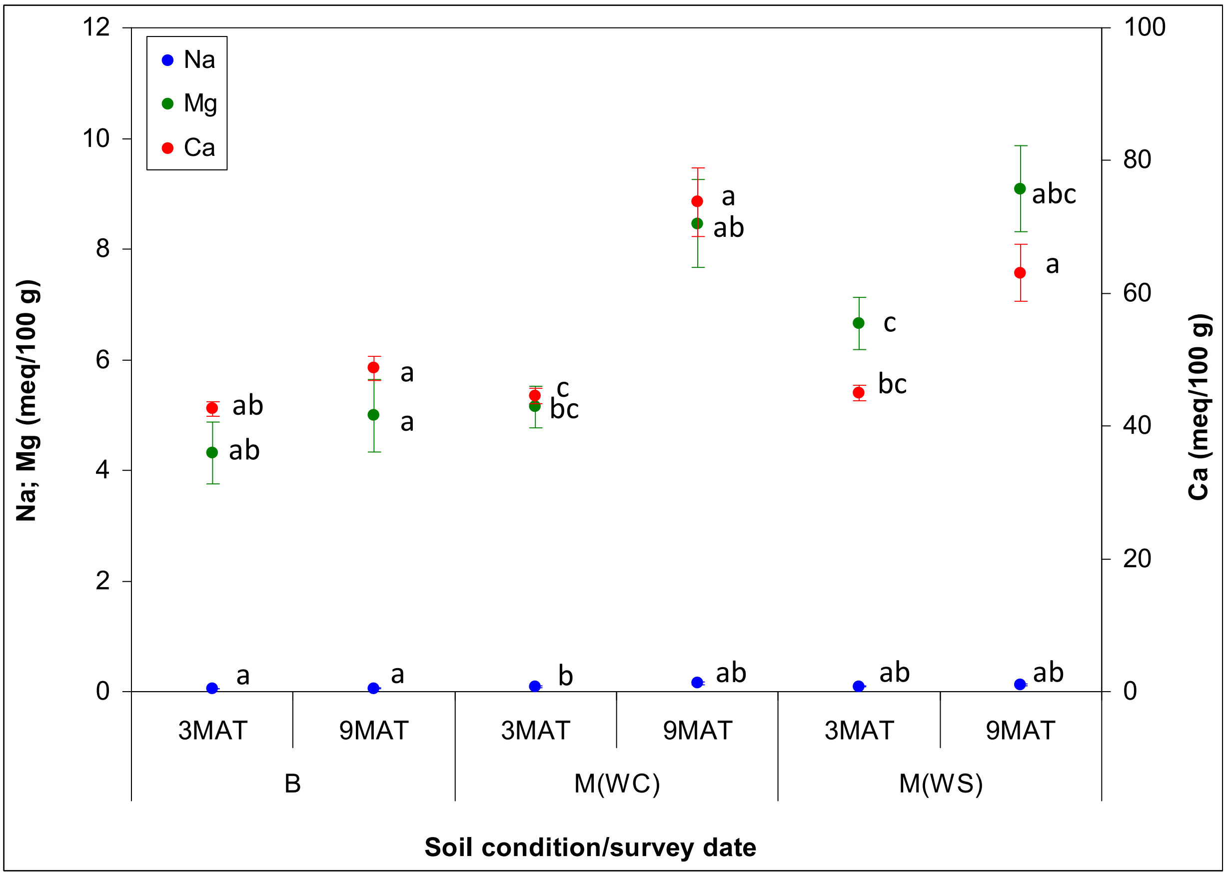
Figure 2 – Texture of samples of soils collected under three conditions (burned, B, mulched with wood chips, M(WC), and mulched with wheat straw, M(WS)) and two survey dates (at 3MAT and 9MAT) in Liétor (Castilla La Mancha, Central Eastern Spain). Legend: SaC = sand content; SiC = silt content; ClC = clay content. Different letters indicate significant differences in the interaction soil condition × survey time after Tukey's test ($p < 0.05$).

Regarding the significant differences found among the analysed soil parameters, both soil pH and EC were constant among the three soil conditions at 9MAT (close to 9 for pH, and to 0.20 mmhos/cm for EC). While the pH decreased at 3MAT (from 8.35 ± 0.04 in M(WC) plots to 8.44 ± 0.035 in B and M(WS) soils), the EC underwent the reverse changes, with increases up to 0.55 ± 0.02 mmhos/cm in M(WC) plots (Figure 3).


pH
EC
pH
EC (mmhos/cm)
9.5
9.0
8.5
8.0
7.5
0.8
0.6
0.4
0.2
0.0
a
b
a
b
a
b
a
b
a
b
a
b
3MAT
9MAT
3MAT
9MAT
3MAT
9MAT
B
M(WC)
M(WS)
Soil condition/survey date


OM
C/N
TN
OM (%); C/N
TN (%)
35
30
25
20
15
10
5
0
0.5
0.4
0.3
0.2
0.1
0.0
a
ab
ab
a
a
a
a
b
b
a
ab
ab
a
ab
ab
a
ab
ab
3MAT
9MAT
3MAT
9MAT
3MAT
9MAT
B
M(WC)
M(WS)
Soil condition/survey date


N-NO3
TP
K
N-NO3; TP (%)
K (meq/100 g)
3MAT
9MAT
B
M(WC)
M(WS)
Soil condition/survey date


Na
Mg
Ca
Na; Mg (meq/100 g)
Ca (meq/100 g)
3MAT
9MAT
B
M(WC)
M(WS)
Soil condition/survey date

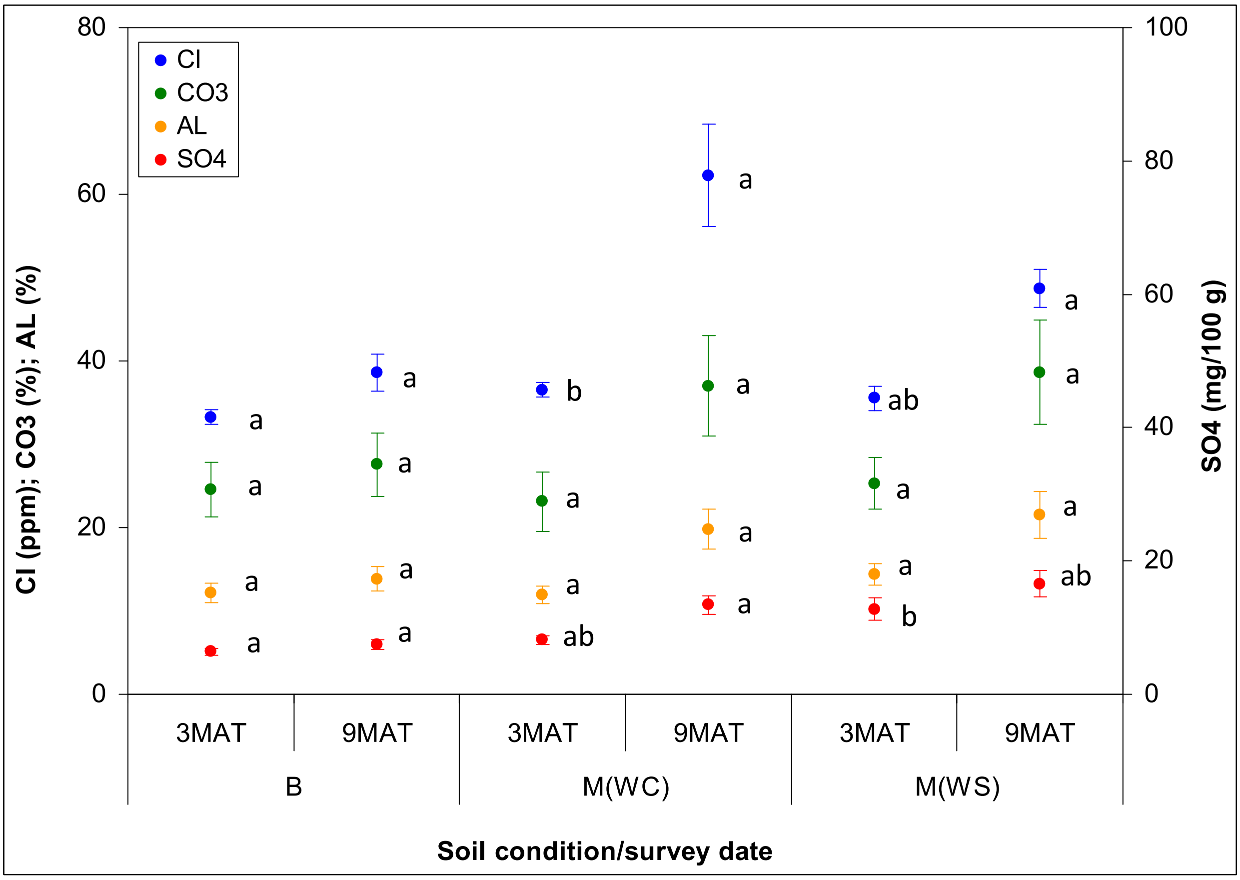


Figure 3 – Main chemical properties of samples of soils collected under three conditions (burned, B, mulched with wood chips, M(WC), and mulched with wheat straw, M(WS)) and two survey dates (at 3MAT and 9MAT) in Liétor (Castilla La Mancha, Central Eastern Spain). Legend: EC = electrical conductivity; OM = organic matter; TN = total nitrogen; C = carbon; N = nitrogen; TP = total phosphorous; K = potassium; Na^+ = sodium; Ca^{2+} = calcium; Mg^{2+} = magnesium; Cl^- = chloride; SO_4^{2-} = sulphates; CO_3^{2-} = carbonates; AL = active limestone. Different letters indicate significant differences in the interaction soil condition × survey time after Tukey's test ($p < 0.05$).

The OM content was higher at 9MAT in the mulched soils (8.24 ± 0.51% in M(WC) plots and 7.62 ± 0.64% in M(WS) plots)), although not significantly, compared to the burned and untreated plots (5.42 ± 0.42%). At 3MAT, this content significantly decreased down to 4.80 ± 0.42%, 5.31 ± 0.50% and 5.94 ± 0.72% in the B, M(WC) and M(WS) plots, respectively. The same trend was noticed for TN content of soils under the three conditions. Higher contents were found at 9MAT in the mulched sites (from 0.25 ± 0.02% in the M(WS) plots to 0.29 ± 0.01% in the M(WC) soils) compared to the B areas (0.19 ± 0.01%), with decreases at 3MAT (from a minimum of 0.17 ± 0.01% in B plots to a maximum of 0.19 ± 0.015 in the mulched areas). Given such variability in C and N, their ratio at 9MAT (in the range 19.1 ± 0.84 in B plots to 27.8 ± 2.59 in M(WC) sites) decreased at 3MAT down to a lowest value recorded in the M(WC) soils (16.4 ± 0.55) (Figure 3).

As outlined above, the changes in both N-NO_3 and TP contents of soils were not significant among the three soil conditions and over time. The lowest N-NO_3 and TP values were measured at 3MAT in the B plots (10.4 ± 2.31% and 8.75 ± 1.67%, respectively), while the highest contents were detected at 9MAT for M(WC) sites (20.8 ± 4.05% and 17.1 ± 2.25%). In contrast, the K content, which was significantly different among the three soil conditions and over time, was lower in the B plots in both seasons (0.86 ± 0.11 at 9MAT and 0.76 ± 0.1 meq/100 g at 3MAT) compared to the mulched plots. In the latter sites, K decreased from 1.74 ± 0.19 meq/100 g (M(WC) plots) and 1.29 ± 0.12 meq/100 g (M(WS)) at 9MAT down to 1.12 ± 0.13 and 0.96 ± 0.09 at 3MAT (for M(WC) and M(WS) sites, respectively (Figure 3).

Regarding the cation dynamics in the experimental soils, the B soil always showed the lowest contents at 3MAT (0.05 ± 0.001 for Na^+, 42.6 ± 1.15 for Ca^{2+} and 4.32 ± 0.56 for Mg^{2+}). At this time, the cation contents in mulched soils were higher, with the maximum values measured in the M(WS) (0.09 ± 0.01 meq/100 g for Na^+, 45 ± 1.21 meq/100 g for Ca^{2+} and 6.65 ± 0.47 meq/100 g for Mg^{2+}. These contents decreased at 9MAT, and the lowest values were detected in M(WS) plots for Na^+ (0.12 ± 0.01 meq/100 g) and Mg^{2+} (8.46 ± 0.8 meq/100 g), and M(WC) sites for Ca^{2+} (44.6 ± 1.20 meq/100 g) (Figure 3).

Likewise to what observed for cations, the anion contents increased at 9MAT compared to at 3MAT for all soil conditions. At all survey dates, both Cl^- and SO_4^{2-} were higher in the mulched soils compared to the B plots, but decreases were detected at 3MAT. The maximum values were measured in the M(WC) plots for Cl^- (62.3 ± 6.13 ppm) and in the M(WS) sites for SO_4^{2-} (16.6 ± 2.02 meq/100 g) at 9MAT, while the lowest were noticed in the M(WS) sites for Cl^- (35.5 ± 1.43 ppm) and in the M(WC) soils for SO_4^{2-} (8.13 ± 0.67 meq/100 g) at 3MAT. The differences in the CO_3^{2-} content of soils were not significant with the lowest value measured at 3MAT in the M(WC) soils (23.1 ± 3.52%) and the highest at 9MAT in the M(WS) plots (38.6 ± 6.23%). The AL was in the range 12.2 ± 1.2% (B soils at 3MAT) to 21.5 ± 2.85% (M(WS) plots at 9MAT), and the seasonal differences were significant (Figure 3).

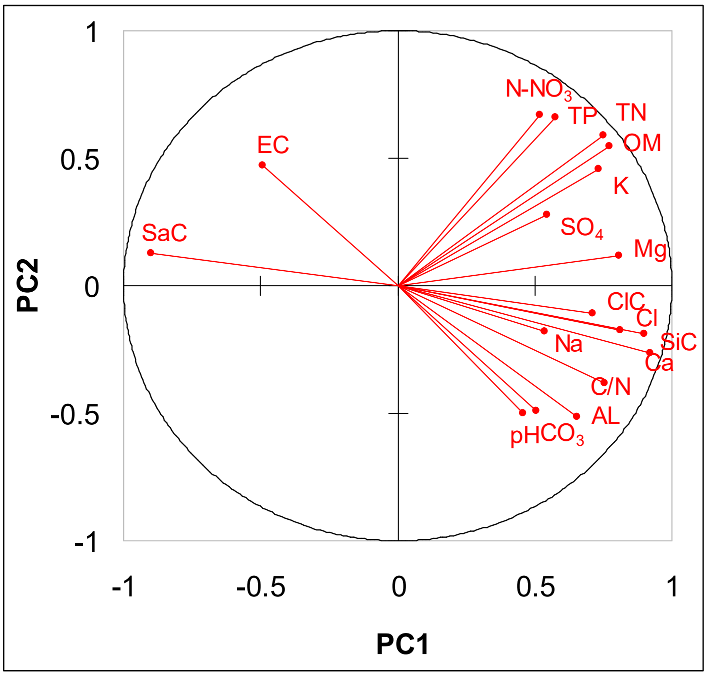
PCA provided four main Principal Components, which explained together 85.6% of the total variance of the original variables. PC1 and PC2 explain 66.7% of this variance, while the third and fourth PCs explain another 12.1% and 6.9%, respectively. The first component is associated to the texture, OM, TN and its ratio, K, AL and all ions (except CO_3^{2-}) of soils with positive loadings over 0.545 (with the exception of SaC, whose loading is negative). The pairs of soil properties N-NO_3 and TP (PC2), Na^+ and CO_3^{2-} as well as pH and EC weigh on the PC2, PC3 and PC4 with loadings that are over 0.603 and always positive, except for Na^+ and pH (Table 2 and Figure 5a). It is worth to notice an evident gradient B > M(WS) > M(WC) along the PC1; along this gradient the B soils are associated with lower SaC and EC and high values of all the other investigated properties on one side, while, on the other side, the soil mulched with straw and mainly with wood chips are characterized by higher SiC, ClC, OM, nutrient and ion contents and lower EC and SaC (Figure 5b).

Table 2 - Factor loadings of the original variables (main chemical properties of soils) on the first four Principal Components (PC1 to PC4) provided by PCA, applied to soil samples collected under three conditions (burned, B, mulched with wood chips, M(WC), and mulched with wheat straw, M(WS)) and two survey dates (at 3MAT and 9MAT) in Liétor (Castilla La Mancha, Spain).

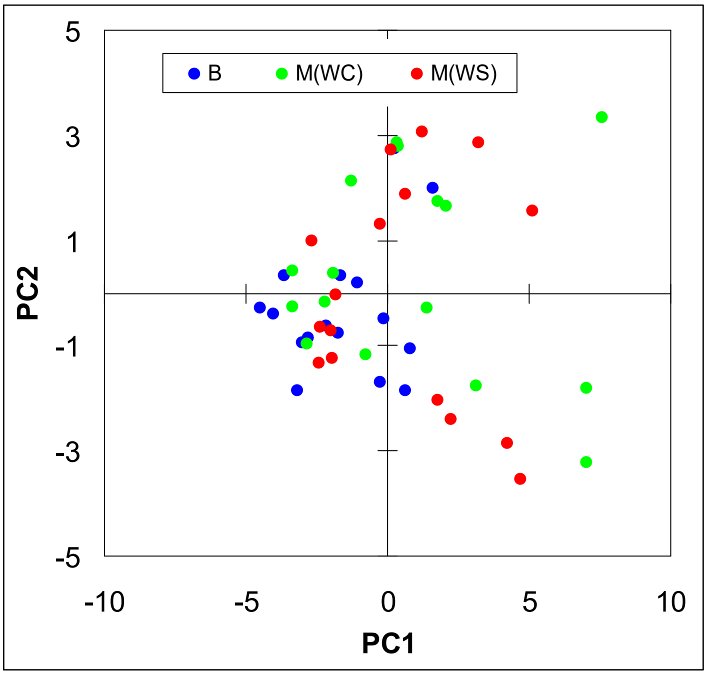
Soil properties	**Principal component (PC)**			
	PC1	**PC2**	**PC3**	**PC4**
SaC	**-0.899**	0.126	-0.315	-0.071
SiC	**0.901**	-0.190	0.063	0.120
ClC	**0.713**	-0.109	0.609	0.004
pH	0.456	-0.499	-0.258	**-0.667**
EC	-0.491	0.470	0.165	**0.691**
OM	**0.752**	0.592	-0.046	-0.117
TN	**0.771**	0.545	0.090	-0.154
N-NO_3	0.517	**0.670**	0.011	-0.113
C/N	**0.754**	-0.381	-0.414	0.213
TP	0.576	**0.658**	0.244	-0.142
K	**0.734**	0.457	0.146	-0.041
Na^+	0.538	-0.180	**-0.603**	0.286
Ca^{2+}	**0.920**	-0.264	-0.038	0.118
Mg^{2+}	**0.808**	0.116	-0.296	0.144

Cl	**0.813**	-0.175	-0.348	0.154
SO_4^{2-}	**0.545**	0.278	-0.469	0.057
CO_3^{2-}	0.505	-0.489	**0.624**	0.084
AL	**0.654**	-0.514	0.413	0.163

Notes: 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; values in bold for each PC correspond to the factor for which the loading is the largest.



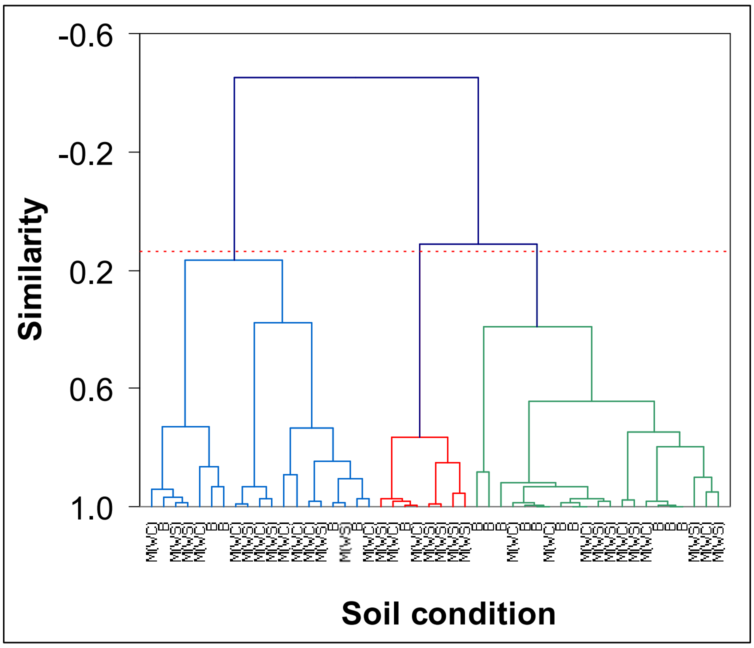
(a)



(b)

Figure 5 - Loadings of the original variables (main physico-chemical properties of soils) (a), and their scores on the first two Principal Components (PC1 and PC2) provided by PCA, applied to soil samples collected under three conditions (burned, B, mulched with wood chips, M(WC), and mulched with wheat straw, M(WS)) and two survey dates (at 3MAT and 9MAT) in Liétor (Castilla La Mancha, Spain). Legend: SaC = sand content; SiC = silt content; ClC = clay content; EC = electrical conductivity; OM = organic matter; TN = total nitrogen; $N\text{-}NO_3$ = 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.

The PCA coupled to AHCA grouped the soils according to the soil conditions. Three clusters were evidenced, in which the samples are grouped without a clear distinction. In more detail, most samples collected in B are in the first cluster, while the others are grouped in the third cluster. The latter cluster include samples of all the soil conditions, and the second cluster groups M(WC) and M(WS) samples with only one sample collected in B soils (Figures 4 and 5b).



Cluster composition		
1	**2**	**3**
B	B	B
B	M(WC)	B
B	M(WC)	B
B	M(WS)	B
B	M(WS)	B
B	M(WS)	M(WC)
B	M(WS)	M(WC)
M(WC)	M(WS)	M(WC)
M(WC)		M(WC)
M(WC)		M(WC)
M(WC)		M(WC)
M(WC)		M(WC)
M(WC)		M(WC)
M(WS)		M(WS)
M(WS)		M(WS)
M(WS)		M(WS)
M(WS)		M(WS)
M(WS)		M(WS)
B		M(WS)
B		
B		

Figure 6 - Dendrogram of the original variables (main physico-chemical properties of soils) and cluster composition provided by the Agglomerative Hierarchical Cluster Analysis (AHCA) applied to soil samples collected under three conditions (burned, B, mulched with wood chips,

M(WC), and mulched with wheat straw, M(WS)) and two survey dates (at 3MAT and 9MAT) in Liétor (Castilla La Mancha, Spain); the y-axis of the dendrogram reports the similarity level, while the red dotted line the clustering level.

4. DISCUSSION

4.1. Variability of soil properties between untreated and mulched soils and over time

The one-year monitoring of forest soil burned by a wildfire and mulched using straw or wood chips has revealed that, in the few months after the treatments (3MAT), no significant differences were detected in almost all the physico-chemical properties. In contrast, the mulching treatments played significant effects on OM, nutrients (TN and K), all cations and two anions (Cl^- and SO_4^{2-}) nine months after the treatments (9MAT).

The soil texture was not significantly modified by mulching compared to the burned but untreated sites. This effect is somewhat expected, since mulching plays a low disturbance on soil, in contrast to wildfire. The differentiated effects of erosion between untreated and mulched sites with selective detachment of soil particles may explain the changes in soil texture. The mulch material protects soil from erosion (mainly due to its rainsplash form), while the burned soils remain exposed to rainfall erosivity. This results in lower runoff and erosion in burned and mulched areas compared to untreated sites (Zavala et al. 2009; Shakesby 2011). Here, rainsplash and overland flow may erode some particle fractions from bare soil, while, in mulched areas, the cover of vegetal residues shadows the surface layer of soil, which were less subjected to the rainfall erosivity and soil detachment (Carrà et al. 2021). However, a previous study evidenced that the erosion rates measured in the experimental soils under the same conditions are low (Díaz et al. 2022). These authors demonstrated significantly lower soil losses in soils mulched with wheat straw and wood chips (the same materials used in the present study) compared to the burned and non-mulched sites.

In the few months after the treatments, this study revealed a limited variability in the main chemical properties of burned soils between the untreated and mulched sites, with the exception of EC and SO_4^{2}. The increase in EC in mulched soils compared to untreated soils is expected after intense rainfalls at 3MAT, since the ions released by ash after fire easily percolate into the sub-surface soil layers, thanks to the higher infiltrability of mulched soils compared to the untreated sites (e.g., (Prosdocimi et al. 2016; Bombino et al. 2019; Carrà et al. 2021). Nine months after the treatments, significant differences were detected in OM, TN, K, all cations and some anions, while the other soil properties remained unvaried. In more detail, pH, EC, N-NO_3, C/N, TP, AL and CO_3^{2-} were not influenced by soil management compared to the effects of wildfire noticed in burned and untreated sites. Mulching did not alter these chemical properties, since the measurements in the untreated sites were not significantly different compared to the mulched soils. Also (Gómez-Rey and González-Prieto 2014) found that mulching significantly modified the content of many elements or compounds considered in our study.

In this study, the low variability of pH between the mulched and untreated sites (only -0.4%) at both survey dates may be ascribed to the good buffering capacity of the soil. In contrast, significant increases in OM (+52% for wood chips and +41% for straw) and TN (+52% and +30%, respectively) were measured in the mulched plots compared to the untreated areas many months after the treatments. After mulching, increases in OM and nutrients are expected over time, since the organic residues supplied with mulching early decompose into the soil (Prosdocimi et al. 2016; Bombino et al. 2019), and improve the soil structure and quality (Jordán et al. 2010; Prosdocimi et al. 2016), thanks to their influence on plant growth and other soil processes, such as water retention, nutrient exchange, and soil structure (Mataix-Solera et al. 2011; Muñoz-Rojas et al. 2016). Another possible reason for the OM increase may be the addition of plant residues that were partially pyrolyzed (Caon et al. 2014; Agbeshie et al. 2022), the ash incorporation into the soil (Carra et al. 2021), and the decomposition of forest floor (Scharenbroch et al. 2012). Several authors detected increases in OM and nutrients in burned sites treated with mulching, especially when straw was used, in the short (e.g., Lucas-Borja et al. 2020b; 2021), and long-term (Prats et al. 2019). The significant influence of mulching on soil TN at 9MAT may be due the nitrogen supply deriving from the OM decomposition due to mulch material incorporation. Undoubtedly, the monitoring time of the experimental plots is short, but part of the mulch material may have been presumably incorporated into the soil after decomposition (due to heat in the dry period and micro-organisms of soil) and leaching (due to rainfall and subsequent water infiltration), also considering the small size of these residues. This was visually evident by the progressive disappearance of straw and wood chips throughout the field surveys.

The increase in TN found in this study some months after mulching disagrees with the study by Lucas-Borja et al. (2020c), who, in the same environment, found that the TN content was not different between straw-mulched and untreated sites, and the results by Jonas et al. (2019), who reported few effects of straw mulching on available nitrogen. In contrast, the effects of wood mulching on soil N content were significant and seasonally variable (Rhoades et al. 2017). Gómez-Rey et al. (2013) showed that mulching as emergency stabilisation treatment for burned soil had significant effects on soil N and extractable K, Mg^{2+} and Ca^{2+}. OM and nutrient contents increased in soils burned and mulched with eucalypt residues (Machado et al. 2022), but the latter authors warn that this effect can increase the risk of contamination of ground and surface waters.

Also the contents in cations and some anions in the topsoil were significantly higher at 9MAT in mulched sites (from +26% of Cl^- in plots mulched with straw to +153% of Na^+ in sites treated with wood chips) compared to the untreated soils. These effects may be due to the ash leaching into the surface layer of soil, supported by the higher infiltration generally recorded in the mulched sites in comparison to the untreated areas. The higher concentrations of ions in mulched soils may be in contrast with the slight and non-significant changes in EC between these sites and the untreated plots. We ascribe this apparent contrast to three considerations: (i) presumably the monitored cations and anions could have balanced the electrical charges shown by EC; (ii) not all the ions have been measured in this study (for instance, phosphates, fluorides, and compounds of aluminium, manganese and iron), and therefore it may be likely the presence of these cations or anions that may have balanced the increases in some other ions; (iii) EC may also decrease in soils exposed to high temperatures (500 °C or even more, as presumably happened in our site due to the high severity of fire), due to the destruction of clay minerals, and formation of oxides and coarse particles (Wondafrash et al. 2005; Zavala et al. 2014). The increases in some soil anions and cations due to the fire in both treated and untreated sites highlight the importance of ash due to burning (Pereira et al., 2018), which releases these ions and increases their content in burnt soils (Cawson et al. 2012; Alcañiz et al. 2020). Moreover, the increase in cation and anions contents of soil after fire has been reported by several authors (e.g., (Khanna and Raison 1986; Shrestha and Chen 2010; Elliott et al. 2013).

The significant variability of soil texture over time found in the experimental plots may depend on the displacement of some particles of soil due to erosion and leaching at 3MAT. In more detail, in the wetter periods the rainfall erosivity and surface runoff could have detached the more erodible soil fractions (such as silt) in the untreated soils compared to the mulched sites. Moreover, in the non-mulched areas, the abundant infiltration could have decreased the silt and clay contents of soil. Both effects (erosion and leaching) have consequently increased the sand fraction in the topsoil of the untreated sites. Increases in water infiltration due to mulching is a positive effect in semi-arid climates, where heavy rainstorm may result in very high surface runoff and erosion (Shakesby 2011; García-Ruiz et al. 2013). However, where the soil is affected by heavy changes in its properties (e.g., due to wildfire), infiltration may cause percolation of polluting compounds (such as nitrates, sulphates, phosphates) into groundwater.

The same significant variability over time detected for the soil texture was evident for almost all the chemical properties, except for $N\text{-}NO_3$, TP, SO_4^{2-} and CO_3^{2-}. In general, the contents of many compounds or ions in the soil were higher at 9MAT than few months after the treatments (3MAT), and these variations should be again due to the leaching effects after the rainfall in the wetter period. The high temperatures of these semi-arid areas at 9MAT result in a very high soil heating, which may accelerate some soil processes, such as the OM mineralisation, nutrient volatilisation and oxidation of other compounds. In line with our findings, a study by (Gómez-Rey et al. 2013) did not find any clear temporal trends for total soil C and N content, likely due to the large OM pool in their experimental soils.

4.2. Variability of soil properties between soils mulched with straw and wood chips

The comparison of the analysed properties between soils mulched with wheat straw and wood chips do not show significant differences both in textural and chemical parameters. The lack of significance in soil texture between the two types of mulch (variations in soil fractions between 15 and 25%) may derive from the similar erodibility of soils detected by (Díaz et al. 2022) in the same experimental site. Also for the OM, nutrients, cations and some ions, which showed a significant variability many months after mulching, the variability between M(WC) and M(WS) plots was low (less than 30%) and not significant. It is worth to notice that the increasing trends of OM and TN in mulched soils were more pronounced in soils treated with wood chips compared to straw-mulched sites (+8% for OM and +15% for TN). Moreover, increasing trends to higher concentrations of most cations and anions (with the exceptions of Mg^{2+} and SO_4^{2-}) in the soils mulched with wood chips compared to the areas mulched with straw (from +17% for Ca^{2+} to 28% for Cl^-) were evident. The lack of significant variability in the chemical properties few months after the treatments (3MAT) may be due to the too low time elapsed from mulch application and soil surveys. However, the detected trends of changes in OM, nutrients, cations and some ions led to significant differences in these properties between the untreated soils and the sites mulched with wood chips. These trends deserve a better understanding of the mineral composition as well as decomposition and mineralisation rates of organic compounds in the two mulch materials.

PCA and AHCA showed that overlapping of the clusters including soil samples collected in the plots mulched with different vegetal residues is noticeable, but also the discrimination of the soil properties between burned and untreated, and burned and mulched soils is not sharp. This basic similarity in many physico-chemical soil properties among the three soil conditions may be related to the fact that significant differences were not found in several properties between the two mulches. The same conclusion was achieved by Navidi et al. (2022), who compared the effects of mulching to untreated soils on soil properties of burned pine forests in Spain, and by Fernández-Fernández and González-Prieto (2020), who found a significant similarity of soil properties (especially at a depth of 2-5 cm) between soils mulched with straw and untreated sites in North-Western Spain. According to Gómez-Rey and González-Prieto (2014), the similarity among unburned, burned but not treated, and burned and mulched soils is achieved after a time of 4 to 8 months after a wildfire, as shown by the progressive overlapping of soil clusters sampled over a time variable between few weeks and one year.

4.3. Limitations of the study and future research needs

This investigation was carried out at the plot scale, but this spatial approach should not be a limiting factor of our study (as it happens in the case of investigations on surface runoff and soil erosion), since the variability in soil properties is generally evaluated point by point on the treated soils, similarly to what done in our experiments. Of course, an upscale of the investigation could be more informative about the spatial variations of these changes according to the natural variability of soil characteristics, which may be altered by wildfire and mulch application.

Further research is suggested, in order to measure the time needed by the soil properties in mulched sites to recover until the typical pre-fire values, which should be explored by comparisons between the soils treated with straw and wood chips, and the unburned sites. Other investigations should analyse the changes in the properties of the mulched soils over a longer time compared to the duration of the monitoring activity carried out in this study. It would be interesting to assess how straw and wood chips decompose and are incorporated into the soil, and to what extent the decomposing compounds or elements (organic matter, nutrients and ions) influence the quality and health in burned and treated sites.

5. Conclusion

The investigation has demonstrated that, in wildfire-affected pine forests of the semi-arid environment, mulching with straw or wood chips did not play significant effects on the texture and chemical properties of burned but untreated sites few months after the treatment. In contrast, significant changes may be expected over time in organic matter, some nutrients and many ions, when many months are elapsed. This result answers to the first research question about which soil properties undergo changes after mulching in wildfire-affected areas few months after treatments and over time compared to untreated areas. Moreover, no significant differences were detected in all soil properties between the two mulches, and this addresses the second research question about the possible variability of soil properties depending on the applied mulch material. These low changes were confirmed by PCA coupled with AHCA, which did not show a clear discrimination among the three soil conditions. However, a noticeable and significant variability of many of these properties over time is evident.

This study shows that mulching does not result in degradation of soil properties in the short-term after a wildfire and post-fire treatments, and thus helps land managers to protect the semi-arid Mediterranean forests against the negative impacts of high-severity fires. However, caution should be paid by forest managers, who implement mulching as post-fire management action, since an excessive leaching of nitrogen or ions into the deeper layers of soil may result in an increase in the risk of contamination of ground and surface waters.

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Conflict of interest statement

All authors declare no conflict of interest.

Data availability

Data will be made available upon request to the authors.

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