Short-term changes in soil properties after prescribed fire and mulching with fern in Mediterranean forests

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Abstract

Prescribed fire, although having low intensity and being able to reduce the risk of wildfire may modify soil properties in the short term, with possible increases in runoff and erosion risk. Soil mulching with vegetation residues is one of the most common post-fire management strategies. Residues of fern, which is abundant on the Mediterranean forest floor, may be used to replace straw for mulching fire-affected areas. However, the effects of prescribed fires are not completely understood, and there is no data regarding the use of fern to protect soil after fire in the literature. To fill this gap, selected soil chemical parameters were analysed, on a comparative basis, in three Mediterranean forests (pine, oak and chestnut) in Calabria (Southern Italy). These parameters were measured immediately and one year after fire in unburned, burned and not treated, and burned and mulched soils. Changes in soil chemical properties among the different treatments were significant, and the effects of the prescribed fire and mulching were dependent on the time elapsed from their application and forest species. In general, mulching was not effective in limiting the changes in the monitored soil properties compared to the pre-fire values. Each forest species showed different temporal trends in changes of soil properties.

Keywords: organic matter; nutrients; macro-elements; vegetation cover; post-fire management.

1. Introduction

Fire is a natural phenomenon with positive and negative impacts on forest ecosystems (Pereira et al. 2021). High-severity fires heavily impact the forest areas of the Mediterranean Basin, where the semi-arid climate conditions are favourable for wildfires (Cerdá and Mataix-Solera 2009; Inbar et al. 2014; Hueso-González et al. 2018).

Fire induces important changes in almost all soil properties (Zavala et al. 2014; Badía et al. 2017), such as organic matter, nutrient contents, changes in hydraulic conductivity, and microbial communities (Certini 2005; Shakesby 2011; Inbar et al. 2014). These changes in soil properties alter many processes in forest ecosystems, such as hydrology, plant regeneration, carbon and nutrient cycles (Certini 2005; Neary 2009). Every year local administrations make great efforts to limit the risk of wildfire, adopting diverse prevention strategies with varying effectiveness. The use of the prescribed fire - the planned use of low-intensity fire to eliminate the fuel that can generate high-intensity fires (Fernandes et al. 2013; Alcañiz et al. 2018) - has been increasingly gaining popularity among forest managers (Úbeda et al. 2005; Neary and Leonard 2021), mainly in USA, Australia and the Iberian Peninsula (Klimas et al. 2020). Many regions in these countries are prone to wildfire, and authorities have prioritized prescribed fire due to the numerous experiments that have demonstrated its feasibility to limit the wildfire risk (Alcañiz et al. 2018; Lucas-Borja 2021). In general, the changes in soil properties after a prescribed fire are limited (Lucas-Borja et al. 2019). Moreover, prescribed fire is thought to be beneficial for many ecosystem services, such as natural hazard regulation and pest and disease control (Pereira et al. 2021). However, although being of low intensity with lower impacts compared to wildfires, prescribed fire can also exert negative effects on soil properties (Alcañiz et al. 2018; Francos and Úbeda 2021). Some studies which analyzed soil changes after prescribed fires detected increases in pH, electrical conductivity, total carbon and nitrogen, magnesium, calcium and potassium in burned soils (e.g., Úbeda et al. 2005; Scharenbroch et al. 2012; Alcañiz et al. 2020).

However, how these compounds or elements vary after low-intensity fires differs. For instance, total carbon content may decrease or its changes may be extremely small or not significant (Úbeda et al. 2005; Alcañiz et al. 2018). Likewise, the changes in nitrogen may increase (Kennard and Gholz 2001; Shakesby et al. 2015; Alcañiz et al. 2016), be stable (Moghaddas and Stephens 2007; Neill et al. 2007; Lavoie et al. 2010) or even decrease (San Emeterio et al. 2016; Badía et al. 2017; Alcañiz et al. 2020).

The duration of the effects of prescribed fire on soil properties is also debated in the literature. Some authors report unaltered pH values and ephemeral variations in electrical conductivity (Badía et al. 2017; Alcañiz et al. 2020), while, one year after the prescribed fire, other research shows marked decreases in nitrogen (Blankenship and Arthur 1999; Muqaddas et al. 2015) as well as the recovery to pre-fire contents of magnesium and calcium (Alcañiz et al. 2020). It has been found that the recovery of pre-fire soil properties may take place over short (Zhao et al. 2015) or long (Alcañiz et al. 2016) time spans, depending on fire temperature and residence time, topography of the burned area, rainfall, and degree of vegetation regeneration (Úbeda et al. 2018; Girona-García et al. 2019). Therefore, further research is needed to better understand the effects of prescribed fires in environments with contrasting characteristics (Hubbert et al. 2006; Hueso-González et al. 2018).

One of the most detrimental effects of prescribed fire is the possible increase in runoff and erosion in the short term (Lucas-Borja et al. 2019), due to vegetation removal and sudden changes in the properties of soils (Cawson et al. 2012; Alcañiz et al. 2018). This is an important concern when risk of wildfire endangers forests on steep slopes with highly erodible soils, such as in many environments of Southern Europe (e.g., Fortugno et al. (2017); Bombino et al. (2021b) in Southern Italy). To the authors' best knowledge, so far no studies have evaluated the soil changes after prescribed fire in these environments, where the wildfire and erosion risks are high, due to climatic and geomorphological characteristics.

Soil mulching with vegetation residues is one of the most common post-fire management strategies to limit runoff and erosion in the short term (Lucas-Borja et al. 2019; Zema 2021). Mulching protects soils with cover (Zituni et al. 2019), and can increase water infiltration and soil quality over time, thanks to the supplied organic matter and nutrients (Prosdocimi et al. 2016). However, post-fire mulching is not always beneficial for soil properties. For instance, in pine forests of Central Eastern Spain, Lucas-Borja et al. (2018) measured lower infiltration rates when soil is not saturated compared to unburned and untreated forest areas, especially in the dry seasons. Fernández-Fernández et al. (2016) stated that mulching is not effective in reducing soil erosion and subsequent loss of nutrients; in an experiment carried out in North-Western Spain, these authors showed that the reduction in soil erosion was due to moderate precipitation rather than mulching, and the concentration of some elements in sediments led to problems for vegetation growth and soil health. Moreover, the use of straw, which is commonly used as mulch material, is not always suitable in forest areas, since biomass transport from agricultural sites may be expensive; moreover, these vegetal residues often contain agro-chemicals and parasites, and thus development of non-native vegetation and diseases to forest plants are possible (Bento-Gonçalves et al. 2012). Fern (*Pteridium aquilinum* (L.) Kuhn) is a vascular plant that can grow in semi-arid climates, where the water competition among plants is high (Bombino et al. 2019). Since fern is abundant on the Mediterranean forest floor, its residues may replace straw for mulching fire-affected areas. Fern can be directly cut on the forest floor (without being transported from distant sites) and does not bring non-native seeds or chemical residues into the forest ecosystem. Fern can be cut in adjacent forests, where the fire and erosion risks are lower, and applied as it is (that is, without desiccation, as usually carried out for straw) on soil. Moreover, fresh fern may be more rapidly and easily degraded and incorporated in soil compared to other dried residues.

However, the changes in the properties of soils mulched with fern residues should be properly evaluated after the prescribed fire, particularly in the short term, when the impact of the fire is higher (Lucas-Borja 2021; Zema 2021). Unfortunately, no data on using fern to protect soil after fire is present in literature. Due to this gap in research, little is known about the effective of fern mulching in limiting soil changes after fire. To fill this gap, the present study evaluates short-term changes in soil properties and covers after a prescribed fire and mulching treatment with fern in three Mediterranean forests (pine, oak and chestnut) in Calabria (Southern Italy). The selected properties have been analysed on a comparative basis in unburned, burned and not treated, and burned and mulched soils immediately and one year after fire. More specifically, the research questions of this study are the following: (i) does prescribed fire modify the soil properties in the short term after burning? (ii) is mulching with fern able to reduce these changes? The answers to these questions aim to give more insight to land managers about the possible changes in burned soils due to low-intensity fire and post-fire management.

2. Material and methods

2.1. Study area

Three forest sites in an area in the municipality of Samo (Calabria, Southern Italy) were selected for this investigation (Figure 1). This area exhibits the typical climatic characteristics of semi-arid zones ("Csa" class, "Hot-summer Mediterranean" climate, according to Koppen (Kottek et al., 2006), with mild and rainy winters, and warm and dry summers. The mean annual precipitation and temperature are 1102 mm and 17.4 °C, respectively. The minimum and maximum temperatures are - 4.3 and 43.1 °C, respectively (weather station of Sant'Agata del Bianco, geographical coordinates 4217548 N, 595159 E, period 2000-2020).

The soils of the experimental sites - Haplic Cambisols, according to the World Reference Base for Soil Resources classification dated 2014 - were homogenous, with a loamy sand texture (10.6 ± 2.57% of silt, 8.76 ± 0.61% of clay, and 80.7 ± 2.68% of sand), except for an unburned area of the pine forest, which was sandy loam (10.1 ± 1.01% of silt, 9.0 ± 0.01% of clay, and 81.0 ± 0.99% of sand).

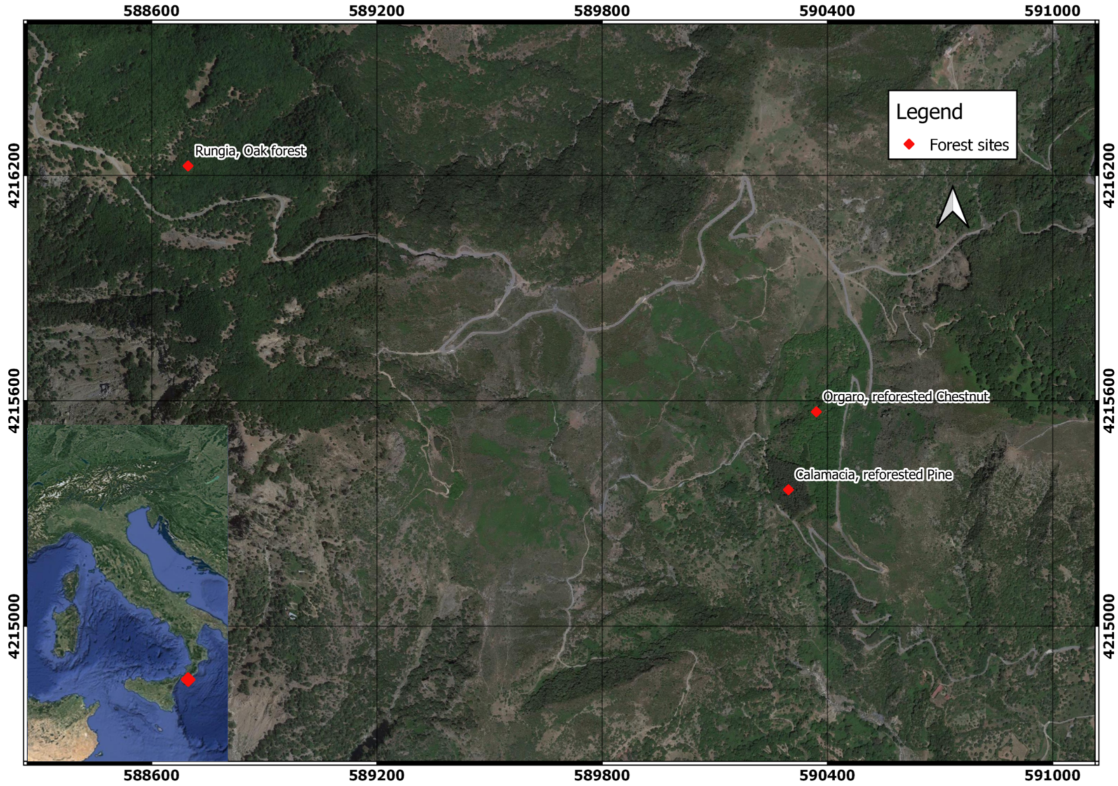


Figure 1 – Geographical location (Southern Calabria, Italy) and aerial view of study area with the experimental forest sites (Samo).

Of the three forest sites, one was a pine (*Pinus pinaster* Aiton) in the locality of Calamacia, and one a chestnut stand (*Castanea sativa* Mill.) in the locality of Orgaro, both reforested between 20 and 30 years ago, respectively. The third site was a natural stand of oak (*Quercus frainetto* Ten.) in the locality of Rungia. Site elevation was in the range 650 to 950 m a.s.l., while their mean slope was about 20% for all stands (Table 1).

Table 1 - Main characteristics of the experimental forest sites (Samo, Calabria, Southern Italy).

<table>
<tr><th colspan="2" rowspan="2">Characteristics</th><th colspan="6">Site</th></tr>
<tr><th colspan="2">Rungia</th><th colspan="2">Calamacia</th><th colspan="2">Orgaro</th></tr>
<tr><td colspan="2">UTM coordinates</td><td>588635 E</td><td>4216172 N</td><td>590293 E</td><td>4215327 N</td><td>590389 E</td><td>4215530 N</td></tr>
<tr><td colspan="2">Aspect</td><td colspan="2">North-East</td><td colspan="2">South-West</td><td colspan="2">West</td></tr>
<tr><td colspan="2">Altitude (m a.s.l.)</td><td colspan="2">900-950</td><td colspan="2">650-700</td><td colspan="2">700-750</td></tr>
<tr><td colspan="2">Slope (%)</td><td colspan="2">19.1 ± 1.65</td><td colspan="2">20.0 ± 0.82</td><td colspan="2">20.3 ± 0.96</td></tr>
<tr><td rowspan="4">Tree layer</td><td>species</td><td colspan="2">Oak
(Quercus frainetto Ten.)</td><td colspan="2">Pine
(Pinus pinaster Aiton)</td><td colspan="2">Chestnut
(Castanea sativa Mill.)</td></tr>
<tr><td>density (n/ha)</td><td colspan="2">225 ± 44.7</td><td colspan="2">950 ± 86.4</td><td colspan="2">725 ± 89.1</td></tr>
<tr><td>diameter at breast height (cm)</td><td colspan="2">40.7 ± 8.9</td><td colspan="2">28.3 ± 9.4</td><td colspan="2">20.2 ± 5.6</td></tr>
<tr><td>height (m)</td><td colspan="2">18.2 ± 1.9</td><td colspan="2">20.5 ± 1.4</td><td colspan="2">9.6 ± 1.2</td></tr>
<tr><td>Shrub layer</td><td>species</td><td colspan="2">Cyclamen hederifolium, Bellis perennis L.</td><td colspan="2">Quercus ilex L., Rubus ulmifolius S., Bellis perennis L.</td><td colspan="2">Rubus ulmifolius S., Pteridium aquilinum L., Bellis perennis L.</td></tr>
</table>

Tree density was higher in the pine (about 950 trees/ha) and chestnut (725 trees/ha) stands compared to the oak forest (225 trees/ha). The chestnut forest showed the lowest mean values of tree height (10 m) and diameter (20 cm), while the pine and oak trees were taller (18 - 20 m) and had a larger mean diameter (28 and 40 cm, respectively). Shrub formations mainly consisted of *Quercus ilex L., Rubus ulmifolius S., Bellis perennis L.* (pine forest), *Cyclamen hederifolium, Bellis perennis L.* (oak) and *Rubus ulmifolius S., Pteridium aquilinum L., Bellis perennis L.* (chestnut) (Table 1).

2.2. Prescribed fire operations and mulching application

The prescribed fire was carried out in three areas (each of about 250 m^2) of the three forest stands on 10 June 2019 with the support of the Forest Regional Agency (Calabria Verde) and the surveillance of the National Corp of Firefighters (Figure 2a). Wind was practically absent and air humidity was between 50 and 60%. The same ignition technique was used for all forest sites, which furthermore had the same fuel characteristics. The main conditions during the fire (temperatures of flame, air and soil) were measured at a soil depth of 2.5 cm - the mid-point of the surface layer (0-5 cm), where the main effects of the prescribed fire occur (considering that soil is a poor heat conductor, Certini 2005; Pereira et al. 2018) - by a thermocouple connected to a datalogger (Table 2).

The burn severity of soils after the prescribed fire was evaluated according to the classification by Parson et al. (2010). Accordingly, one day after the prescribed fire, the ground surface of all sites was visually checked, observing ash colour and fine roots. Following Parson et al. (2010), the burn severity of all sites were low, that is, with small change from pre-fire status, black ground surface with recognizable fine fuels remaining on surface, and fine roots unchanged.

Table 2 – Main conditions during prescribed fire operations in the experimental forest sites (Samo, Calabria, Southern Italy).

<table>
<tr><th colspan="3" rowspan="2">Characteristics</th><th colspan="3">Site</th></tr>
<tr><th>Rungia</th><th>Calamacia</th><th>Orgaro</th></tr>
<tr><td colspan="3">Main forest species</td><td>Oak</td><td>Pine</td><td>Chestnut</td></tr>
<tr><td rowspan="6">Temperature (°C)</td><td rowspan="2">fire flame</td><td>mean</td><td>98</td><td>88.3</td><td>75</td></tr>
<tr><td>max</td><td>720</td><td>712</td><td>645</td></tr>
<tr><td rowspan="2">air</td><td>mean</td><td>43</td><td>25.7</td><td>29.1</td></tr>
<tr><td>max</td><td>180</td><td>102</td><td>139</td></tr>
<tr><td rowspan="2">soil</td><td>mean</td><td>21</td><td>21.9</td><td>24.7</td></tr>
<tr><td>max</td><td>26.9</td><td>22.7</td><td>28.8</td></tr>
<tr><td rowspan="2">Residence time
(% on total fire duration)</td><td colspan="2">mean temperature</td><td>44.4</td><td>18.0</td><td>69.7</td></tr>
<tr><td colspan="2">max temperature</td><td>17.2</td><td>1.6</td><td>9.3</td></tr>
</table>

In these burned areas, three small portions (about 9 m^2) in each site were mulched with a cover (more or less 3 to 5 cm of thickness) of fern residues, cut from an adjacent zone, and distributed over the ground at a dose of 500 g/m^2 of fresh weight (equivalent to 200 g/m^2 of straw dry matter, usually applied in burned and mulched areas after fire (Vega et al. 2014; Lucas-Borja et al. 2018) (Figure 2b).

A third area, unburned and at a distance of less than 10 m from the burned areas, in each site was selected as a "control".

(a)

(b)

Figure 2 - Prescribed fire operations (a) and fern mulch application to burned soil immediately after fire (b) in the experimental forest site (Samo, Calabria, Southern Italy).

2.3. Experimental design

The experimental design consisted of three forest stands (pine, oak and chestnut) × three soil conditions (unburned, burned and not treated, and burned and mulched, the latter two hereafter simply indicated as "burned" and "mulched", respectively) × two survey dates (one day and one year after fire) × three sampling points (Figure 3). In these forests, measurements of soil properties and covers were carried out according this experimental design on both survey dates. The collection of samples within a very short reciprocal distance (lower than 20-25 metres) should have minimized the effect of spatial heterogeneity of soil, and allowed the attribution of the measured changes due to the treatments applied (prescribed burning and mulching).

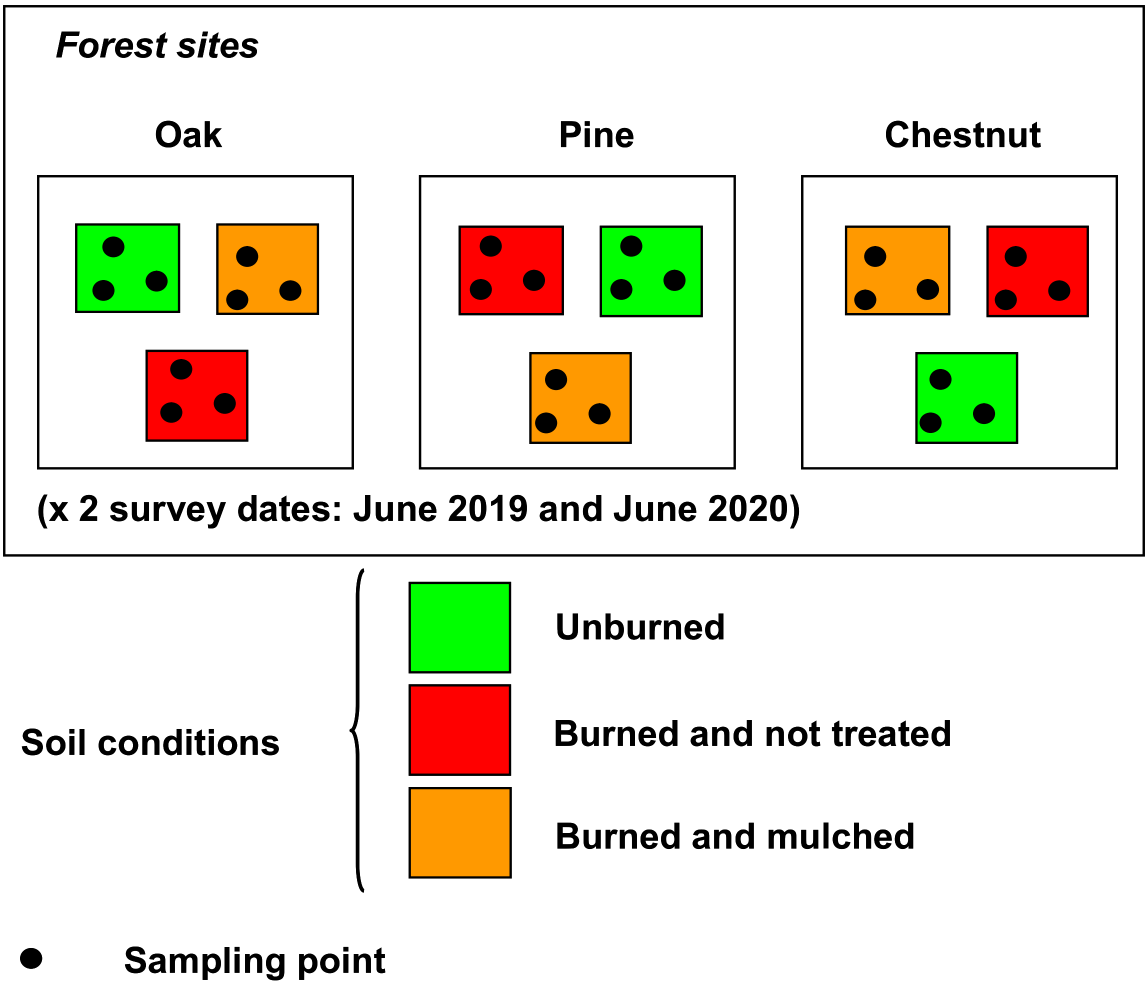


Figure 3 – Scheme of the experimental design (Samo, Calabria, Southern Italy).

2.4. Monitoring of the soil parameters

From each forest site and soil conditions, and immediately after the prescribed fire (one day), samples of soil were collected from between 0 and 5 cm below the soil surface (since the prescribed fire only affects the surface layer of soil (Alcañiz et al. 2018; Pereira et al. 2018). The sampling points were randomly chosen in three small plots (each of 3 m^2), surrounding the point in which the temperature was measured (max distance of 50 cm).

One year later (June 2020), the soil was sampled in the same points as in the surveys carried out immediately after fire. After collection, the soil samples were transported to the laboratory, where the main chemical properties (pH, electrical conductivity, contents of organic carbon, nitrogen, ammonium, potassium, magnesium, calcium, fluorides, chlorides, nitrates, phosphates, and sulphates) were determined. These properties were identified from the relevant literature (Certini, 2005; Cawson et al., 2011; Alcaniz et al., 2018) as the main soil properties that prescribed fire usually modifies. Moreover, we measured in field a set of soil covers (shrub, litter, ash and bare soil). All sampling operations were carried out in three replications.

2.4.1. Measurement of soil properties

Samples of soils were analysed to determine the size distribution of the mineral particles (texture). Soil texture was detected by using the hydrometer method with sodium hexametaphosphate as a dispersant (Bouyoucos 1962). The final classification was done using the USDA triangle method. The values of pH were measured using a soil:water suspension ratio of 1:2.5 (w/v) with a glass electrode. Electrical conductivity (EC) was determined in distilled water by using a 1:5 residue/water suspension, mechanically shaken at 15 rpm for 1 h to dissolve soluble salts and then detected by Hanna instrument conductivity meter. Organic carbon (OC) was determined by dichromate oxidation method, according to (Walkley and Black 1934), and titration with iron-sulphate ($FeSO_4$, 0.2 N). Total nitrogen (N) was measured using the method by Kjeldahl (1883). The concentration of water-extractable ions, ammonium (NH_4^+), potassium (K^+), magnesium (Mg^{2+}), calcium (Ca^{2+}), fluorides (F^-), chlorides $(Cl)^-$, nitrates (NO_3^-), phosphates (PO_4^{3-}), and sulphates (SO_4^-) was determined by ionic chromatography after extraction of the samples with bidistilled water (soil: water 1:10) for 24 h at 25 °C (Wang et al., 2013) to detect ion concentration (mg/g dry soil) by using a chromatography system (Dionex ICS-1100).

2.4.2. Measurement of soil covers

To evaluate whether the changes in soil surface properties (henceforth "covers") had impacts on the changes of subsurface soil layer, the shrub and litter cover, and the bare soil, stoniness in percent over the total surveyed area were also measured at the same dates as the chemical properties. Moreover, we also measured the area (as a percentage) covered by ash, which was not removed, to consider its effect on soil changes. The measurements were carried out in nine adjacent areas (each 5 m long x 5 m wide, at a maximum distance of 3 m from the areas where soil properties were measured). The grid method (Vogel and Masters 2001) for shrub cover, and the photographic method for the remaining variables (litter cover, bare soil, stoniness, and ash) were used. The grid method was applied, using a 0.50 x 0.50-m grid square on the sampling areas (upstream, in the middle, and downstream of each plot).

2.5. Statistical analyses

MANOVA (Multivariate ANalysis Of VAriance) was applied to all soil parameters (response variables) separately for the three forest species, assuming as factors the soil condition (unburned, burned, and mulched) and measurement date (one day and one year after fire). The pairwise comparison by Tukey's test (at $p < 0.05$) was also used to evaluate the statistical significance of the differences in the response variables. In order to satisfy the assumptions of the statistical tests (equality of variance and normal distribution), the data were subjected to normality Anderson-Darling's test or were square root-transformed whenever necessary.

Following this, a Principal Component Analysis (PCA) was applied, in order to identify the existence of meaningful derivative variables (Principal Components, PCs) (Rodgers & 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 standardizing the original variables (expressed by different measuring units) and using Pearson's method to compute the correlation matrix. This matrix allowed the identification of relationships among the soil properties analysed. The first three PCs, explaining at least at least a percentage of 70% of the original variance, have been retained.

Finally, the soil samples 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).

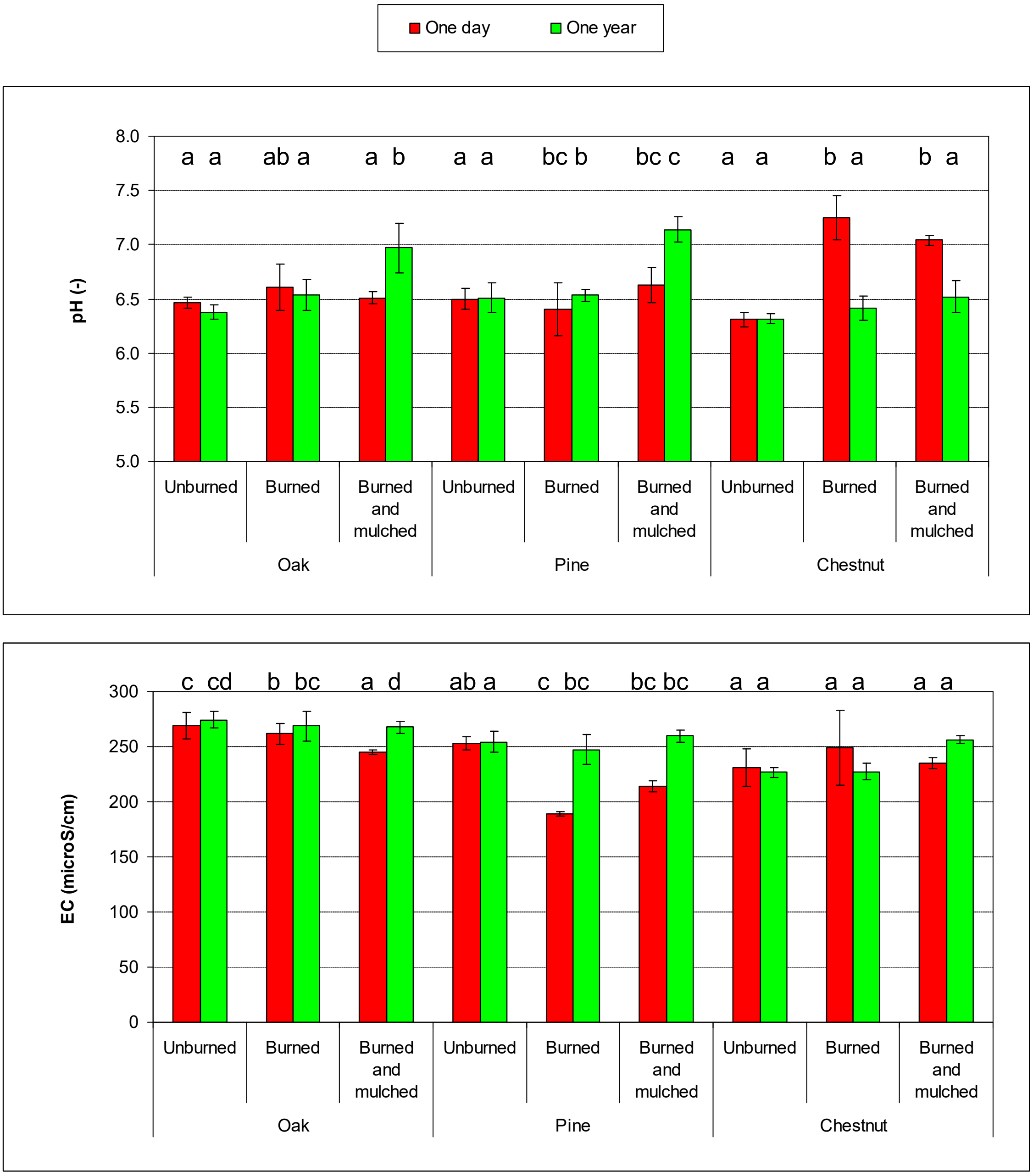
The statistical analysis was carried out using the XLSTAT release 2019 software.

3. Results

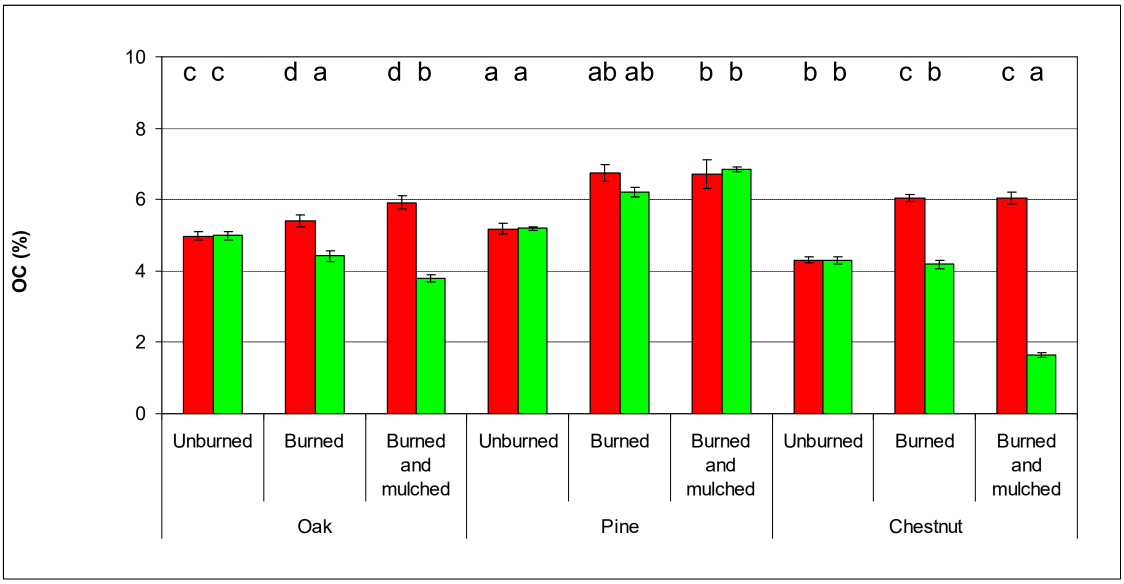
3.1. Chemical properties of soils

Burning and mulching noticeably altered soil pH and EC in the pine stand one year after the prescribed fire with an increase of one pH unit. Conversely, compared to the unburned soils, significant increases (by 11.6% in mulched areas and 14.8% in burned sites) were measured in the chestnut forest immediately after the fire, while a noticeable decrease (-11.6% and -7.39%, respectively) was observed in burned and mulched sites one year after the fire (Figure 4). No significant pH variations (less than 2%) were observed in soils in the oak forest. One year after the fire, EC generally increased in all forest soils, and particularly in pine (+30.9%, burned soils, and +21.4%, mulched sites) (Figure 4).

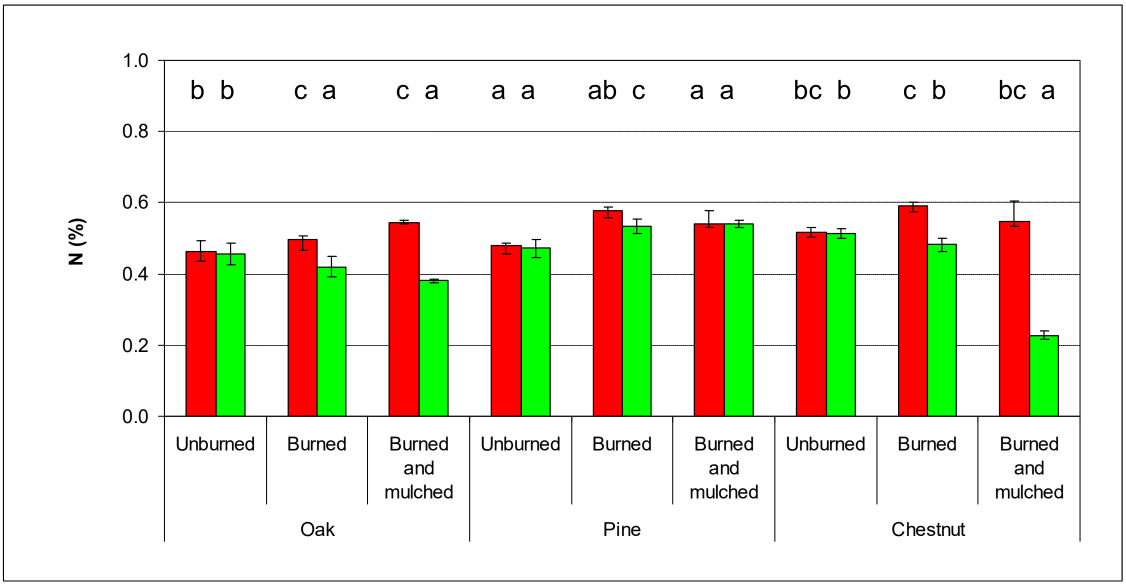
The OC content of soils, which showed a limited variability in the unburned sites, significantly increased immediately after the fire (Figure 4). The greatest increase was observed in chestnut forest (+40.2% for both burned and mulched soil conditions). In the oak forest, OC decreased one year after the fire (-18.2%, burned soils, -35.9%, mulched sites), and a very high decrease (-73%) was observed in mulched chestnut site (Figure 4).



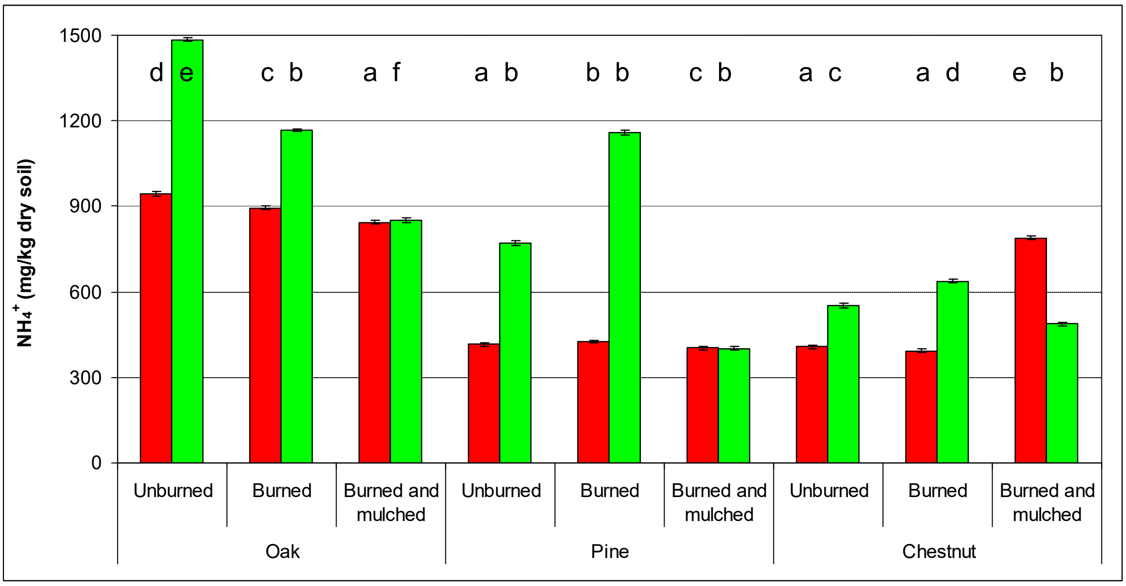
One day
One year
pH (-)
8.0
7.5
7.0
6.5
6.0
5.5
5.0
a a
ab a
a b
a a
bc b
bc c
a a
b a
b a
Unburned
Burned
Burned and mulched
Unburned
Burned
Burned and mulched
Unburned
Burned
Burned and mulched
Oak
Pine
Chestnut
EC (microS/cm)
300
250
200
150
100
50
0
c cd
b bc
a d
ab a
c bc
bc bc
a a
a a
a a
Unburned
Burned
Burned and mulched
Unburned
Burned
Burned and mulched
Unburned
Burned
Burned and mulched
Oak
Pine
Chestnut



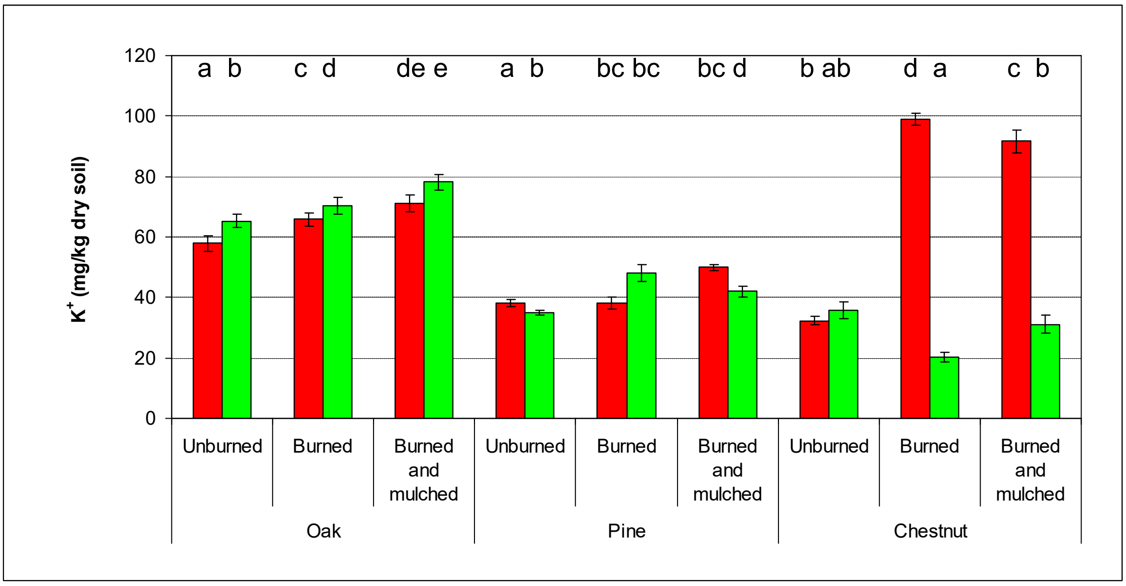
OC (%)
10
8
6
4
2
0
c c
d a
d b
a a
ab ab
b b
b b
c b
c a
Unburned
Burned
Burned and mulched
Unburned
Burned
Burned and mulched
Unburned
Burned
Burned and mulched
Oak
Pine
Chestnut



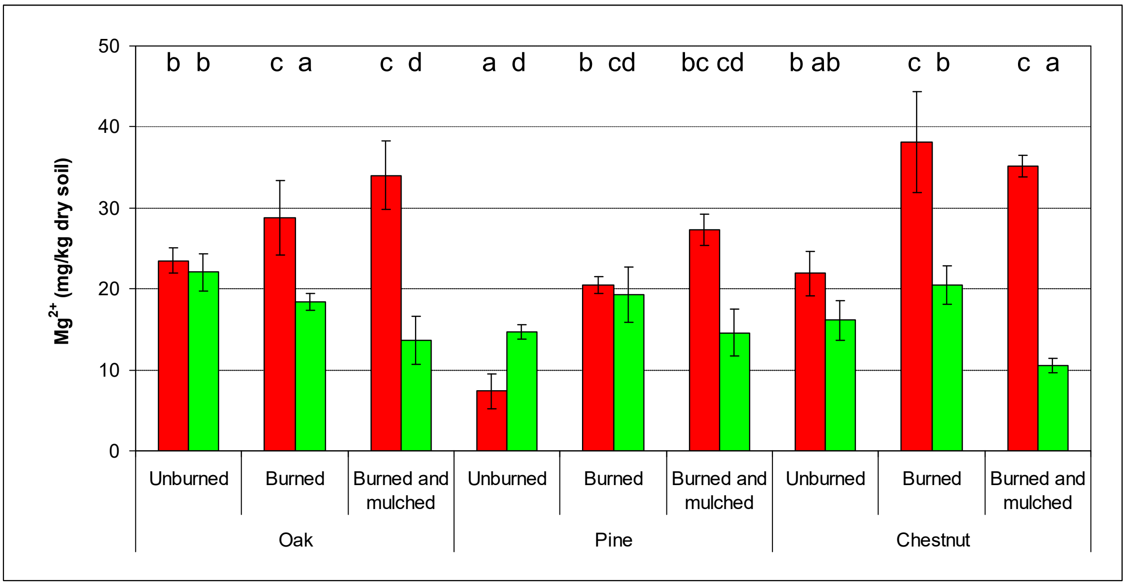
N (%)
1.0
0.8
0.6
0.4
0.2
0.0
b b
c a
c a
a a
ab c
a a
bc b
c b
bc a
Unburned
Burned
Burned and mulched
Unburned
Burned
Burned and mulched
Unburned
Burned
Burned and mulched
Oak
Pine
Chestnut



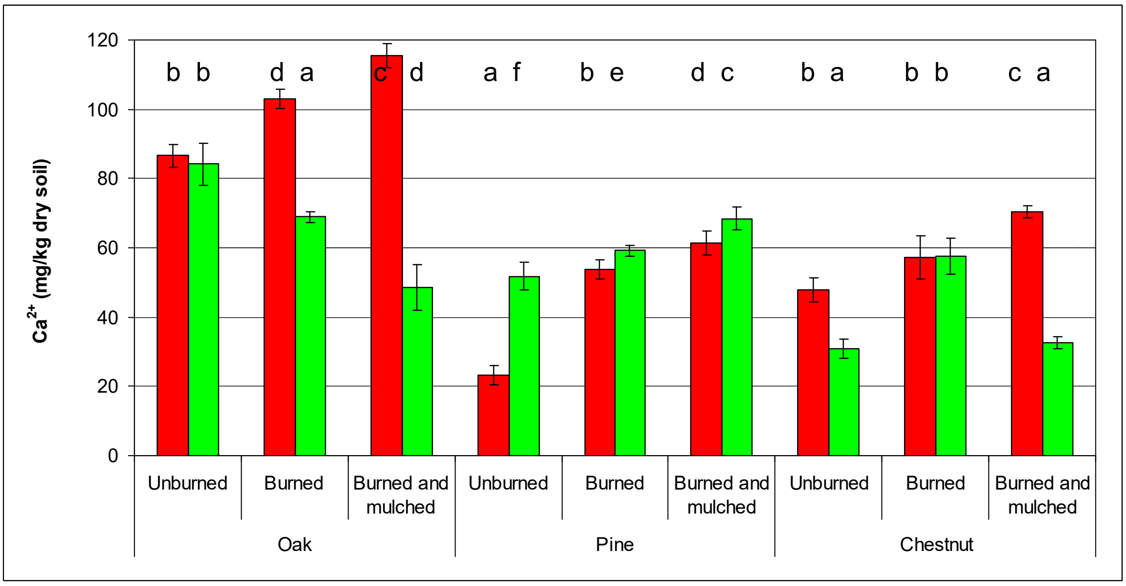
NH_4^+ (mg/kg dry soil)
1500
1200
900
600
300
0
d e
c b
a f
a b
b b
c b
a c
a d
e b
Unburned
Burned
Burned and mulched
Unburned
Burned
Burned and mulched
Unburned
Burned
Burned and mulched
Oak
Pine
Chestnut



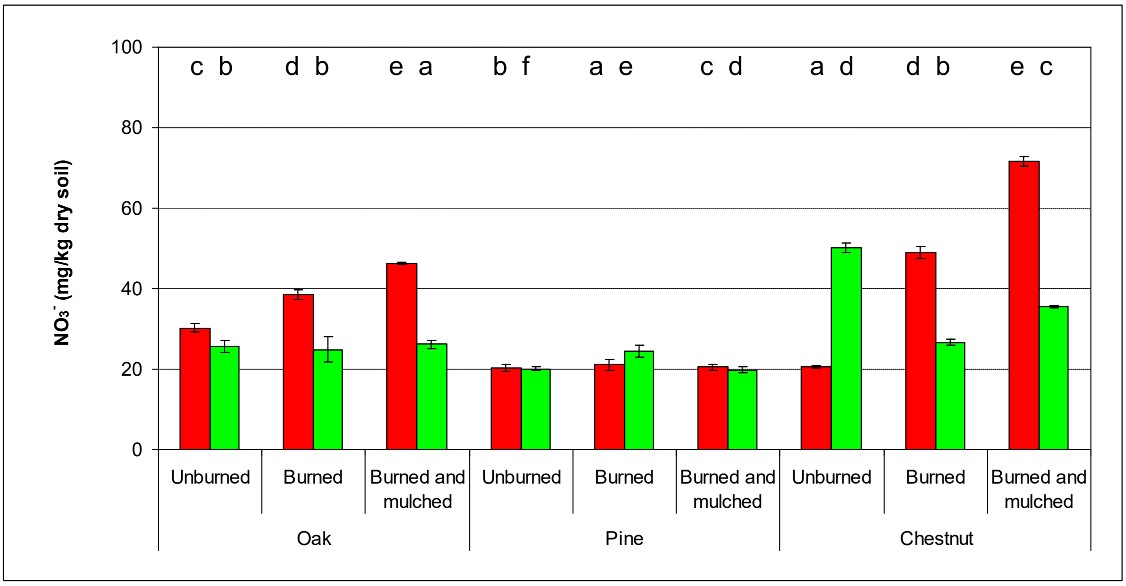
K+ (mg/kg dry soil)
120
100
80
60
40
20
0
a b
c d
de e
a b
bc bc
bc d
b ab
d a
c b
Unburned
Burned
Burned and mulched
Unburned
Burned
Burned and mulched
Unburned
Burned
Burned and mulched
Oak
Pine
Chestnut

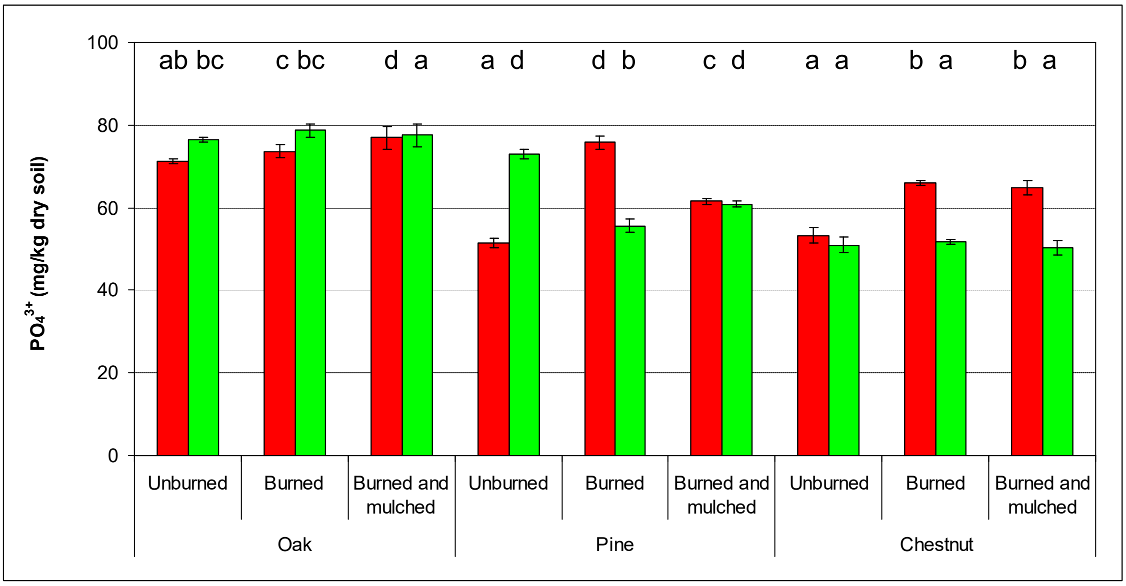


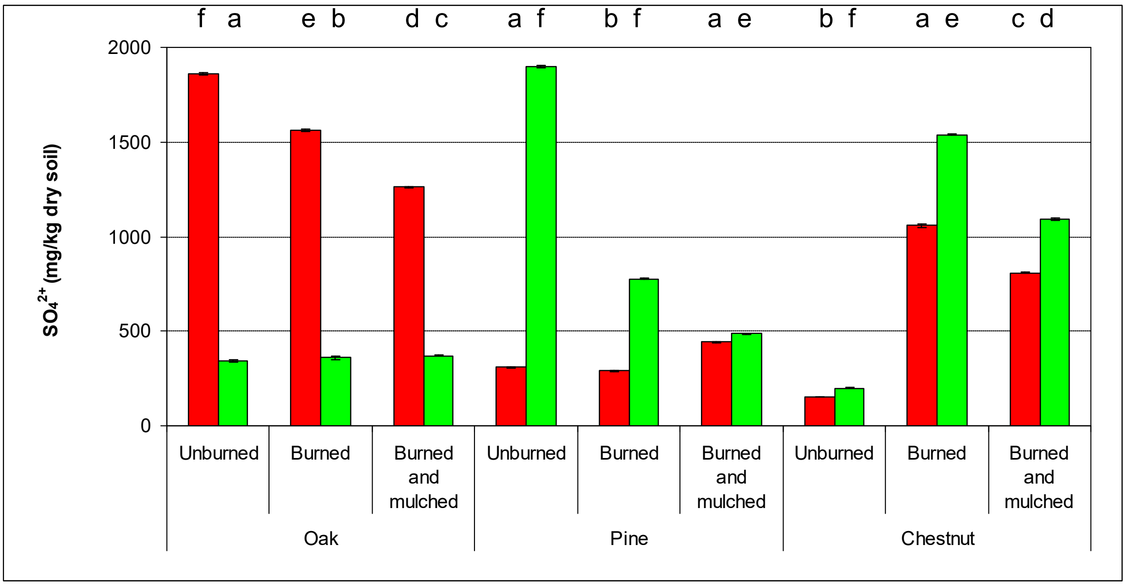
Mg2+ (mg/kg dry soil)
50
40
30
20
10
0
b b
c a
c d
a d
b cd
bc cd
b ab
c b
c a
Unburned
Burned
Burned and mulched
Unburned
Burned
Burned and mulched
Unburned
Burned
Burned and mulched
Oak
Pine
Chestnut

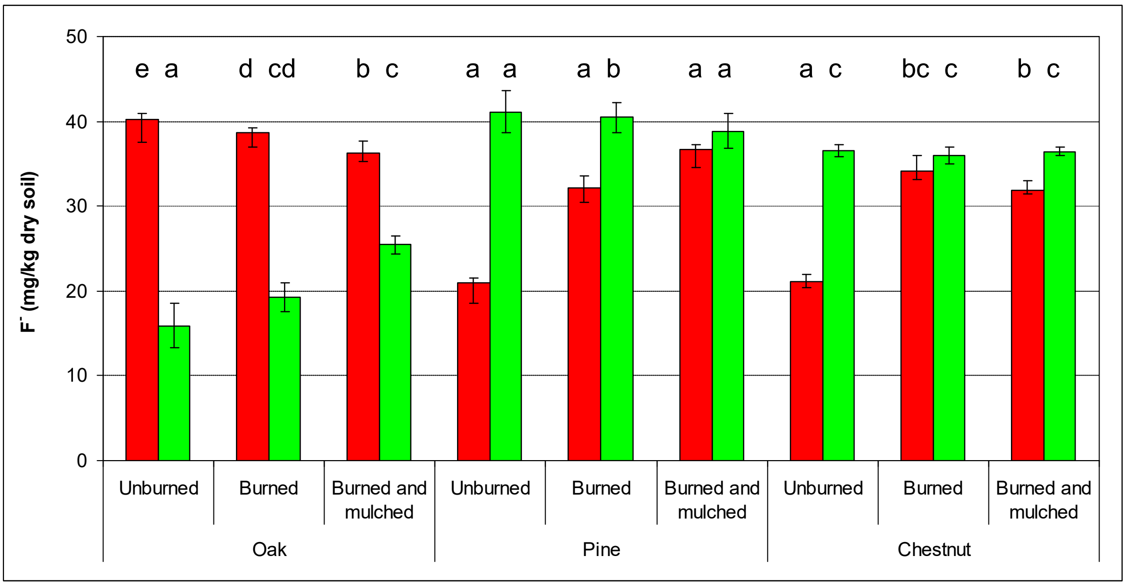


Ca2+ (mg/kg dry soil)
120
100
80
60
40
20
0
b b
d a
c d
a f
b e
d c
b a
b b
c a
Unburned
Burned
Burned and mulched
Unburned
Burned
Burned and mulched
Unburned
Burned
Burned and mulched
Oak
Pine
Chestnut


NO3- (mg/kg dry soil)
100
80
60
40
20
0
c b
d b
e a
b f
a e
c d
a d
d b
e c
Unburned
Burned
Burned and mulched
Unburned
Burned
Burned and mulched
Unburned
Burned
Burned and mulched
Oak
Pine
Chestnut


PO43+ (mg/kg dry soil)
100
80
60
40
20
0
ab bc
c bc
d a
a d
d b
c d
a a
b a
b a
Unburned
Burned
Burned and mulched
Unburned
Burned
Burned and mulched
Unburned
Burned
Burned and mulched
Oak
Pine
Chestnut


SO42+ (mg/kg dry soil)
2000
1500
1000
500
0
f a
e b
d c
a f
b f
a e
b f
a e
c d
Unburned
Burned
Burned and mulched
Unburned
Burned
Burned and mulched
Unburned
Burned
Burned and mulched
Oak
Pine
Chestnut



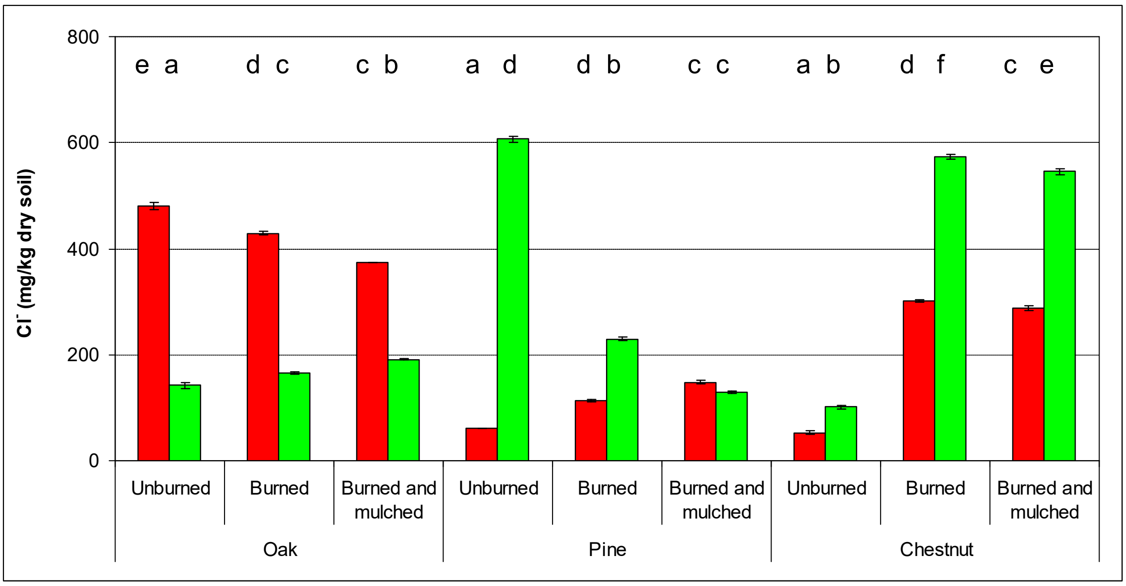


Figure 4 – Soil physico-chemical properties (mean ± standard deviation) measured after the prescribed fire and soil mulching with fern at two survey dates (one day and one year after the fire) in the experimental forest sites (Samo, Calabria, Southern Italy).

Notes: EC = electrical conductivity; OC = organic carbon; N = nitrogen; NH_4^+ = ammonium; K^+ = potassium; Mg^{2+} = magnesium; Ca^{2+} = calcium; NO_3^- = nitrates; PO_4^{3-} = phosphates; SO_4^- = sulphates; F^- = fluorides; Cl^- = chlorides. Different letters indicate significant differences among soil conditions of each forest site at $p < 0.05$.

The differences in N content of soils due to prescribed fire and mulching were not significant in the oak forest (-6.8%, burned sites, and -17.4%, mulched soils), while it significantly increased in pine (+30.3%, burned, and +29.8%, mulched sites) and chestnut (+14.4% and +5.6%, respectively) soils (Figure 4). Also, for this parameter, the variability was significant over time, except for pine forest. One year after the fire, the N content of burned soils significantly decreased compared to the unburned sites, particularly when the soils were mulched, with a maximum variation of -58.3% in chestnut forest. Only for pine forest, the interaction of soil condition × survey date was not significant (Figure 4).

Soil ions (NH_4^+, Mg_2^+, Ca_2^+, F^- and Cl^-) significantly changed among conditions and survey date. The interactions between these factors were significant. Compared to the unburned sites, significant increases in Mg^{2+} and Ca^{2+} were observed in burned (up to 176% for Mg^{2+}, and 131% for Ca^{2+}, in pine forest) and mulched (up to 268% for Mg^{2+} , and 164% for Ca^{2+}, in pine forest) soils for all species immediately after the fire, while, one year after, a general decrease in these ion concentrations were noticed (on average -44.1% for Mg^{2+}, and –20.3% for Ca^{2+}) (Figure 4). The NH_4^+ concentration was practically the same immediately after the fire (except in the mulched soils of chestnut forest, +93.8%), and was subject to noticeable increases (up to 172% in mulched soils of pine) over time (Figure 4).

The contents of K^+, NO_3^- and PO_4^{3-}in soils were significantly different among the soil conditions in all forest sites, but for all these properties the time was not significant in pine forests. The same was found for the interaction of soil condition × survey date for K^+ (Figure 4). The latter element, as also found for Mg^{2+} and Ca^{2+}, increased immediately after the fire (on average by about 75%), and particularly in chestnut forest, +206% in burned soils). In the chestnut forest, a marked decrease (on average by 73%) was noticed one year after the fire. A similar trend was detected for NO_3^- and PO_4^{3-} (an increase immediately after the fire, on average + 78.1% for NO_3^- and +20.6% for PO_4^{3-}, and a decrease one year after the fire, by 27% for NO_3^- and 10.6% for PO_4^{3-}) compared to the unburned sites), with some exceptions (NO_3^- in pine forests, and PO_4^{3-} in oak soils) (Figure 4).

The analysis of Pearson's matrix reveals interesting correlations among the soil properties (Table 3). It is worth highlighting that the most significant correlation (r over 0.90) was detected between SO_4^{2-} and Cl^- on both the survey dates, and the correlations between EC and ion concentrations are not significant immediately after the fire (Table 3).

PCA separately applied on the two survey dates provided three principal components, which together explain 80.2% (one day after the fire) and 76.2% (one year after the fire) of the original variance; the first two components explain 68.42% and 59.6% of this variance.

In more detail, according to the PCA related to the surveys carried out immediately after the fire, K^+, Mg^{2+}, Ca^{2+}, NO_3^-, $PO_4^{3-,}$ SO_4^{2-}, Cl^- and had high loadings (> 0.5) on PC1, while EC, C, N, and NH_4^{+-} were effective on the PC2, and pH on the third PC (Figure 5a and Table 4). For the surveys carried out one year after the fire, PC1 was associated with high EC, NH_4^+ K^+, Mg^{2+}, Ca^{2+} and F^-, while C, N and their ratio weighed on PC2 (loadings over 0.5), and NO_3^-, SO_4^{2-}, Cl^- and on PC3 (Figure 5b and Table 4).

AHCA allowed the soil samples to be clustered according to the soil conditions and forest species. More specifically, immediately after the fire, three similar clusters of soil samples were evident: (i) unburned soils of all forest species; (ii) burned and mulched soils of oak and chestnut; (iii) burned and mulched soils of pine (Figures 5c ad 6a). One year after the fire, the clusters of soil were characterized by a higher level of similarity, 0.30, compared to the survey one day after the fire, 0.21; the following three clusters were depicted by AHCA: (i) oak soils (unburned and mulched) and burned soils of chestnut; (ii) unburned soils of pine and chestnut; (iii) burned soils of oak and pine, and mulched soils of chestnut and pine (Figures 5d and 6b).

Table 3 - Correlation matrix of the soil parameters measured after the prescribed fire and mulching with fern at two survey dates (one day and one year after the fire) in the experimental forest sites (Samo, Calabria, Southern Italy).

Soil parameter	**pH**	**EC**	**OC**	**N**	**NH_4^+**	**K^+**	**Mg^{2+}**	**Ca^{2+}**	**NO_3^-**	**PO_4^{3-}**	**SO_4^{2-}**	**F^-**	**Cl^-**
	One day after the fire												
pH	**1**	0.245	0.306	0.366	0.056	**0.723**	**0.506**	0.018	**0.471**	-0.064	0.279	0.292	0.350
EC		**1**	**-0.550**	**-0.512**	**0.448**	0.162	-0.115	-0.025	-0.014	-0.357	**0.572**	0.171	**0.473**
OC			**1**	**0.671**	-0.128	0.346	**0.416**	0.287	0.276	**0.440**	-0.088	0.380	0.053
N				**1**	-0.308	**0.498**	**0.613**	0.318	**0.472**	**0.482**	-0.200	0.013	-0.048
NH_4^+					**1**	0.290	0.276	**0.556**	0.325	0.151	**0.772**	**0.541**	**0.814**
K^+						**1**	**0.822**	**0.544**	**0.889**	**0.491**	**0.481**	0.221	**0.607**
Mg^{2+}							**1**	**0.719**	**0.758**	**0.540**	0.355	0.322	**0.528**
Ca^{2+}								**1**	**0.639**	**0.763**	**0.481**	0.274	**0.618**
NO_3^-									**1**	**0.649**	0.295	-0.063	**0.450**
PO_4^{3-}										**1**	0.242	-0.015	0.346
SO_4^{2-}											**1**	**0.660**	**0.972**
F^-												**1**	**0.691**
Cl^-													**1**
	One year after the fire												
pH	**1**	**0.543**	0.325	0.062	0.231	0.309	**0.404**	**0.505**	**-0.520**	0.109	-0.168	0.107	-0.264

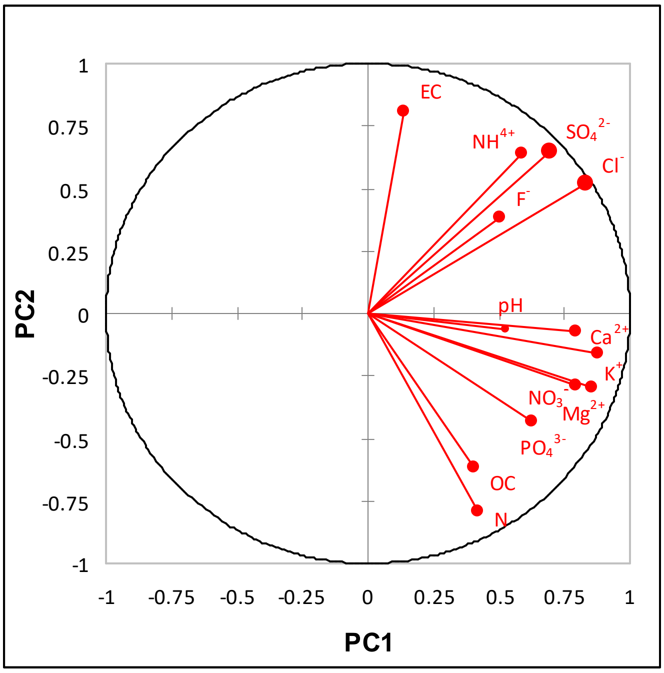
EC		**1**	-0.045	-0.337	**0.708**	**0.752**	**0.628**	**0.705**	**-0.519**	**0.557**	-0.258	**-0.519**	-0.271
C			**1**	**0.896**	0.068	-0.083	0.031	0.306	**-0.409**	0.138	-0.070	0.175	-0.375
N				**1**	-0.033	-0.259	-0.013	0.150	-0.101	-0.056	-0.047	0.212	-0.325
NH_4^+					**1**	**0.660**	**0.911**	**0.883**	-0.352	0.325	-0.210	**-0.523**	-0.292
K^+						**1**	**0.567**	**0.516**	-0.340	**0.645**	**-0.562**	**-0.582**	**-0.554**
Mg^{2+}							**1**	**0.885**	-0.295	0.127	-0.173	-0.345	-0.247
Ca^{2+}								**1**	**-0.557**	0.294	-0.148	**-0.456**	-0.285
NO_3^-									**1**	**-0.549**	-0.302	0.084	-0.137
PO_4^{3-}										**1**	-0.108	**-0.542**	-0.188
SO_4^{2-}											**1**	**0.479**	**0.943**
F^-												**1**	**0.401**
Cl^-													**1**

Notes: EC = electrical conductivity; OC = organic carbon; N = nitrogen; NH_4^+ = ammonium; K^+ = potassium; Mg^{2+} = magnesium; Ca^{2+} = calcium; NO_3^- = nitrates; PO_4^{3-} = phosphates; SO_4^- = sulphates; F^- = fluorides; Cl^- = chlorides; for each variable values in bold correspond to the factor for which the factor loading is the largest. values in bold are significant at $p < 0.05$.

Table 4 - Factor loadings of the soil properties on the first three Principal Components provided by the PCA after the prescribed fire and soil mulching with fern at two survey dates (one day and one year after the fire) in the experimental forest sites (Samo, Calabria, Southern Italy).

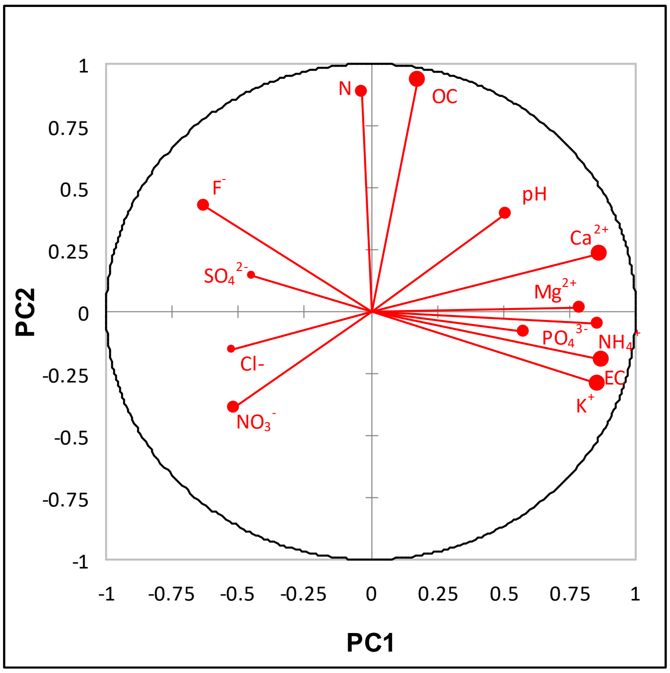
Soil parameter	Survey time					
	One day after the fire			**One year after the fire**		
	PC1	PC2	PC3	PC1	PC2	PC3
pH	0.274	0.004	**0.668**	0.259	0.153	0.032
EC	0.018	**0.654**	0.087	**0.762**	0.036	0.053
C	0.164	**0.383**	0.006	0.032	**0.879**	0.031
N	0.178	**0.626**	0.028	0.001	**0.781**	0.096
NH_4^+	0.344	**0.414**	0.077	**0.734**	0.003	0.020
K^+	**0.773**	0.026	0.101	**0.728**	0.082	0.022
Mg^{2+}	**0.735**	0.090	0.006	**0.621**	0.000	0.032
Ca^{2+}	**0.635**	0.005	0.256	**0.748**	0.056	0.048
NO_3^-	**0.632**	0.083	0.000	0.267	0.153	**0.357**
PO_4^{3-}	**0.389**	0.184	0.296	0.335	0.007	0.012
SO_4^{2-}	**0.487**	0.424	0.002	0.200	0.020	**0.724**
F^-	0.256	0.147	0.013	**0.402**	0.184	0.059
Cl^-	**0.691**	0.273	0.003	0.279	0.024	**0.674**

Note: EC = electrical conductivity; OC = organic carbon; N = nitrogen; NH_4^+ = ammonium; K^+ = potassium; Mg^{2+} = magnesium; Ca^{2+} = calcium; NO_3^- = nitrates; PO_4^{3-} = phosphates; SO_4^- = sulphates; F^- = fluorides; Cl^- = chlorides; for each variable values in bold correspond to the factor for which the factor loading is the largest.



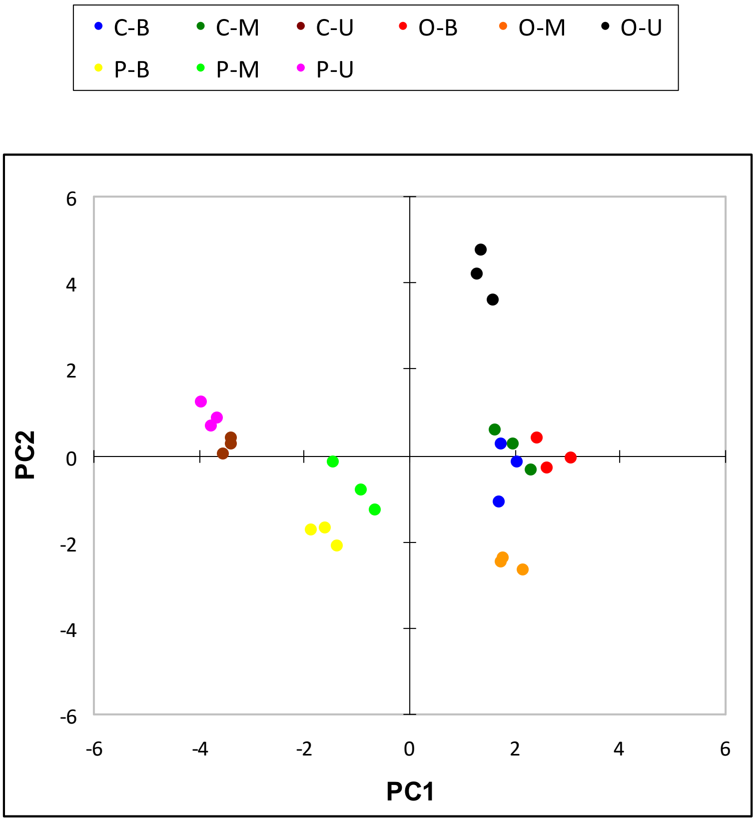
EC
NH4+
SO42-
Cl-
F-
pH
Ca2+
K+
NO3-
Mg2+
PO43-
OC
N
1
0.75
0.5
0.25
0
-0.25
-0.5
-0.75
-1
PC2
-1
-0.75
-0.5
-0.25
0
0.25
0.5
0.75
1
PC1

(a)

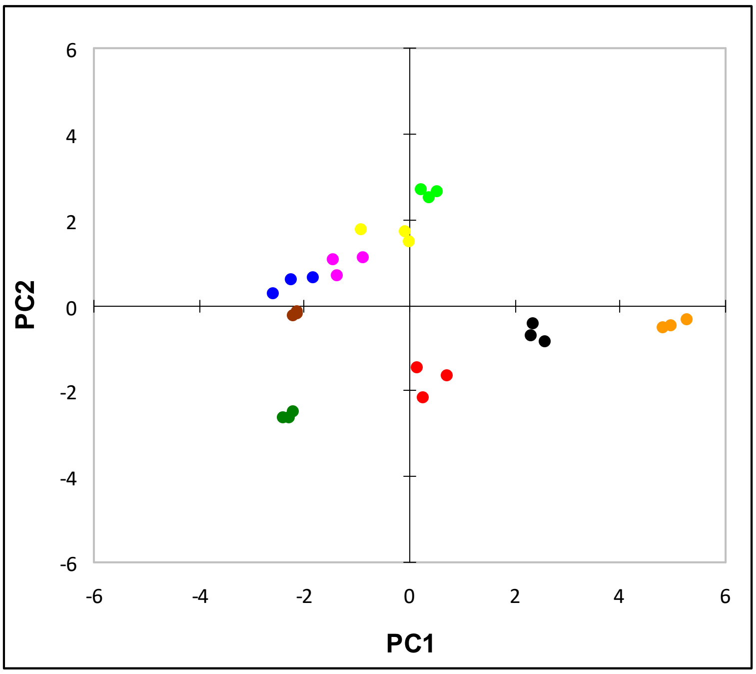


N
OC
F-
pH
Ca2+
SO42-
Mg2+
PO43-
NH4+
EC
K+
Cl-
NO3-
1
0.75
0.5
0.25
0
-0.25
-0.5
-0.75
-1
PC2
-1
-0.75
-0.5
-0.25
0
0.25
0.5
0.75
1
PC1

(b)


C-B
C-M
C-U
O-B
O-M
O-U
P-B
P-M
P-U
6
4
2
0
-2
-4
-6
PC2
-6
-4
-2
0
2
4
6
PC1

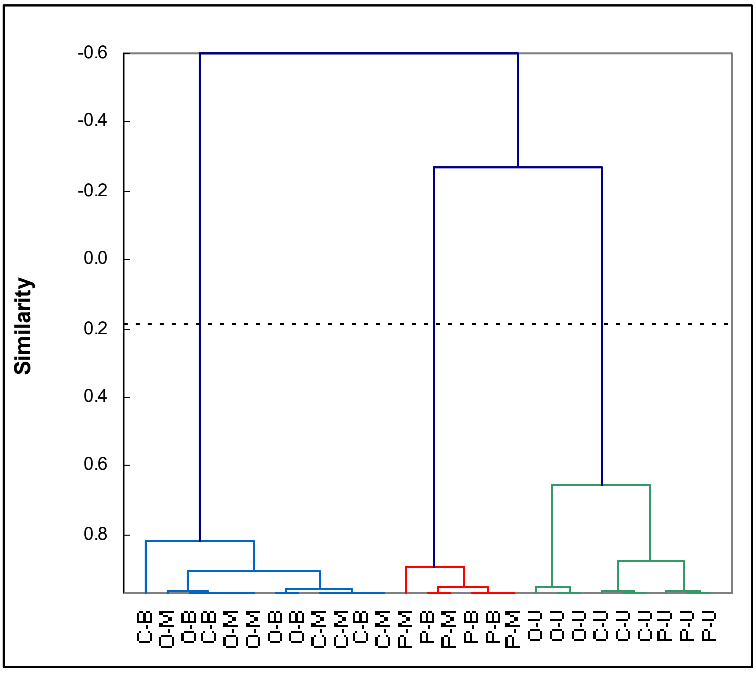
(c)


6
4
2
0
-2
-4
-6
PC2
-6
-4
-2
0
2
4
6
PC1

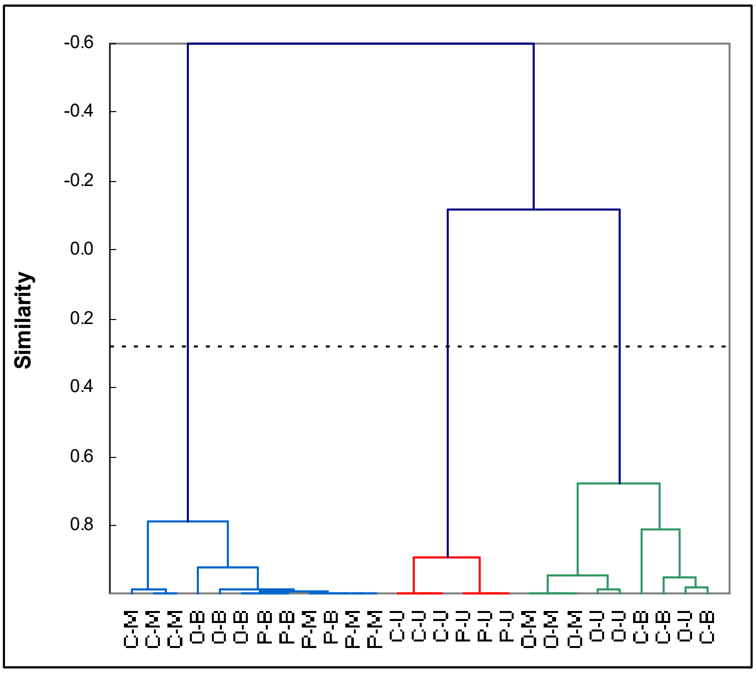
(d)

Figure 5 - Loadings of the soil properties (a) and scores of the soil samples (b) on the first two Principal Components (PC1 and PC2) provided by the PCA after the prescribed fire and soil mulching with fern at two survey dates (one day, a and c, and one year, b and d, after the fire) in the experimental forest sites (Samo, Calabria, Southern Italy).

Notes: EC = electrical conductivity; OC = organic carbon; N = nitrogen; NH_4^+ = ammonium; K^+ = potassium; Mg^{2+} = magnesium; Ca^{2+} = calcium; NO_3^- = nitrates; PO_4^{3-} = phosphates; SO_4^- = sulphates; F^- = fluorides; Cl^- = chlorides; O = oak; P = pine; C = chestnut; U = unburned; B = burned; M = burned + mulching; for each variable values in bold correspond to the factor for which the factor loading is the largest.



(a)



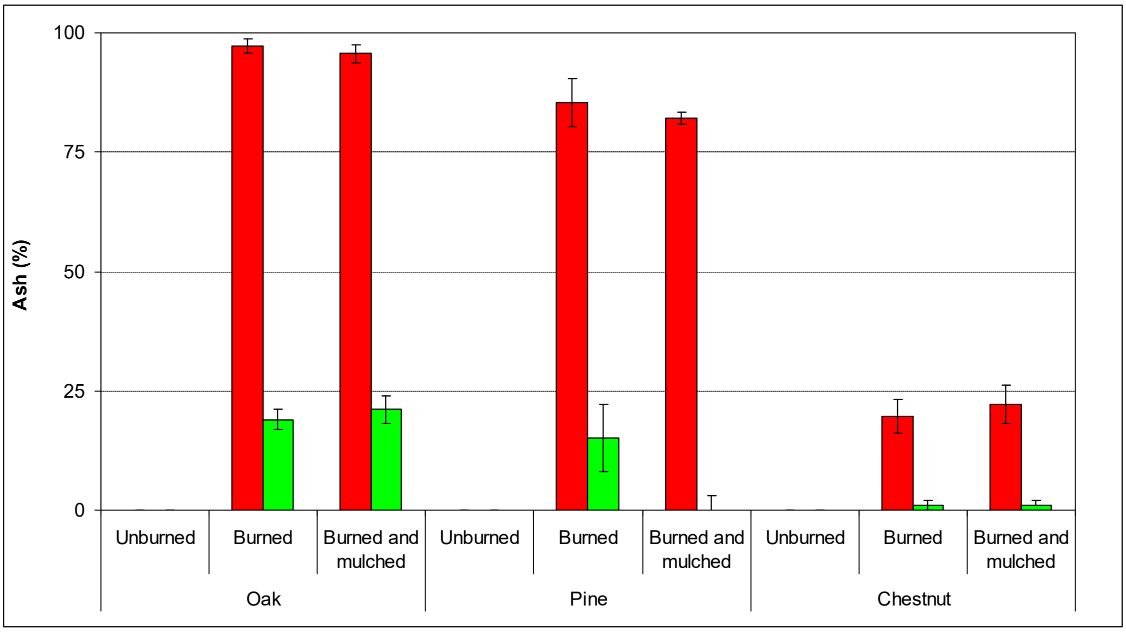
(b)

Figure 6 - Dendrogram provided by the Agglomerative Hierarchical Cluster Analysis (AHCA) of the soil properties after the prescribed fire and soil mulching with fern at two survey dates (one day, a, and one year, b, after the fire) in the experimental forest sites (Samo, Calabria, Southern Italy).

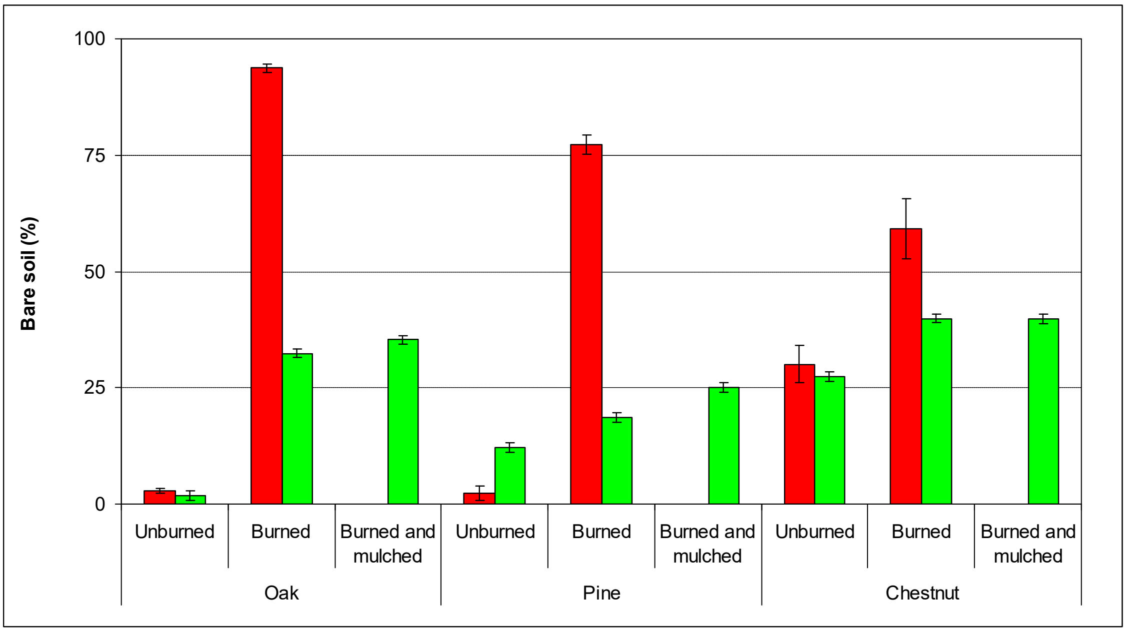
Notes: the y-axis reports the similarity level, while the dotted line the clustering level; O = oak; P = pine; C = chestnut; U = unburned; B = burned; M = burned + mulching; the dashed line is the level .*3.3. Soil covers*

Immediately after the fire, the soils of the three forest stands were covered in ash, in particular in oak and pine rather than chestnut (higher than 85% for oak and pine, and only 20% in chestnut). Fire also removed shrubs and herbaceous vegetation, and burned litter (especially in pine and oak, where it was more abundant compared to chestnut), leaving from 63% (chestnut) to 94% (pine) of bare soil (Figure 7).

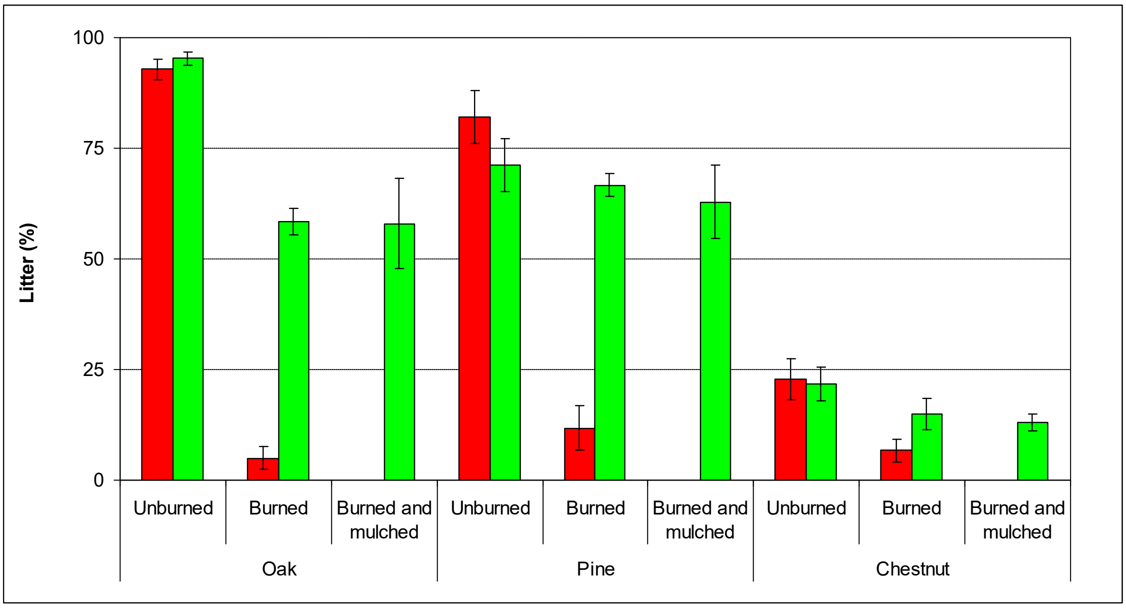
One year after the fire, the ash had almost completely disappeared, except in pine (burned sites) and oak (burned sites, mulched or not), where the maximum ash cover was lower than 25%. Shrub vegetation had regenerated, particularly in the mulched sites (up to 40% in chestnut forest), and litter covered the soils, especially in pine (up to 67%) and oak (95%), but less in chestnut forest (maximum litter cover equal to 15%). Vegetation recovery and litter covering over time caused reductions in the areas with bare soil, which decreased to 43% in chestnut (mulched sites), 36% in oak (burned soils, with or without mulching), and 32% in pine (mulched sites) (Figure 7). It should be highlighted that the differences in vegetation recovery between burned and mulched soils were limited (not higher than 2-3%) and never significant, and the same was noticed for litter cover (< 5%) and ash (< 15% in pine forest) (Figure 7).



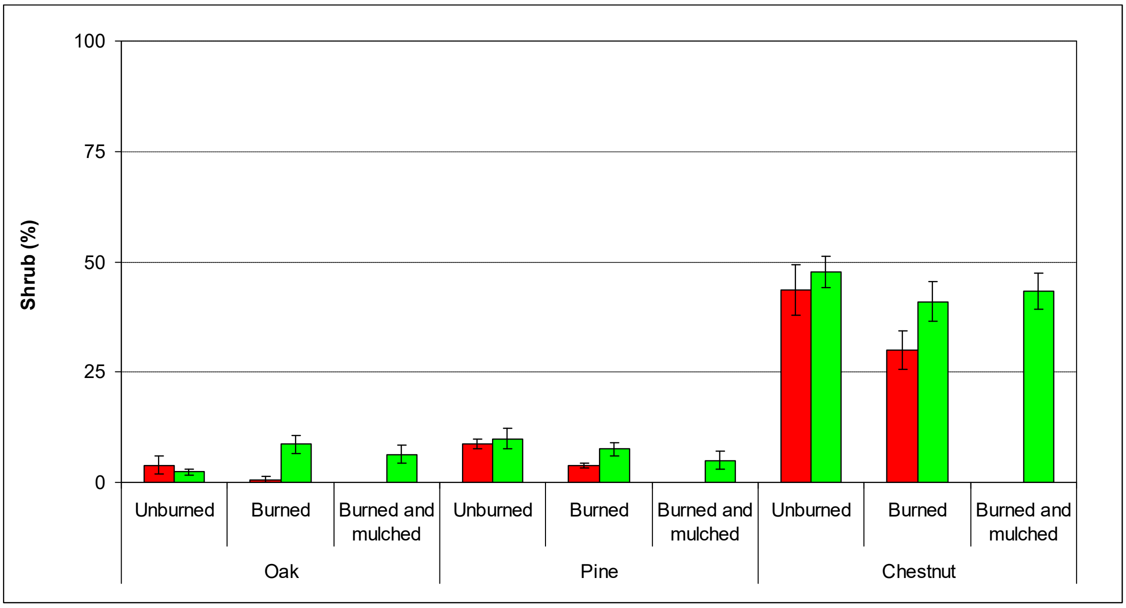
Ash (%)
100
75
50
25
0
Unburned
Burned
Burned and mulched
Unburned
Burned
Burned and mulched
Unburned
Burned
Burned and mulched
Oak
Pine
Chestnut



Bare soil (%)
100
75
50
25
0
Unburned
Burned
Burned and mulched
Unburned
Burned
Burned and mulched
Unburned
Burned
Burned and mulched
Oak
Pine
Chestnut



Litter (%)
100
75
50
25
0
Unburned
Burned
Burned and mulched
Unburned
Burned
Burned and mulched
Unburned
Burned
Burned and mulched
Oak
Pine
Chestnut



Shrub (%)
100
75
50
25
0
Unburned
Burned
Burned and mulched
Unburned
Burned
Burned and mulched
Unburned
Burned
Burned and mulched
Oak
Pine
Chestnut

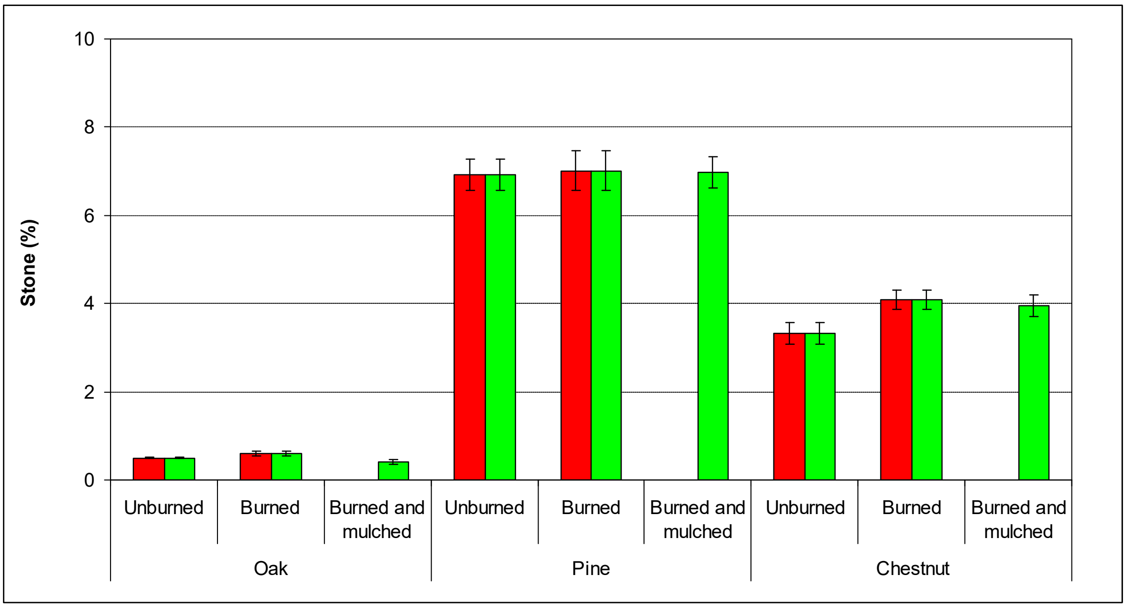


Figure 7 - Soil covers (mean ± standard deviation) after the prescribed fire and soil mulching with fern at two survey dates (one day and one year after the fire) in the experimental forest sites (Samo, Calabria, Southern Italy).

Note: no surveys were carried out in mulched soils, since soil cover with fern mulch was 100% and ash cover was the same as the burned soils.

4. Discussion

4.1. Changes in soil properties in burned soils

In this study, the soil pH was affected by burning immediately after the fire, although these changes were significant for two forest stands (pine and chestnut). One year after burning, these effects were significant in oak and chestnut soils. Although the individual processes that could explain these variations were not directly measured, the increase in pH could be due to consumption of organic acids during the oxidation of litter (Úbeda et al. 2005; Cawson et al. 2012; Binkley and Fisher 2019) and complete oxidation of organic matter (Mataix-Solera et al. 2009; Bodí et al. 2014; Hueso-González et al. 2018). Other authors ascribe the pH increase in burned soils to the incorporation of ash into the soil (Sherman et al. 2005; Pereira et al. 2016; Alcañiz et al. 2020), which usually releases carbonates, base cations and oxides in the ash cations (Certini 2005; Ekinci 2006; Fonseca et al. 2017), but this may be excluded in our study, since the ash cover in chestnut and pine soils (where the pH increases were significant) was higher compared to oak sites (where this increase was less noticeable).

The increases in pH detected in our study are in close accordance with the majority of studies of soil changes after low-intensity fires (Kennard and Gholz 2001; Scharenbroch et al. 2012; Badía et al. 2017). However, some other studies showed that pH values can remain unaltered, due to the low intensity of prescribed fires (Marcos et al. 2009; Badía et al. 2017; Hueso-González et al. 2018), except when fire was periodically repeated (Alcañiz et al. 2018). In general, the literature states that prescribed fire does not have a long-term effect on the soil pH, since this parameter depends on the time that ashes remain in the soil (Mataix-Solera and Guerrero 2007; Fonseca et al. 2017).

Also, EC significantly increased after burning, and this effect lasted for at least one year. EC rises in fire-affected soils (also in the case of low-intensity fire) due to the incorporation of ash (Úbeda and Outeiro 2009; Scharenbroch et al. 2012; Fonseca et al. 2017), release of soluble ions during the combustion of organic matter (Certini 2005; Alcañiz et al. 2018), and formation of black C (Certini 2005; Alcañiz et al. 2020). The increase in EC detected in this study may be surprising, since this effect is not reflected in the ion content. It is likely that this increase may be due to other ions that were not measured in this study (e.g., carbonates, sodium). An indirect confirmation of this effect may be the lack of significance of correlations between EC and concentrations of ions measured in this study.

The significant increases in EC detected in this study agrees with the results of many other authors (Granged et al. 2011; Scharenbroch et al. 2012; Alcañiz et al. 2020). However, the literature is not in agreement about the duration of these effects, since some studies report that EC is ephemerally increased by fire (Naidu and Srivasuki 1994; Hernández et al. 1997; Cawson et al. 2012), while other authors stated that one year after the prescribed fire EC values decrease, but never below their pre-fire levels (Alcañiz et al. 2020).

Immediately after the prescribed fire, the burned soils showed significantly higher OC contents compared to the unburned sites. These significant variations were present one year in pine forest, while, in burned soils of oak and chestnut, C contents significantly decreased. After a fire it is normal to find increased soil OC (Alcañiz et al. 2018), and this is presumably due to the incorporation of unburned or partially unburned slash fragments into the soil or to the incomplete combustion of the organic matter (Soto and Diaz-Fierros 1993; Úbeda et al. 2005; Alcañiz et al. 2020). Our results agree with Alcañiz et al. (2016), Binkley et al. (1992) and Armas-Herrera et al. (2016), who reported increased soil C immediately after a prescribed fire, and decreases in this soil property one year after the fire compared to the unburned soils (Alcañiz et al. 2018; Hueso-González et al. 2018). However, we should bear in mind that the dynamic of OC content in soil is highly variable also after a fire of low intensity, since this variability depends on various factors, such as fire characteristics, ecosystem type, and land topography (Alcañiz et al. 2018).

The same variations among the analysed soil conditions (unburned vs. burned soils) and survey dates, detected for OC was observed for N content of soils. Increase in N was recorded immediately after the fire in burned soils, followed by significant reductions one year after. The similar trends detected for OC and N contents are again in close accordance with (Alcañiz et al. 2020), who found increases in N in soils subject to burning at low intensity, due to ash incorporation and forest floor decomposition (Scharenbroch et al. 2012; Girona-García et al. 2018; Alcañiz et al. 2020). The low temperatures of prescribed fire facilitates the incorporation of N that is present in large amounts in ash (Úbeda et al. 2005; Khouri and Prendes 2006), and in the forest floor, which decomposing releases a substantial amount of N (Schoch and Binkley 1986; Certini 2005). The decrease in N one year after the fire agrees with the results of Muqaddas et al. (2015) and Blankenship and Arthur (1999), who reported a marked loss of total N two years after a fire (Alcañiz et al. 2018). In any case, the N variability among soil conditions and time supports the suggestion of Dimitrakopoulos and Martin (1994) and Úbeda et al. (2005) that also fires with low intensity are able to produce noticeable changes in N concentrations. Another reason for the N variability may be the sensitivity of N to fire, due to its multiple forms in the soil, since N can be volatilised, added and rapidly mobilised by plants (Úbeda et al. 2005).

The increases in the other soil properties immediately after the fire, such as Mg^{2+}, Ca^{2+}, K, NO_3^-, PO_4^{3-}, showed the key role of ash due to burning (Pereira et al., 2018a), which likely released these ions, increasing their content in burned soils (Cawson et al., 2012). This result agrees with Alcañiz et al. (2020), who measured significant increases in Mg^{2+}, Ca^{2+} and K^+ contents, followed by a recovery of original pre-fire levels of Mg^{2+} and Ca^{2+}, but not K^+. In contrast, Hueso-González et al. (2018), Arévalo et al. (2007) and Brye (2006) reported non-significant increases in many ions after a low intensity burning.

Vegetation and litter burning caused noticeable increases in P content only in pine and chestnut soils, although this enrichment declined in the short term, in close accordance with Cawson et al. (2012). However, the effects of fire are often ephemeral, since the recovery of pre-fire concentrations is achieved some months after the fire, such as, for instance, for K^+ in chestnut, Ca^{2+} and NO_3^- in oak and chestnut, Mg^{2+} in all forest soils). In accordance with our results, Khouri and Prendes (2006) reported that K^+ and P can return to pre-fire values after one to three months. In general, the trends detected in this study agree with several studies (Kennard and Gholz 2001; Switzer et al. 2012; Shakesby et al. 2015).

When the pre-fire values do not recover one year after the fire (e.g., K^+ and PO_4^{3-} in oak, Ca^{2+} and SO_4^- in pine), the soil changes due to fire can last years (Lavoie et al. 2010; Scharenbroch et al. 2012; Alcañiz et al. 2016). This recovery may be the result of leaching processes due to runoff

(Úbeda and Sala 2001; Úbeda et al. 2005), erosion (Fonseca et al. 2011, 2017), and plant consumption (Alcañiz et al. 2018). Moreover, this variability over time is not always due to the effect of fire, as shown by the variations detected for some properties also in the unburned soil (e.g., Mg^{2+} and Ca^{2+} in pine and chestnut, NO_3^- in chestnut, PO_4^{3-} in pine). Overall, the soil changes measured in this study strictly depend upon the analyzed property and tree species (Kutiel and Shaviv 1992; Cawson et al. 2012).

4.2. Changes in soil properties in mulched soils

Immediately after the fire, the burned soils of pine and chestnut treated with mulching showed significant reductions in pH, which did not recover after one year in comparison to the unburned sites. In all forest soils, the OC and N contents were significantly higher one day after the fire, and these variations were observed also after one year in pine forest, while, in soils of oak and chestnut, OC and N significantly decreased. EC also increased throughout the observation period. Therefore, mulching was not effective in limiting the variations in these soil properties.

The lower OC content detected in this study in the mulched soils of oak and chestnut may appear surprising. Presumably, the incorporation of the dead material supplied with mulching was not sufficient to balance the decreases in OC detected one year after the fire in burned soils; it not could be excluded that part of the organic matter applied with fern (presumably the soluble form) was leached by the infiltrating precipitation, which was higher in mulched areas compared to the burned sites (Carrà et al. 2021). However, according to Cawson et al. (2012), the recovery of soil organic matter after the fire is generally fast, because it starts with the natural vegetation or its artificial reintroduction, thanks to the high productivity of secondary ecological succession. The higher shrub cover measured in this study for chestnut soils may also be an indication of higher plant uptake of OC and N due to regeneration, although this explanation should be confirmed by specific ecological surveys.

The higher water infiltration in all forest sites, and plant uptake measured in the chestnut forest may again explain the reduced content of N in mulched soils. In general, variations in total N availability seem to be associated with herbaceous vegetation growth (De Lillis, M 1993; Marcos et al. 1999), and the rapid drop in this soil property in the post-fire recovery period could be attributed to leaching, microbial immobilization and plant uptake (Antos 2003) as well as volatilisation (Úbeda et al. 2005; Binkley and Fisher 2019; Romeo et al. 2020).

It is interesting to note that the increase or decrease in any property was not influenced by mulching; thus, this treatment did not affect the properties of burned soils. This deserves more investigation, since, when vegetation residues are used as mulch material, organic matter content can increase (Jordán et al. 2010; García-Orenes et al. 2012; Prosdocimi et al. 2016). Presumably, the time elapsed from mulch application was too short in order to complete incorporation of vegetal residues into soil or part of the mulch cover was displaced by water, hampering soil incorporation (Bombino et al. 2021a).

4.3. Relationships among the soil properties

At both survey dates, among all the soil properties investigated in this study, PCA provided some key parameters, which clearly modify soil characteristics among the different conditions and tree species studied. At both dates, EC and ion concentrations exert a noticeable influence on the first PC, and furthermore OC and N contents together influenced the second PC. Therefore, it is the role of ash that determines changes in EC and ion concentrations, and burning and mulching that cause changes in OC and nutrients. This holds true for different tree species and variable conditions. It is interesting to note that, immediately after the fire, burning determined significant differences in soils of all forest species (grouped in the same cluster, while the mulched soils were differently clustered). After one year, the disturbance factors (burning and mulching) altered the similarity among all the soil conditions and forest species, and no evident clusters of soils with the same condition can be noted, thus proving the transient effects of prescribed burning and soil mulching on soils.

5. Conclusions

The study showed that prescribed fire and post-fire management with fern mulching had noticeable impacts on the soil of three Mediterranean forest species. The changes in the soil's chemical properties were often significant, but the effects of the prescribed fire and mulching were often transient, since the changes depend on the ash production and incorporation, seasonality and forest species. Significant increases in EC, total C and N content, and ion concentrations were detected in burned soils (mulched or not) immediately after the fire, while soil pH was less affected by these disturbance factors. For some properties the increases were ephemeral with reductions detected one year after the fire (e.g., OC and N), while, for other parameters (e.g., EC, K^+ and NH_4^+), the pre-fire values were not restored. It is important to highlight that, in general, mulching was not effective in limiting the changes in the monitored soil properties compared to the pre-fire values. Each forest species showed different temporal trends in changes of soil properties. This was confirmed by the combined Principal Component Analysis and Agglomerative Hierarchical Cluster Analysis, which clearly differentiated the diverse soil conditions and forest species in homogenous clusters.

Overall, the study confirmed that prescribed fire, although being a low-intensity fire, is able to induce significant changes in soil properties. These changes depend on both soil properties and forest species considered. Mulching with fern is unable to limit the changes in chemical properties of soils. Future research paths should validate the findings of this study, which are specific to the semi-arid Mediterranean climate. Forests and soils in different environments (due to weather, pedology, ecology) may produce other trends in soil changes due to both prescribed fire and mulching. Moreover, a specific hydrological study on its effectiveness on runoff and erosion on forest hillslope may justify its use to mitigate the hydrogeological risks in wildfire-affected areas, exploiting its economic convenience and naturalness compared to other mulch materials. Extending the analyses to the microbiological properties of soils (e.g., enzyme contents, microbial respiration) may clarify other effects, which were not studied in this investigation. Finally, the general aim of this study was the identification of the indirect effects of burning and post-fire treatment on forest soils regardless of the direct cause. A specific and deeper analysis of individual or homogenous types of soil properties (e.g., nutrients, ions, covers) may be beneficial to fully understand the processes that have determined the observed changes. This may also resolve any apparent disagreement in the literature.

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