J. Hydrol. Hydromech., 70, 2022, 4, 462–474
https://doi.org/10.2478/johh-2022-0028

sciendo Journal of Hydrology and Hydromechanics Institute of Hydrology SAS

Variability of soil properties with fire severity in pine forests and reforested areas under Mediterranean conditions

Manuel Esteban Lucas-Borja[1], Cristina Fernández[2], Pedro Antonio Plaza-Alvarez[1], Bruno Gianmarco Carrà[1], Demetrio Antonio Zema[3*]

[1] Castilla La Mancha University, School of Advanced Agricultural and Forestry Engineering. Department of Agroforestry Technology and Science and Genetics, Campus Universitario s/n, E-02071, Albacete, Spain.
[2] Centro de Investigación Forestal-Lourizán, Xunta de Galicia, P.O. Box 127, 36080 Pontevedra, Spain.
[3] Mediterranean University of Reggio Calabria, Department AGRARIA, Località Feo di Vito, I-89122 Reggio Calabria, Italy.
[*] Corresponding author. E-mail: dzema@unirc.it

Abstract: It is well known how fires affect the properties of forest soils depending on its severity. A better understanding of the magnitude of these impacts is essential to setup effective management actions after fire against the losses of soil and biodiversity. However, physical, chemical and biological processes in burnt soils are complex, resulting in a diversity of fire-induced changes, as acknowledged in many literature studies. Moreover, these changes may be even variable between natural forests and reforested areas. This study explores the changes in the most important soil properties with fire severity, from low to high. The main chemical parameters of soils were measured after field sampling in different pine forests (burnt natural stands, reforested areas as well as unburnt sites) of Castilla La Mancha (Central Eastern Spain). In comparison to the unburnt soils, the investigation has shown in the burnt areas: (i) no evident changes in soil pH at all fire severities, except in natural stands burnt at a very high severity (showing an increase of about 10%); (ii) increases in the organic carbon content (by about 70%) of soils burnt at a moderate fire severity under both forest ecosystems, and in reforested areas at very high fire severities (+95%); (iii) small differences in the nitrogen content of soil, except for a significant increase measured in soils burnt at an moderate fire severity under both the natural pine stand and reforested area (about +300%); (iv) a limited variability of the phosphorous content in the soil, with only an increase in soils under natural pine stands burnt at moderate fire severity (by 250%); (v) increases in magnesium and potassium contents in soils burnt at the highest fire severities for both land conditions, and decreases in calcium content in reforested areas burnt at the highest severity. Due to some negative impacts (increase in pH and decrease in organic carbon), the implementation of post-fire management actions at natural pine stands burnt at the highest fire severity should be a priority over reforested areas. Overall, this study did not show a straightforward pattern between soil properties, fire severity and land condition. This means that other parameters (for instance, the hydrological properties of soils) that were not explored in this investigation could have played an important role, and therefore must be taken into consideration when defining post-fire management actions.

Keywords: Pine natural stand; Pine reforestation; Soil changes; Soil organic carbon; Nutrients; Post-fire management.

1 INTRODUCTION

Wildfires heavily affect forest ecosystems, due to removal of the vegetation cover and changes in soil properties. These impacts determine loss in biodiversity and modify the hydrological processes in forest soils (Moody et al., 2013; Shakesby, 2011). While the hydrological changes expose the soil to erosion (Lucas-Borja et al., 2020a), changes in the physico-chemical properties of soils can be severe and often irreversible, compromising the recovery of vegetation (Zema, 2021). However, other factors (e.g., vegetation removal, which leaves the soil bare, and soil water repellency, which induces soil hydrophobicity) can also account for the negative impacts of fire on forests (Lucas-Borja et al., 2022; Zema et al., 2022).

Moreover, forest fires result in ash deposition, changes in the structure, concentrations and forms of soil elements or compounds (Badía et al., 2017; Zavala et al., 2014) as well as in alterations of its biological properties (Agbeshie et al., 2022; Pellegrini et al., 2018). For instance, organic matter and nutrient contents decrease after fire, and changes in microbial communities composition and enzymatic activity are common (Carra et al., 2021; Inbar et al., 2014; Lucas-Borja et al., 2020c). The forest type (natural or reforested stand), age (young or old stands) and management practices (that is, forest operations) can play an important role in driving the soil properties after fire (Jarvis et al., 2013; Neary et al., 1999; Zema, 2021; Zema et al., 2021b, 2021a).

The post-fire physico-chemical and biological processes in soils can be extremely complex, due to the large variability of driving factors (ash release, vegetation cover, morphology as well as post-fire weather patterns and post-fire land management (Pereira et al., 2018; Robichaud et al., 2020; Salis et al., 2019)). With regard to the main chemical properties of forest soils, pH should not change following low to moderate fires (Agbeshie et al., 2022; Alcañiz et al., 2018; Valkó et al., 2016), while noticeable modifications are expected after high-intensity wildfires (Agbeshie et al., 2022; Zavala et al., 2014). Organic carbon content generally increases in burnt areas compared to unburnt soils after low severity fires (Agbeshie et al., 2022; Caon et al., 2014), but decreases after medium- or high-intensity fires (Mataix-Solera et al., 2011). Burning volatilises part of the organic nitrogen in soils (Binkley and Fisher, 2019; Certini, 2005; Turner et al., 2007), which is converted into inorganic forms (Certini, 2005), thereby contributing to the maintenance of total nitrogen. Phosphorous is also altered by fires (Cade-Menun et al., 2000), but the total content often increases (Serrasolsas and Khanna, 1995). The cation contents of burnt soils generally increase due to ash deposition (e.g., (Certini, 2005; Elliott et al., 2013; Khanna and Raison, 1986; Shrestha and Chen, 2010).

The changes in soil chemical properties induced by burning can lead to contrasting impacts on soils (e.g., in organic matter and nutrient contents), which also depend on the specific environmental conditions of the fire-affected areas. These contrasting results require more research with specific field investigations in environments with different characteristics. These investigations should give scientists and land managers insight about the type and magnitude of the expected changes in soil chemical properties after fire. The influence of fire on soils has not been comprehensively studied as compared to the effects on vegetation (Agbeshie et al., 2022), although several studies addressing soil properties in burnt forests have been carried out in different Mediterranean ecosystems (e.g., Inbar et al., 2014; Neris et al., 2013; Wittenberg et al., 2011). Less studies exist that have investigated changes in soil physico-chemical properties under different fire severities and different forest types (e.g., natural stands, reforested areas and managed forests). It is well known that the magnitude of soil changes depends strongly on fire severity (Certini, 2005; Zavala et al., 2014; Zema, 2021). The latter is considered as a key descriptor of soil changes after fire, due to its implications on the hydrological response (Fernández et al., 2020; Fernández and Vega, 2016; Fernández-Alonso et al., 2019). The analysis of soil chemistry after burning in natural and reforested areas has also been insufficient, and this leaves open issues about soil degradation in areas where fire impacts sum up to the disturbance caused by planting and machinery operations. Since the fire effects on soil properties are complex issue, the knowledge about the changes in soil properties induced by fire is not enough to setup effective practices for the conservation of forest soils (Agbeshie et al., 2022; Zhang and Biswas, 2017). Therefore, more knowledge is needed on the impacts of forest management actions on burnt soils, to limit its degradation.

To fill this gap, this study explores the variability of several important chemical soil properties with fire severity (from zero to five, according to the modified classification proposed by Vega et al., 2013) - in two forest ecosystems (a natural pine stand that has not been managed or subjected to any disturbances in several decades, and a reforested area) of Castilla La Mancha (Central Eastern Spain). The specific objectives of this research are the following: (i) evaluating the changes in pH, carbon, nutrients, and cations in soils subjected to fires with different severity (from low to high); (ii) assessing whether the main soil properties of natural pine stands are more sensitive to fires than reforested areas; (iii) identifying possible similarities in soil chemistry among the different land conditions and fire severities under investigation. To achieve these aims, we hypothesise that: (i) the higher is the fire severity, the higher is the change in a specific soil property); and (ii) fire effects differ between natural and reforested areas.

2 MATERIALS AND METHODS

2.1 Study area

The study area is located in the municipality of Liétor (province of Albacete, region of Castilla-La Mancha, Spain, 38º30'40.79" N; 1º56'35.02" W, Figure 1). Its elevation ranges between 520 and 770 m above the mean sea level. The climate is semi-arid, and it is categorized as type BSk according to the Köppen classification (Kottek et al., 2006), with mean annual temperature and precipitation of 16.6 °C and 321 mm, respectively. Soils are classified as Calcid Aridisols (Nachtergaele, 2001), with a sandy loam texture. The study sites have a northwest exposition and a mean slope of 15–25%. The dominant overstory vegetation consists of Aleppo pine (*Pinus halepensis* Mill.) with a shrub layer of kermes oak (*Quercus cocciferae*) (Peinado et al., 2008). Before the wildfire, the stand density and tree height ranged from 500 to 650 trees/ha and from 7 to 14 m, respectively. The understory vegetation also includes *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. The economic value of the understory species decreased in the mid of the 20th century, and this led to agricultural abandonment and reforestation by Aleppo pines of natural origin. Therefore, a mixture of natural pine (not affected by wildfire in the last 100 years) and reforested stands of Aleppo pine, of about 60–70 years old, composes the study area. The vegetation before the fire was heavily anthropized, with Aleppo pine trees of natural origin in valley and shady areas where moisture accumulates and/or in very steep and inaccessible areas; and reforested pine stands in areas of poor soils and steep slopes.

In July 2021, a wildfire burnt a large part of the forest area, both natural pine stands and reforested areas, where the vegetation was fully burned by crown fire. No fire history was registered over the last 100 years in the selected area. The extent of the fire-affected areas by different fire severities is difficult to assess, since all severity types are mixed in the study area. One week after the wildfire, a study area of about 10 ha was selected, including both unburnt and burnt forests, the latter subjected to a crown fire with 100% tree mortality (Figure 1). The soils of the study area are very homogenous with small spatial variability, as shown, for instance, by the high similarity of soil texture between unburnt and burnt soils (Table 1).

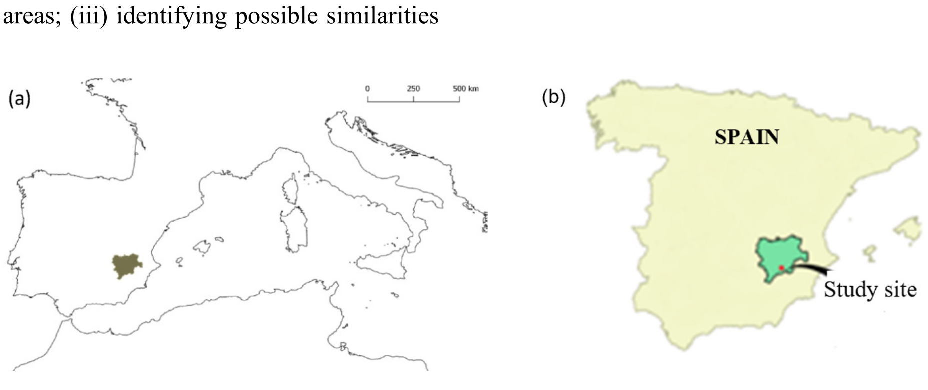


Fig. 1. Geographical location of Albacete province (a) and the study site of Liétor (b), within the region of Castilla La Mancha (Central Eastern Spain).

Table 1. Average texture of unburnt and burnt (at low and high severity) soils in the study area.

Soil texture	Soil condition					
	Unburnt		Low-severity fire		High-severity fire	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
SaC (%)	42.80	2.41	42.85	1.19	41.43	1.72
SiC (%)	33.35	0.77	34.70	0.83	33.78	1.33
ClC (%)	23.85	2.18	22.50	0.70	24.75	0.39

SaC - sand content; SiC - silt content; ClC - clay content.

2.2 Experimental design

One week after the wildfire of 2021, and before the first rainfall event, the burnt area was delimited together with adjacent unburnt areas. In these areas, 32 plots (each of 20 cm x 20 cm) were randomly installed as follows: 14 plots were established in the burnt natural pine stand; 14 plots were identified in the burnt pine reforested areas. In both areas, the vegetation was fully burnt by a crown fire. Four additional plots were selected in an unburnt area close to the areas affected by the wildfire, two in the natural pine stand and two in the reforested area. The minimum reciprocal distance among all plots was 300 metres, to avoid pseudo-replication (that is, not statistically independent observations or correlations of measurements in time or space). In each plot, sampling areas characterised by different soil burn severities were identified (Figure 3).

The soil burn severity was assessed in each plot using a modification of the classification proposed by Vega et al. (2013). This classification consisted of the following levels of soil burn severity (Figure 2):

- Very low severity (Level 1): bare soil together with soil with limited burnt litter, but limited duff consumption;
- Low severity (Level 2): bare soil together with burnt litter;
- Moderate severity (Level 3): Oa soil layer totally charred and covering mineral soil, with some ash and black carbon on the surface;
- Moderate to high severity (Level 4): forest floor completely consumed (bare soil), but soil organic matter not consumed and surface soil intact; mostly grey soil colour (due to ash) on the soil surface;
- High severity (level 5): forest floor completely consumed, soil organic matter on the soil surface consumed and soil structure altered within a depth of less than 1 cm; grey soil colour (with orange colour on the surface).

A “level 0” of the soil burn severity was attributed to the unburnt soils.

Therefore, the experimental design consisted of three land conditions (burnt natural stand vs. burnt reforested area vs. unburnt forest) × five fire severities (class 1 to 5). The number of replications for each fire severity were variable, from two (class 3) to four (class 0, unburnt area) (Figure 3).

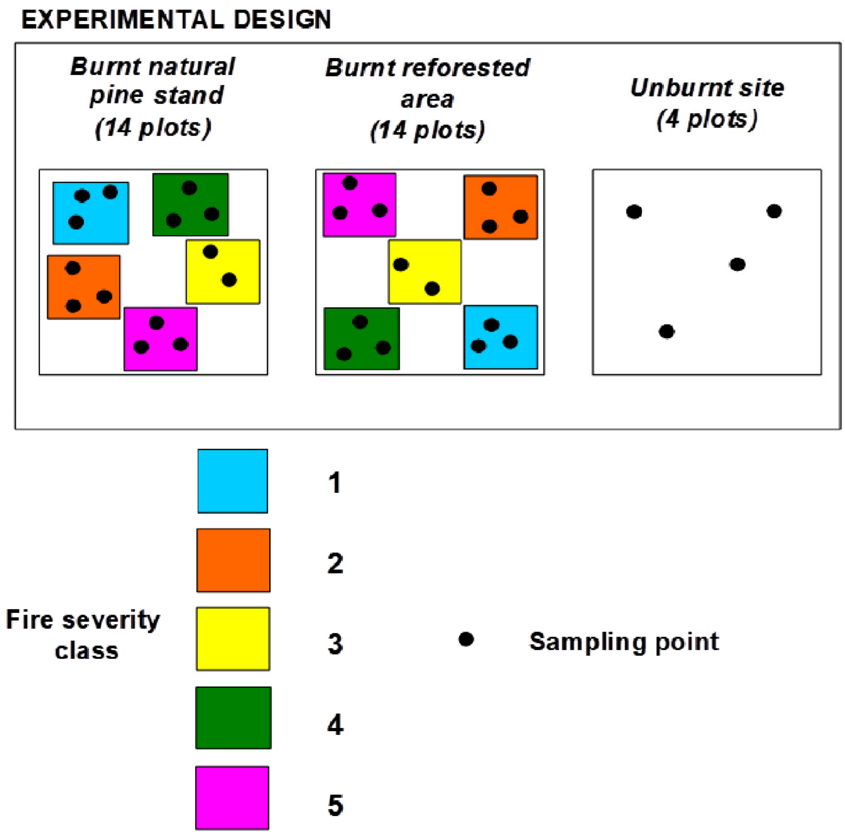


Fig. 2. Scheme of the experimental design implemented at the study site.

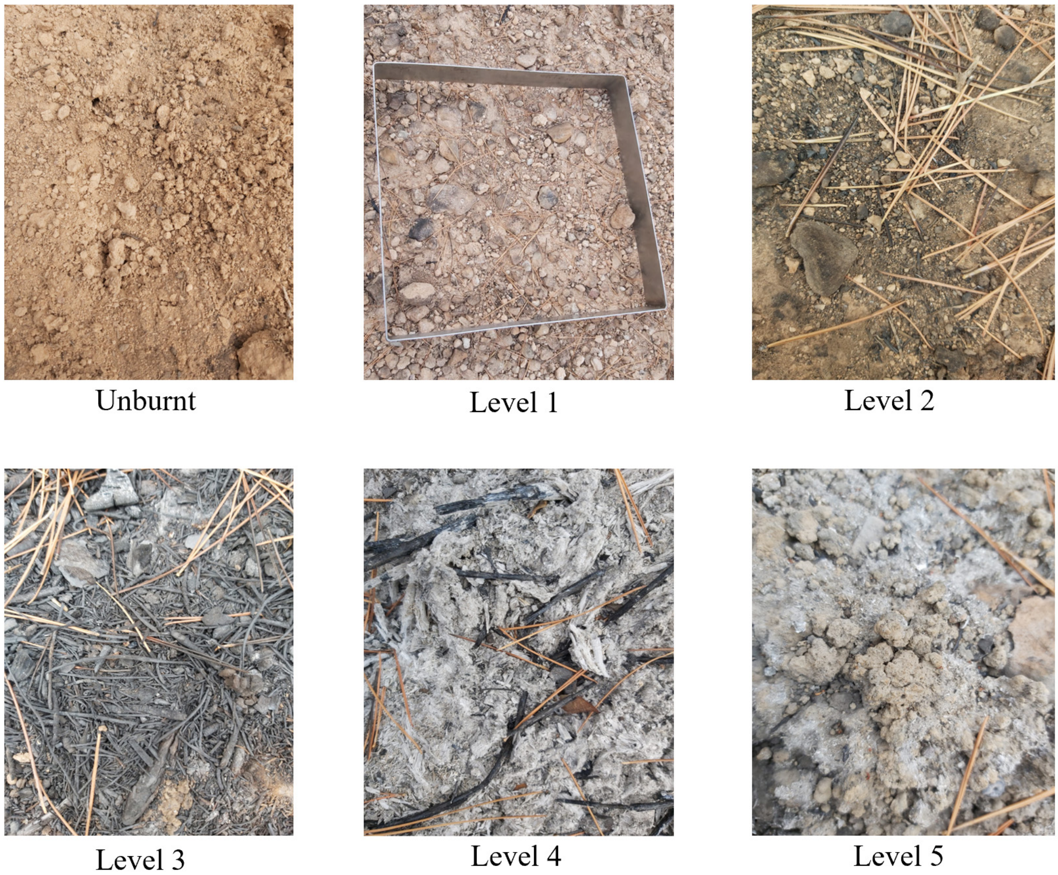


Fig. 3. Soil burning severity levels observed at the study site.

For each level of soil burning severity and unburnt areas, soil samples were collected using a cylindrical plastic collar (diameter of 10 cm and 3 cm of height) at a depth between 2 and 5 cm in the 32 sampling areas, to measure the main chemical properties. Due to the low variability of soil properties for the two areas (lower than 5%), and the high disturbance exerted by fire compared to forest management, we considered one value of each property for the unburnt areas (assumed as "control"). This choice allowed the reduction in the number of comparisons among the different land conditions and fire severity levels.

The samples were transported to the laboratory in the same plastic collars, to keep them intact, and preserved in a fridge at 4 °C. The soil analyses were carried out two weeks after the fire.

2.3 Analysis of soil chemical properties

Each soil sample was air dried, homogenized and sieved (< 2 mm) before analysis. Total soil carbon (TC) was determined in a Leco elemental analyzer (Leco Corporation, St Joseph, MI). Inorganic carbon (IC) was determined on samples at 400 ºC for 4 hours after calcination. Organic carbon (OC) was calculated as the difference between TC and IC. Total nitrogen (TN) was determined using the Kjeldhal's method as modified by Mulvaney and Bremner (1978). Although this method measures organic and ammonia nitrogen, the presence of nitrites (unstable forms of nitrogen, which are easily oxidised to nitrates) and nitrates (generally leached into deeper soil layers), should be very low in the topsoil, and therefore negligible. Moreover, this does not alter the differences in nitrogen among the different land conditions and fire severities investigated in this study. The soil pH was determined in distilled water, at a soil:solution ratio of 1:2.5. The content of total phosphorous (TP) and cations (potassium, K^+, calcium, Ca^{2+}, and magnesium, Mg^{2+}) were determined by ICP spectrometry after nitric-perchloric acid digestion (Lucas-Borja and Delgado-Baquerizo, 2019).

2.4 Statistical analysis

A 2-way ANOVA (ANalysis Of VAriance) was separately applied to the different soil properties (individually considered as response variables), assuming as factors the land condition (unburnt soil, burnt natural stand and reforested area) and fire severity (levels 1, 2, 3, 4, and 5). Whenever significant differences were found, a pairwise comparison was performed using the Tukey's test (at $p < 0.05$ as significance level). 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.

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

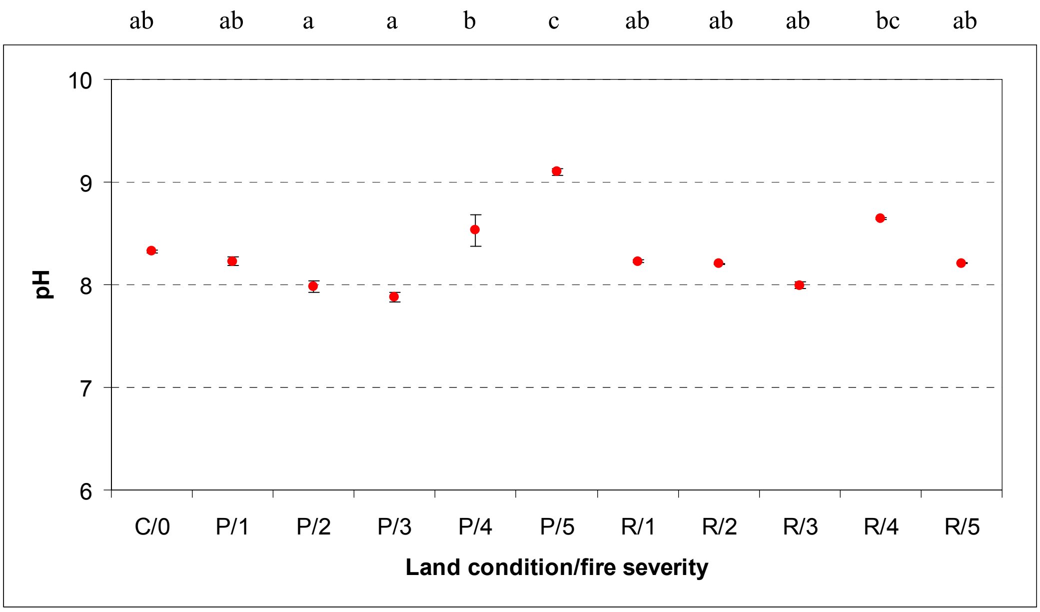
Finally, the observations were grouped in clusters using Agglomerative Hierarchical Cluster Analysis (AHCA), a distribution-free ordination technique to group samples with similar characteristics by considering an original group of variables. The Euclidean distance was used as a measure of similarity-dissimilarity (Zema et al., 2015). All statistical analysis was carried out using the XLSTAT 2019 software.

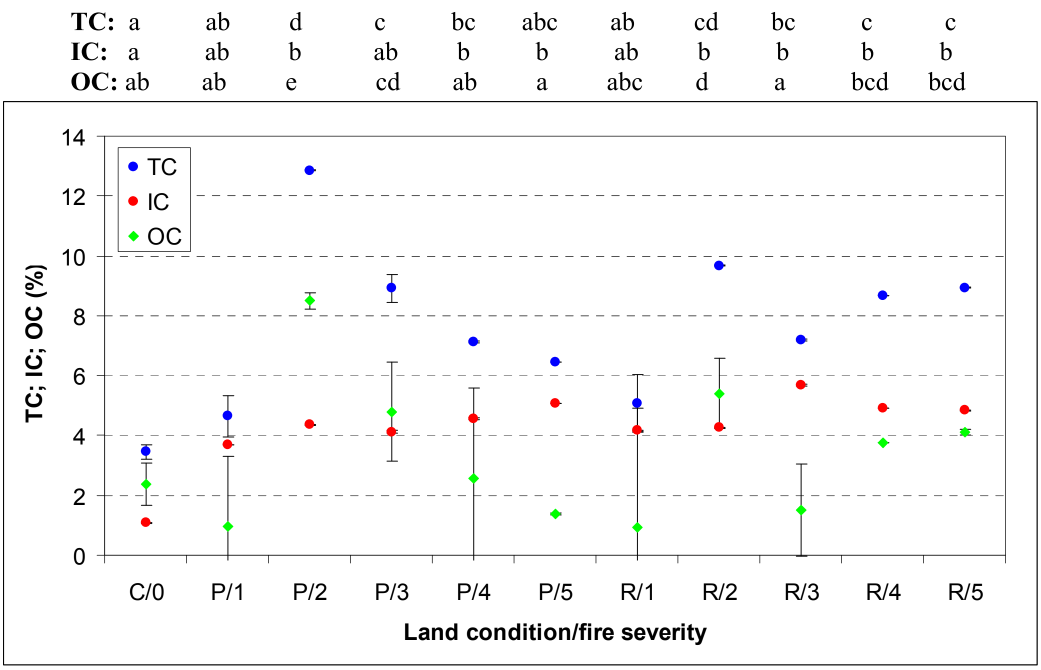
3 RESULTS

3.1 Variability of soil chemical properties

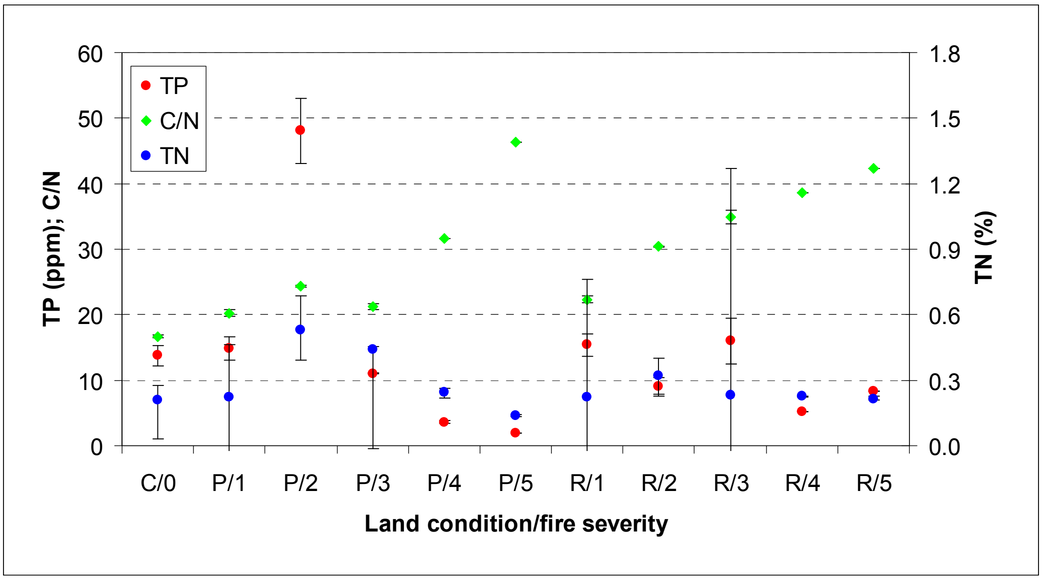
In the experimental conditions, fires resulted in changes in soil properties that were significant according to its burn severity and land condition. In more detail, the variability of pH was low and generally not significant among the land conditions and fire severities (in the range of 7.88 ± 0.05, in the control, to 8.65 ± 0.01, in reforested areas burnt at a severity of 5). The pH of the soil in the natural pine stand burnt at the highest severity (9.10 ± 0.03) was an exception, since the pH was significantly different from the other pine sites. Compared to the control, the pH decreased at the lower fire severities (1 to 3), but increased at the fire severity of 4, in both land conditions, and significantly in the reforested area (Figures 3 and 4).

The analysis of changes in carbon content of the soils shows that fire, regardless of its severity, increased the TC compared to the control (3.46 ± 0.24%). The highest content was detected in both land conditions at the intermediate severity (class 2, 12.9 ± 0.02% at the natural pine stand, and class 3, 9.67 ± 0.01%, at the reforested area), these increases being significantly different from all the other sites. Compared to the control (1.08 ± 0.01%), the soil content of inorganic forms of carbon increased with the fire severity in both land conditions, and especially in the reforested area at the highest fire severity. In the natural pine stand, the highest IC was measured at the maximum fire severity (5.08 ± 0.01%), being significantly different compared to the control, but not to the other fire severities.





TP:	a	a	b	a	a	a	a	a	a	a	a
C/N:	a	ab	abc	ab	abcd	d	abc	abcd	bcd	cd	d
TN:	ab	ab	d	cd	ab	a	ab	bc	ab	ab	ab



K^+:	a	a	ab	ab	d	d	a	ab	a	cd	bc
Mg^{2+}:	a	a	a	a	c	a	a	a	a	b	b
Ca^{2+}:	bc	abc	c	abc	abc	a	abc	abc	ab	ab	a

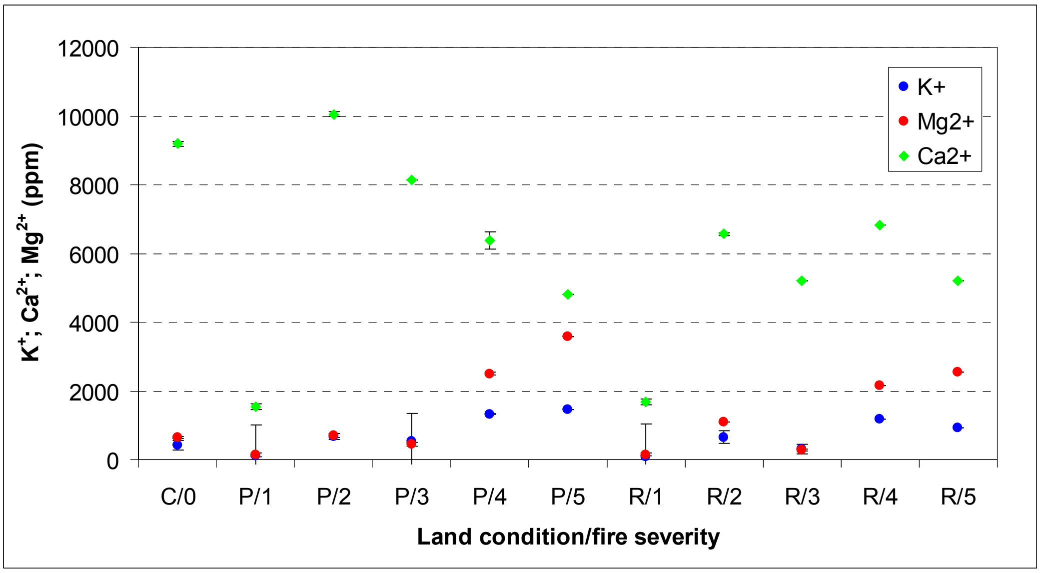


Fig. 4. Values of the main chemical properties of surface soils in an unburnt area, and two forest ecosystem types burnt at five fire severities. The letters (C, unburnt/control; P, pine; R, reforested area) in the x-axis indicate the land condition and numbers (1 to 5) indicate the fire severity. IC - inorganic carbon; OC - organic carbon; TC - total carbon; TN - total nitrogen; C/N - carbon to nitrogen ratio; TP - total phosphorous; K^+ - potassium; Ca^{2+} - calcium; Mg^{2+} - magnesium. Different letters indicate significant differences among fire severities and land conditions, after a Tukey's test at $p < 0.05$.

In the reforested areas, the highest value (5.38 ± 0.03%) was detected at a severity of 3, and all the soils burnt by fires with severity higher than 1 showed a significant increase in the IC content. The noticeable increase in TC was mainly due to the organic forms. In more detail, while, at the lowest severity (class 1), the OC content was not significantly lower compared to the control (2.38 ± 0.70%), an increase in fire severity (class 2) resulted in a very high and significant increase in OC (8.50 ± 0.27% in the pine stand, and 5.41 ± 1.18% in the reforested areas). Significant increases in OC were found at a fire severity of 3 in the natural pine stand, and of 4 and 5 in the reforested area, compared to the control. At a fire severity of 5 in the natural pine stand and at severities of 1 and 3 in the reforested area, a decrease in OC was detected, although not significant. In general, at the moderate fire severity (classes 2 and 3), the OC content was higher in the natural pine stand compared to the reforested area, while the reverse was noticed at the highest fire intensities (classes 4 and 5). The same TC and OC contents were noticed when the fire had the lowest intensity, i.e. class 1 (Figure 4).

Fire significantly increased the TN content of soils burnt at a severity of 2 and 3 in the natural pine stand (0.53 ± 0.16% and 0.44 ± 0.01%, respectively) compared to the control (0.21 ± 0.07%). This increase was not significant in the reforested soils burnt at a severity of 3 (0.32 ± 0.08%). At the other severities, namely severity of 1 and 4 in the natural pine stand as well as severity of 1, and 3 to 5 in the reforested area, TN was not significantly affected by fire). A slight (and not significant) reduction in TN was also measured in the soil burnt at the highest severity (class 5) at the natural pine stand (0.14 ± 0.01%) (Figure 4). TN was higher in the natural pine stand compared to the reforested area at medium fire severities (classes 2 and 3), but similar at the lowest fire severity class (Figure 4).

In the reforested area, the increase in C/N was monotonic but not significant (from 22.34 ± 0.54, class 1, to 42.36 ± 0.01, class 5). Compared to the control (CN of 16.7 ± 0.18), the C/N ratio increased with fire severity, but, for the natural pine stand, this increase was not significant at the lowest fire severities (classes 1 to 4), being only unlike at the highest fire severity (class 5, 46.40 ± 0.01).

The soil TP content was not significantly different between the control (13.75 ± 1.52 ppm) and the different fire severities under both land conditions, except for the soil of the pine stand affected by a fire with severity of 2, which showed a maximum TN value of 48.08 ± 5.00 ppm. Differences in the soil TP contents under the different fire intensities were noticed between the natural pine stand and the reforested area (Figure 4), as found for OC.

No significant differences from the control (413 ± 142 ppm for K^+ and 649 ± 34.3 ppm for Mg^{2+}) were found for both soil K^+ and Mg^{2+} contents at the lower fire severities under both land conditions. These contents significantly increased at the highest fire severity (class 5) up to a maximum of 1442 ± 0.3 ppm for K^+, and of 3591 ± 0.33 ppm for Mg^{2+}, both measured in the pine stand. In contrast, the soil Ca^{2+} content varied strongly with t fire severity under both land conditions, but significant differences were only found for the highest fire severity (class 5). For both land conditions, Ca^{2+} contents were always lower than the control (9191 ± 67.3 ppm), except in the soil of the pine stand burnt at a fire severity of 2, which presented higher although not significantly Ca^{2+} content (10052 ± 60.8 ppm) (Figure 4).

Overall, significant ($p < 0.05$) changes in soil properties were found for both land conditions and fire severities compared to the control. However, some exceptions were detected: (i) pH and TP were not significantly different between the two land conditions; and (ii) no significant differences were found in IC and C/N for the interaction between fire severity and land condition (Table 2).

Table 2. Results of 2-way ANOVA applied to the main chemical properties of surface soils in an unburnt area and two types of forest ecosystems burnt at five fire severities.

Soil parameter	Factor	Degrees of freedom	Sum of squares	Mean squares	F	Prob. > F
pH	Land condition	2	0.07	0.04	1.325	0.287
	Fire severity	4	2.06	0.52	19.361	**< 0.0001**
	Land condition x Fire severity	4	1.23	0.31	11.526	**< 0.0001**
TC	Land condition	2	70.7	35.3	25.507	**< 0.0001**
	Fire severity	4	123	30.8	22.233	**< 0.0001**
	Land condition x Fire severity	4	31.3	7.83	5.648	**0.003**
IC	Land condition	2	33.9	16.9	13.683	**0.000**
	Fire severity	4	31.7	7.9	6.394	**0.002**
	Land condition x Fire severity	4	2.28	0.57	0.461	0.763
OC	Land condition	2	7.31	3.66	9.179	**0.001**
	Fire severity	4	78.0	19.5	48.933	**< 0.0001**
	Land condition x Fire severity	4	38.2	9.55	23.974	**< 0.0001**
TN	Land condition	2	0.04	0.02	11.113	**0.001**
	Fire severity	4	0.24	0.06	30.504	**< 0.0001**
	Land condition x Fire severity	4	0.09	0.02	11.742	**< 0.0001**
C/N	Land condition	2	896	448	15.081	**< 0.0001**
	Fire severity	4	1848	462	15.546	**< 0.0001**
	Land condition x Fire severity	4	215	53.8	1.811	0.164
TP	Land condition	2	238	119	3.289	0.057
	Fire severity	4	2291	573	15.837	**< 0.0001**
	Land condition x Fire severity	4	2140	535	14.792	**< 0.0001**
K^+	Land condition	2	860609	430305	27.700	**< 0.0001**
	Fire severity	4	3645272	911318	58.665	**< 0.0001**
	Land condition x Fire severity	4	220984	55246	3.556	**0.023**
Ca^{2+}	Land condition	2	22897147	11448574	6.458	**0.007**
	Fire severity	4	42658476	10664619	6.015	**0.002**
	Land condition x Fire severity	4	22488038	5622010	3.171	**0.035**
Mg^{2+}	Land condition	2	3094741	1547371	18.681	**< 0.0001**
	Fire severity	4	31093971	7773493	93.848	**< 0.0001**
	Land condition x Fire severity	4	1694008	423502	5.113	**0.005**

IC - inorganic carbon; TOC - organic carbon; TC - total carbon; TN - total nitrogen; C/N - carbon to nitrogen ratio; TP - total phosphorous; K^+ - potassium; Ca^{2+} - calcium; Mg^{2+} - magnesium. The values in bold are significant at $p < 0.05$.

3.2 Analysis of soil chemical properties using PCA and AHCA

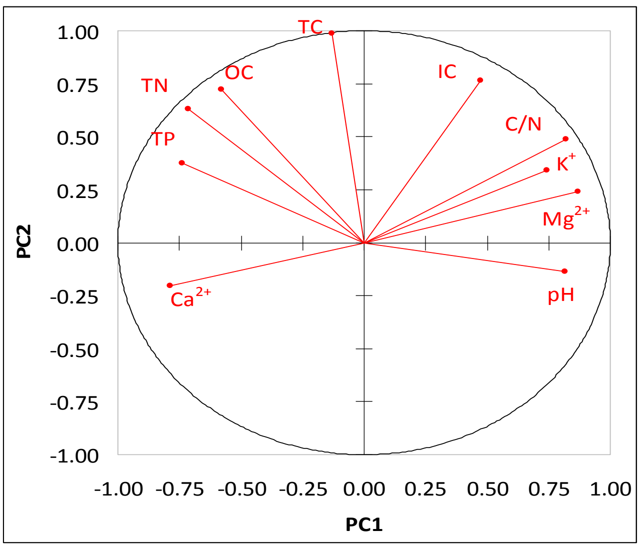
Two Principal Components (PC1 and PC2) were selected after running the PCA. These PCs explained 80% of the variance in soil properties; more specifically, PC1 explain 49% and PC2 31%.

All the investigated properties had high loadings on PC1, except the soil carbon forms. More specifically, pH, C/N, K^+, and Mg^{2+} have positive loadings (> 0.75) on PC1, while TN, TP, and Ca^{2+} negatively weigh on this PC (absolute value of loading over 0.71). In other words, the PC1 increases when pH, C/N, K^+, and Mg^{2+} increases, but decreases when TN, TP, and Ca^{2+} increase. The soil content of carbon significantly influenced the PC2 with high and positive loadings (> 0.72) (Table 2 and Figure 5a).

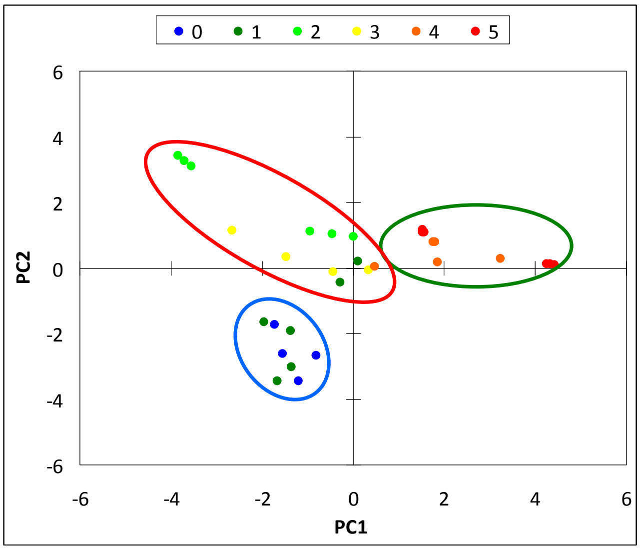
Table 3. Factor loadings of soil chemical properties on the first two Principal Components (PC1 and PC2) of the Principal Component Analysis (PCA) applied to soil samples under three land conditions (control/unburnt, C; natural pine stand, P; reforested area, R) and five fire severities (1, 2, 3, 4 and 5).

Soil property	PC1	PC2
pH	**0.816**	–0.135
TC	–0.130	**0.986**
IC	0.472	**0.766**
OC	–0.578	**0.723**
TN	**–0.714**	0.633
C/N	**0.821**	0.487
TP	**–0.737**	0.377
K^+	**0.745**	0.342
Ca^{2+}	**–0.787**	–0.204
Mg^{2+}	**0.869**	0.241

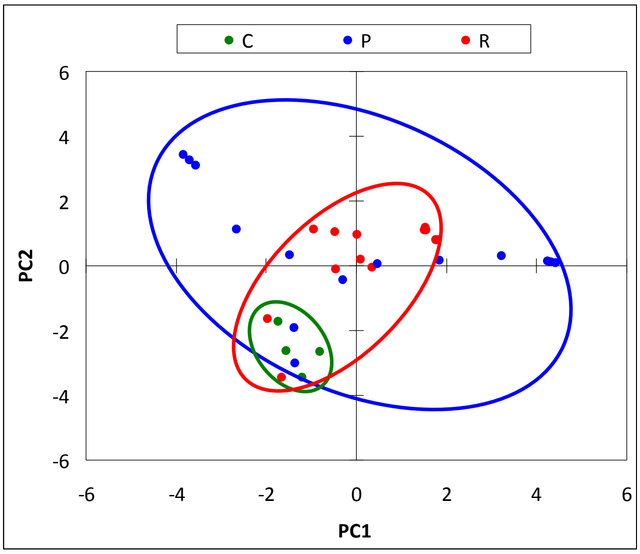
IC - inorganic carbon; OC - organic carbon; TC - total carbon; TN - total nitrogen; C/N - carbon to nitrogen ratio; TP - total phosphorous; K^+ - potassium; Ca^{2+} - calcium; Mg^{2+} - magnesium. The values in bold are significant at $p < 0.05$.



(a)



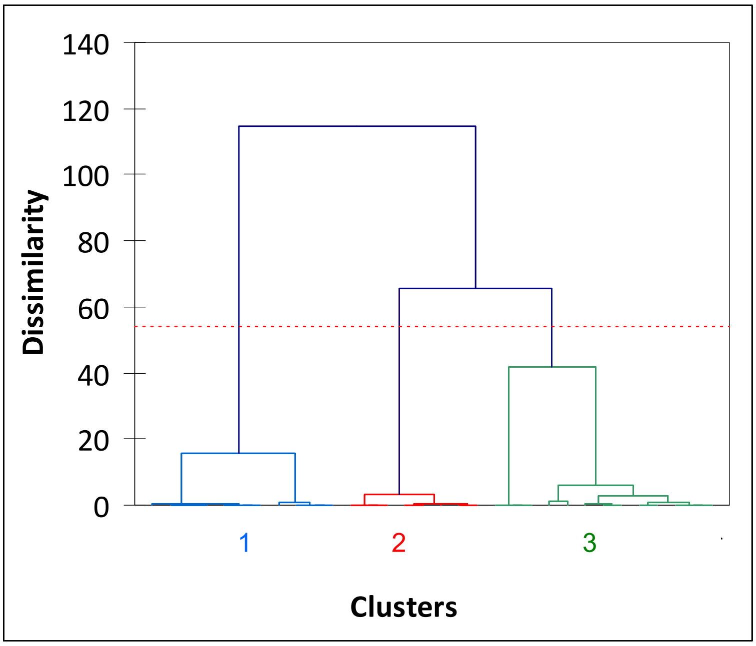
(b)



(c)

Fig. 5. Loadings of the original variables (a, chemical properties of surface soil), and scores with the related clusters (b, for five severity, and c, for land condition) on the first two Principal Components (PC1 and PC2) of the Principal Component Analysis (PCA) applied to soil samples under three land conditions (control/unburnt, C; natural pine stand, P; reforested area, R) and five fire severities (1, 2, 3, 4 and 5). IC -inorganic carbon; OC - organic carbon; TC - total carbon; TN - total nitrogen; C/N - carbon to nitrogen ratio; TP - total phosphorous; K^+ - potassium; Ca^{2+} - calcium; Mg^{2+} - magnesium.

With reference to fire severity, the AHCA clustered the observations in three homogenous groups: (1) samples from unburnt soils; (2) soil samples from the natural pine stand and reforested areas burnt at the lowest fire severity (class 1); 3) soil samples from the natural pine stand and reforested areas burnt at the highest severity (4 and 5) (Figures 5b and 6). The second cluster also included all soil samples from the natural pine stand burnt at a fire severity of 2 and 3, two soil samples burnt at a fire severity of 1 that were not included in group 1 as well as one sample from the natural pine stand burnt at severity of 4. When the clustering was made with reference to the land condition, an overlapping of the three groups is evident, which did not allow the identification of clearly distinct groups (Figures 5c and 6).



Cluster composition		
1	**2**	**3**
C/0	P/2	P/5
C/0	P/2	P/5
C/0	P/2	P/5
C/0	P/4	P/4
P/1	P/3	P/4
P/1	P/3	R/5
R/1	P/1	R/5
R/1	R/2	R/5
	R/2	R/4
	R/2	R/4
	R/3	R/4
	R/3	
	R/1	

Fig. 6. Dendrogram and clusters provided by the Agglomerative Hierarchical Cluster Analysis (AHCA) applied to soil samples under three land conditions (control/unburnt, C; pine, P; reforested area, R) and under five fire severities (1, 2, 3, 4 and 5).

4 DISCUSSION

It is well known how fire effects on soil properties depend on soil burn severity (Vega et al., 2013), but the magnitude of the fire-induced changes on soil has not been simultaneously compared among different fire severities and forest conditions (natural stands or reforested areas), as done in this study.

The analysis of soil chemical properties showed that, in general, the fire did not alter the soil pH compared to unburnt soils (which in our experiment was in the range of neutrality), except at a very high severity. A low fire severity reduced soil pH, while an increase in fire severity significantly raised up the soil acidity, under both land conditions. This agrees with some studies reporting that pH does not change following low to moderate fires (Agbeshie et al., 2022; Alcañiz et al., 2018; Valkó et al., 2016). According to the literature, soil pH is increased by heating as a result of denaturation of organic acids (Certini, 2005) and the increase of sodium and potassium oxides, as well as of carbonates and hydroxides from ash (Pereira et al., 2018; Ulery et al., 1993). Significant increases occur only at high temperatures (over 450–500 °C), under a complete combustion of fuel and consequent release of bases (Arocena and Opio, 2003; Certini, 2005), formation of oxides (Giovannini et al., 1990, 1988), and release of cations (Arocena and Opio, 2003; Giardina et al., 2000; Zavala et al., 2014). Some authors have however observed a decreased in pH also in soils exposed to high temperatures in the laboratory (e.g., Wondafrash et al., 2005), but experiments under laboratory conditions usually do not consider the effect of ash (Zavala et al., 2014).

The content of the total carbon increased in burnt soils, at all fire severities, regardless of land condition. Fires with an extreme severity (very low or very high) did not play a noticeable influence on total carbon contents compared to the unburnt soils, whereas wildfires with medium severity noticeably increased the soil carbon content up to extremely high values (over 10%). The carbon dynamics was more influenced by the organic than the inorganic carbon forms, as confirmed by the higher coefficient of determination (r^2 = 0.80) obtained from a linear regression between the organic and total carbon content, when compared to that of a linear regression between the inorganic and total carbon content (r^2 = 0.23) (data not shown). Inorganic carbon increased with fire severity in natural pine stands compared to the unburnt sites, which is in agreement with other studies carried out in areas burnt by low severity fires, namely prescribed fires (Alcañiz et al., 2018). Organic compounds are very sensitive to fire (Pereira et al., 2018; Zema, 2021), and are essential for soil functionality and plant growth in forests (Lucas-Borja et al., 2020b; Lucas-Borja et al., 2020c). The literature shows that the fire impacts depend on fire severity and duration, available biomass with its moisture, and soil processes (Agbeshie et al., 2022; Reyes et al., 2015; Zavala et al., 2014). After low-intensity fires, the organic carbon content of soil can increase due to partially pyrolyzed plant residues (Agbeshie et al., 2022; Caon et al., 2014), incorporation of ash into the soil (Carra et al., 2021), incomplete combustion of the organic matter (Alcañiz et al., 2020; Soto and Diaz-Fierros, 1993; Úbeda et al., 2005) and forest floor decomposition (Scharenbroch et al., 2012). However, these increases are generally followed by significant reductions one or some years after fire (Carra et al., 2021). In contrast, medium- or high-intensity fires cause a decrease in soil organic carbon content (Mataix-Solera et al., 2011), which may be due to combustion, mineralization, volatilization and solubilisation of soil organic matter (Agbeshie et al., 2022; Rodriguez-Cardona et al., 2020). Depending on severity, fire impacts on the organic soil compounds can include volatilisation of minor constituents, charring, or complete oxidation (Certini, 2005). High temperatures at the soil surface reduce the quantity of organic compounds and induce important changes in its composition (Merino et al., 2018). Severe wildfires volatilize high amounts of carbon and nitrogen, since these compounds start to vaporize at about 200 °C (Pereira et al., 2018), while carbon and nitrogen are totally lost over 550 °C (Gray and Dighton, 2006). However, this loss of organic compounds can be balanced by the supply of partially burnt residues and charred leaves that fall on forest ground immediately after fire (Gimeno-García et al., 2000; Granged et al., 2011b, 2011a; Zavala et al., 2014).

It is interesting to note that in soils burnt at the highest severity, the organic carbon fate was different between the two land conditions, with the natural pine stand showing a decrease in organic carbon and the reforested area evidencing a noticeable increase. This is an important result of this study, since reforestation may promote an increase in soil organic carbon in areas burnt at high fire severity, while, in natural stands, this type of fires may induce a depletion of organic matter and, therefore, a degradation of soil fertility and functionality.

Nitrogen is one of the nutrients most affected by fire (Zavala et al., 2014). Significant increases were detected in this study at the moderate fire severity, and decreases at the highest fire severity (mainly in the natural pine stand). After burning, a fraction of the soil organic nitrogen is lost by volatilisation (Binkley and Fisher, 2019; Certini, 2005; Turner et al., 2007) when soil temperatures exceed 200 °C (Caon et al., 2014). Nitrogen loss following fire may also result from erosion and leaching (Agbeshie et al., 2022; Cheng et al., 2021; Qiu et al., 2021). Moderate to high intensity fires convert most of the organic nitrogen into inorganic forms (Certini, 2005), so that the total nitrogen remains unchanged. According to many authors (Giovannini et al., 1988; Grogan et al., 2000; Rivas et al., 2012; Smithwick et al., 2005; Zavala et al., 2014), the increase in total nitrogen detected in this study may be ascribed to the addition of partially pyrolyzed materials as well as to nitrogen release from dead roots and other parts of the plant, where it was previously immobilized. Still, the effects of forest fires on soil nitrogen can be sometimes contradictory and hard to understand (Agbeshie et al., 2022).

A small variation in soil phosphorous contents was noticed between burnt and unburnt soils, with limited increases at the lowest fire severities and decreases at high-severity. The total phosphorous increases detected at low fire severities may be due to the combustion of vegetation and litter, which modifies the biogeochemical cycle of this element (Certini, 2005). Burning converts the phosphorous content of soil to orthophosphate (Cade-Menun et al., 2000), which results in an enrichment of total phosphorous (Serrasolsas and Khanna, 1995), which quickly declines over time (Certini, 2005). In contrast, the total phosphorous reductions that were measured at the highest fire severities may be due to volatilisation or leaching (Certini, 2005), but these processes require further investigation.

The increases in some soil cations like magnesium after fire, highlights the importance of ash (Pereira et al., 2018a), which is known to release these ions, promoting an increase in burnt soils (Alcañiz et al., 2020; Cawson et al., 2012). Indeed, the increase in soil cation contents after fire has been reported in numerous studies (e.g., (Certini, 2005; Elliott et al., 2013; Khanna and Raison, 1986; Shrestha and Chen, 2010)).

When comparing the changes in soil properties between the two land conditions at each fire severity, it becomes evident that at the highest fire severity soils under natural stands were more propitious to an increase in soil pH and a decrease in OC than those under reforested areas. Although some of these changes were not significant (e.g., the OC content), attention should be paid by forest managers to this variability, in order to prevent soil degradation. The other soil properties evaluated in this study did not experienced significant changes that may lead to negative impacts (e.g., depletion in organic matter or nutrients, soil acidification) on forest soils.

From the combined analysis of the chemical properties of the surface soil layer using PCA and AHCA, two considerations can be drawn. First, it is evident a mismatching between the dynamics of carbon compounds, on one side, and other chemical soil properties, on the other side, as shown by the lack of correlation between the PC1 (on which the chemical properties of soils other than carbon compounds weigh in) and the PC2 (influenced by the different carbon forms). This mismatching may be due to the direct effect of heating on carbon compounds, whereas the other parameters were less sensitive to fire. Second, the similarities among forest ecosystem types subjected to different fire severities (evidenced by the AHCA), point out that fire severity instead of land condition (natural stand or reforestation) is the main driver of changes in soil properties after fire.

5 CONCLUSIONS

This study has analysed the impacts of fires with different severity on the main soil properties in natural pine stands and reforested areas of Central Eastern Spain. The investigation has shown: (i) no evident changes in soil pH, except in the natural stand burnt at a very high fire severity; (ii) increases in the soil organic carbon content of both natural and reforested areas burnt at moderate fire severity , and of reforested areas burnt at very high severities; (iii) limited changes in the soil nitrogen content; (iv) a low variation of the soil phosphorous content, with only a significant increase in the soils under the natural pine stand burnt at a fire severity of 2; (v) increases in magnesium and potassium soil contents at the highest fire severities under both land conditions, and decreases in the calcium soil content under reforested areas burnt at the highest fire severity. Due to some negative impacts on soils, namely an increase in pH and decrease in organic carbon, the adoption of post-fire management actions in natural pine stands should be a priority over reforest areas burnt at the highest fire severity, since the risk of soil quality degradation may be more significant.

This study has also demonstrated that high severity fires do not affect all soil properties (e.g. nutrients, potassium) and that moderate severity fires can significantly modify soil organic carbon and nitrogen contents, whereas low severity fires might not change the soil organic carbon, nitrogen and phosphorous contents under both natural pine stands and reforested areas. Therefore, the working hypothesis that the higher the fire severity, the higher is the change in a specific soil property, should be reconsidered, at least under experimental conditions. Our work indicated that fire severity seems to have been the main driver for changes in soil chemical properties other than land condition. This study has provided a better knowledge on the magnitude of fire impacts on soil chemical properties according to fire severity and land condition. However, more research is needed to better understand the relationships between the fire characteristics and the soil response in environments with different climatic, geomorphological and ecological characteristics. Overall, this study did not show a straightforward pattern between soils properties, fire severity and land condition. This means that other parameters (for instance, the hydrological properties of soils), not explored in this study, should be investigated, to improve the effectiveness of post-fire land management actions.

*Acknowledgements.*Thanks are due for the financial support from EPyRIS (SOE2/P5/E0811) project, funded by the European Union through the SUDOE INTERREG Program. This work was also supported by the Spanish Ministry of Science and Innovation, through PID2021-126946OB-I00.

Data availability. Data is available upon request to the corresponding author.

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Received 11 May 2022
Accepted 20 September 2022