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Effects of Fire on the Organic and Chemical Properties of Soil in a *Pinus halepensis* Mill. Forest in Rocallaura, NE Spain

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Abstract: The present study was conducted following a fire that took place in Rocallaura (NE Iberian Peninsula) in 23 June 2016 with the aim of analyzing the chemical properties of soil in burnt and unburnt areas in order to determine the short-term effects of fire on an ecosystem dominated by *Pinus halepensis* Mill. Transects were laid out in a control area and an adjacent burnt area. Laboratory analyses were performed to determine the chemical properties of the organic and mineral soil layers at 5 cm and 10 cm (total carbon, total nitrogen, organic and inorganic carbon, carbonates, pH, electrical conductivity, and major cations). The results show partial combustion of the organic substrate, with a significant increase in TC, OC, TN, EC and K⁺, and a slight decrease in pH in the post-fire area compared to the control area, demonstrating that the fire was of low intensity and did not generate significant short-term negative impacts on the soil. Soils of this type, with high organic matter content, tend to maintain their structure after a low-intensity fire and retain the nutrients necessary for ecosystem recovery and resilience.

Keywords: wildfire; chemical properties; low intensity fire; forest management



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1. Introduction

Mediterranean society began to use fire 100,000 years ago and has been a major ignition source ever since [1]. Initially, fire was used to create open spaces for new croplands or pastures, and later as a means for anthropic modification of more or less natural sites [2]. As a result of rural depopulation in the past century, the traditionally managed mosaic landscape has shifted toward continuous, extensive areas of forest vegetation. At the same time, the number of recreational visitors has risen globally, that causes impacts in landscapes and also the increase in forest fires and burnt areas in recent decades [3]. All these factors have also led to a change in the forest fire regime [1], driving an upsurge in large forest fires (LFFs) characterized by crown fires, threats to urban interfaces and simultaneous fires, which stretch firefighting resources [4].

In addition, the trend toward rising temperatures and longer periods of drought in the Mediterranean [5,6] with the consequent increase in water stress [7] and accumulation of fuel on the ground [1], has also contributed to the proliferation of large wildfires in Mediterranean climates.

The concept of soil quality can be defined as the capacity of a specific soil type, after disturbance in a natural or managed ecosystem, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation [8]. Soil quality is considered the most dynamic and sensitive measure of soil resilience to change caused by natural or anthropogenic forces [9]. Doran [10] has identified the main indicators used to determine soil quality as follows. Physical: structure, bulk density,

aggregate stability, infiltration, surface soil depth, water retention capacity, and saturated hydraulic conductivity; chemical: organic and inorganic matter, total organic carbon, pH, electrical conductivity, nitrogen, carbonate content, available phosphorus, and total potassium; and biological: soil respiration, biomass carbon, and enzyme-catalyzed reactions.

Fire is one of the natural agents that affects soil quality in Mediterranean forests. They can alter soil quality physically (e.g., aggregate stability, porosity, distribution, hydrophobicity and runoff), chemically (e.g., organic matter, nutrient availability, mineralogy, pH and C/N ratio), and biologically (e.g., biomass productivity, microbial composition and carbon storage) [11,12]. Direct impacts are caused by the rise in temperature in the uppermost centimeters of soil, while indirect impacts are a consequence of the temporary elimination of part of the vegetation cover and the incorporation of ash into the soil and to the water [12]. Soil type, the severity, and frequency of fires at the same site and post-fire weather conditions influence soil properties in the short, medium, and long term [13].

It is important to maintain the full capacities of forest soils because they act as carbon sinks [14]. Fire produces modifications in the forms of carbon and organic matter leading to the existence of carbon. These new forms of soil carbon, because of fire, show reduction in enzymatic degradation. This impact of fire, in some cases, produces a stable organic–mineral interaction under the conditions of the Mediterranean ecosystem (drought and rainfall) [15].

The present study compared pre- and post-fire soil characteristics by means of transects in an unburnt control area and a burnt area. The goal was to determine whether the amount of organic matter in the soil and its chemical characteristics changed in the short term after a fire.

2. Materials and Methods

The study area was located in the Serra de Senadelles, close to the villages of Rocallaura (municipal district of Vallbona de les Monges) and Nàlec, Lleida ($41^{\circ}31'28.0''$ N $1^{\circ}07'12.1''$ E, 615 m a.s.l.) in the NE Iberian Peninsula (Figure 1). More information about this study area can be found in Xifré-Salvadó et al. [16] as well as an extended explanation of used methods and techniques.

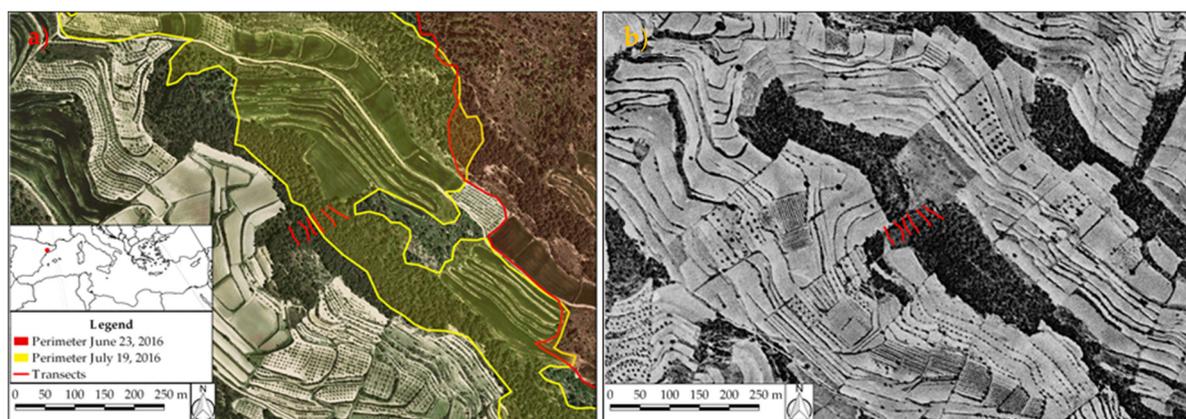


Figure 1. (a) Recent orthophoto of the study area and (b) historical orthophoto (both orthophoto are from “A” series of American flight of 1945–1946). Adapted from [16] and compiled by the authors from ICGC [17].

The vegetation cover in the study area consists of a tree layer of *Pinus halepensis* Mill., a shrub layer composed mainly of *Phillyrea latifolia*, *Quercus coccifera*, *Pistacia lentiscus*, *Quercus ilex*, *Erica multiflora*, and *Rosmarinus officinalis* and a herbaceous layer dominated by several species of moss, *Brachypodium retusum* and occasional individuals from the Orchidaceae family (Figure 2). According to the NDVI index, vegetation is sparse (between 0.2 and 0.4) [18]. The average height of the *Pinus halepensis* is between 7 and 11 m with a mean diameter at breast height (DBH in advance) of between 15 and 20 cm and a basal

area of 20 to 30 m²/ha. Leaf biomass ranges between 3 and 5 t/ha and total biomass is between 60 and 120 t/ha [19].

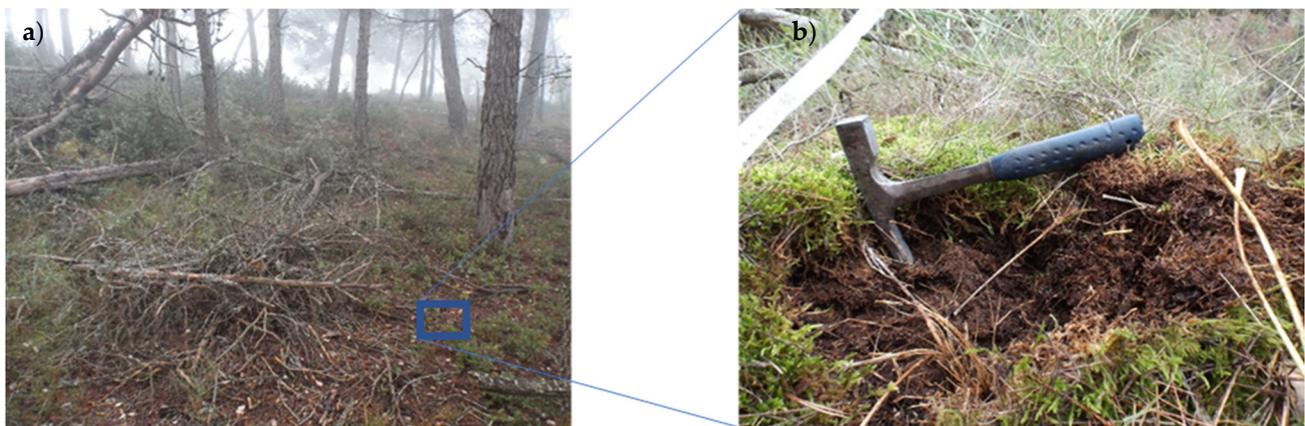


Figure 2. (a) Image of the study area and (b) organic horizon and moss cover. Adapted from Xifré-Salvadó 2020 [16].

The trees are about 70–80 years old, as the forest was last felled or burnt during the Spanish Civil War (1936–1939). A line of old war trenches in the area has restricted forest management from that time to the present day because of the risk of explosion of remaining unexploited artefacts. Rural depopulation, climate conditions and limited forest management has led to a surface layer of moss growth and an increase in soil organic matter content in low-gradient areas (Figure 3).

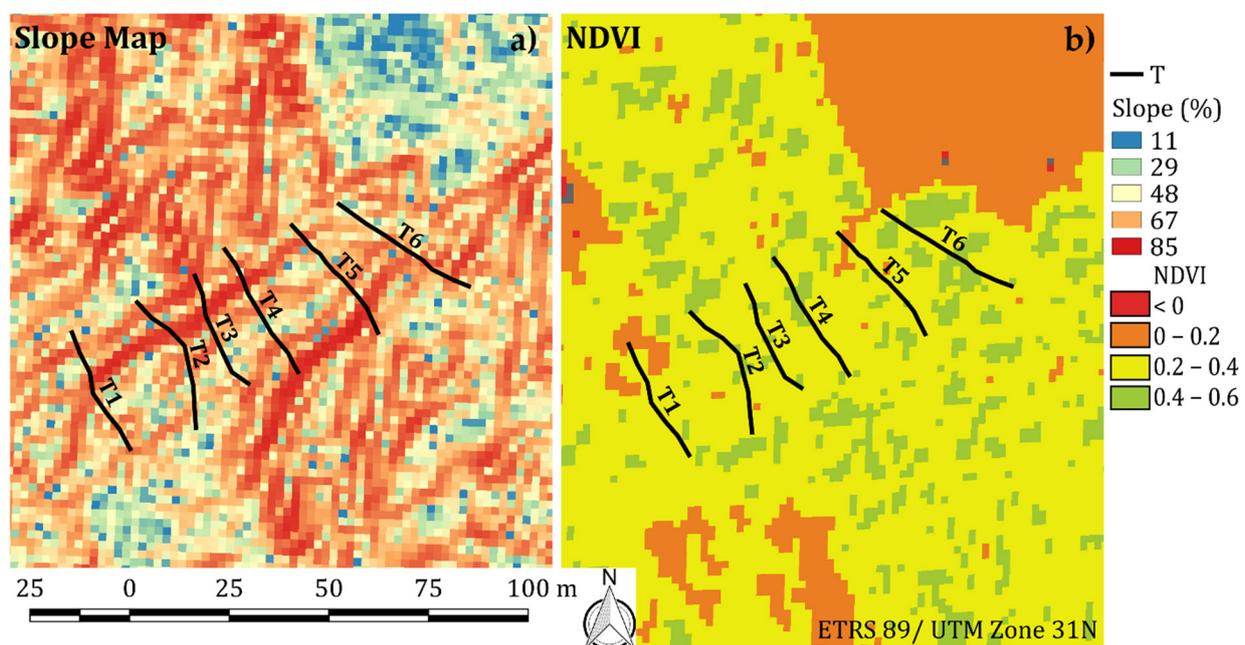


Figure 3. (a) Slope map (%) of the study area and (b) NDVI (Normalized Difference Vegetation Index) from 2012. T indicate Transects. Compiled by the authors from [18,19].

The climate is dry continental Mediterranean, with hot summers (mean maximum temperature of 29.5 °C), mild winters (average temperatures of 12–14 °C), and an overall thermal variation of 17–21 °C. Average rainfall is 350–550 mm with a seasonal regime that is marked by the equinoxes (in descending order: autumn-spring-summer-winter). The drought period is from June to August and the frost-free period is from May to September inclusive [20].

The geological substrate consists of Cenozoic sedimentary deposits, comprising marls with calcareous intercalations in the lower levels (Rupelian-Chattian), shales, sandstones and limestones in the middle levels (Rupelian-Chattian) and clays, silts and fine-grained sandstones with conglomerate intercalations in the upper levels (Rupelian) [19]. The soils are classified as Rendzic-Epileptic Phaeozem according to WRB system [21].

The profile presents a dark surface horizon, with good soil structure and high organic matter content. The O horizon basically consists of pine needles which cover the moss and decomposed plant debris ranging from 1 to 12 cm in depth. The A horizon is 10 to 40 cm thick. The R horizon consists of calcareous rock (Table 1, Figure 2 right).

Table 1. Soil characteristics in the study area.

Horizon	Depth (cm)	pH	CaCO ₃ ⁻ (%)	Fines (%)	Organic Matter (%)	Inorganic Matter (%)	Total Carbon (%)	C/N Ratio	Bulk Density (kg/m ³)
O	1–12	-	2.0–6.7	-	44.4–80.8	19.2–55.6	25.0–41.3	-	48–191
A	5–40	7.6–8.5	11.3–36.3	53–98	7.1–20.7	79.3–92.9	8.0–13.1	23–45	550–1570
R (Calcareous)	>40	-	-	-	-	-	-	-	-

At 21:00 h on 23 June 2016, a fire broke out in the vicinity of Rocallaura, caused by a firecracker set off by a child during the San Juan festivities. It affected 103 ha of forest and agricultural land [22,23]. The temperature was 22 °C, relative humidity was 33% and the wind speed was 9 km/h with gusts of up to 21.4 km/h in a N-NW direction. Weather conditions were adverse: there had been no rain for several days (2.5 mm on 18 June), relative humidity was between 25 and 40%, average temperatures were between 23 and 24 °C and the average daily wind speed had increased from 5.4 km/h to 9 km/h in 3 days [24,25]. Less than a month later, re-ignition occurred in the same study area. See more details in Xifré-Salvadó et al. [16].

2.1. Sampling

Six 40-metre transects were designed following the direction of maximum slope, yielding a total of 60 samples. Three transects were sited in the area affected by a low-intensity fire [26] and the other three in a control area with similar characteristics adjacent to the burnt area (Figure 4). Soil samples (between 0–5 cm and 5–10 cm of soil) weighing approximately 0.4 kg were taken every eight meters (five samples per transect in the control area and six samples per transect in the burnt area).

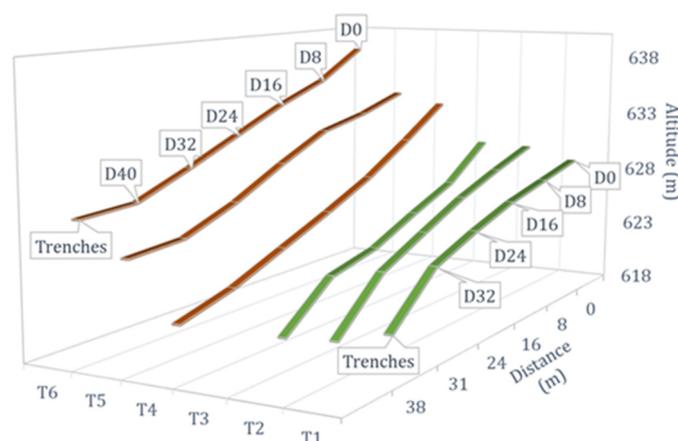


Figure 4. Diagram of the transects designed for the Rocallaura fire according to the distance of each transect (D0, D8, D16, D24, D32, D40) and its slope. T1, T2, T3 indicates the transects in the unburnt (control) area while T4, T5, T6 indicates those in the burnt area. Modified from Xifré-Salvadó 2020 [16].

2.2. Laboratory Analysis

All soil samples were dried at room temperature for 10 days and sieved through a 2 mm mesh. The resulting soil was then prepared for different chemical parameter measurements. The loss on ignition (LOI) method described by Heiri et al. [27] and Santisteban et al. [28] was used to determine organic carbon (OC), inorganic carbon (IC) and carbonates. Each sample was pulverized and then approximately 1 g was weighed out and dried at 105 °C for 24 h [28]. To determine SOM, dried samples were subjected to a temperature of 550 °C for 4 h. They were then cooled in a bell jar (30 min) and weighed [27]. To determine inorganic carbon and carbonates, the same samples were heated at a temperature of 950 °C for 2 h [27].

Total carbon (TC), total nitrogen (TN), exchangeable cations of calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+) and potassium (K^+), available sulfur (S), and available silicon (Si) were analyzed in the Science and Technology Centre laboratories of the University of Barcelona by gas chromatographic separation and thermal conductivity detection using a Flash EA 112 Series elemental analyzer (Thermo-Fisher Scientific, Milan, Italy). To do this, 5 g of soil of each sample is weighed and 100 mL of ammonium acetate is added, shaken manually, a magnet is introduced and left on a magnetic stirrer for 24 h. After this time, the samples are filtered (using a Merk Millipore filter with a diameter of 4.7 cm and a pore size of 0.22 μm) and measured, taking into account that the sample must be diluted 1/10 with deionized water. Data were calculated using Eager 200 software (Thermo-Fisher Scientific, Milan, Italy).

The results obtained using the LOI method (OM, IM, OC, and IC) were verified by means of regression analysis between the total carbon obtained by the LOI method (IC + OC) and the total carbon obtained by the gas chromatographic separation and thermal conductivity detection method. The coefficient of determination was very high ($R^2 = 0.927$, $t = 0.39$), confirming the results obtained using the LOI method: $\text{TC} (\%) = 1.202\text{TC}_{\text{LOI}} (\%) - 3.868$.

To determine pH [1:2.5] and electrical conductivity (EC) [1:2.5], the potentiometric and electrometric methods were used with a pH meter and a conductivity meter, respectively.

2.3. Statistical Analysis

A comparative analysis was performed using the Student's *t*-test and the Mann-Whitney U test to determine statistically significant differences between two quantitative variables: depth (0–5 cm and 5–10 cm) and area (control and post-fire). The variables were divided into four groups: C-0–5 (control area at 0–5 cm), C-5–10 (control area at 5–10 cm), F-0–5 (post-fire area at 0–5 cm), and F-5–10 (post-fire area at 5–10 cm). For all the variables to compare, normality and homogeneity of variance were tested by means of the Shapiro-Wilk (<50 samples) and Levene ($p < 0.50$) tests, respectively. The parametric Student's *t*-test, which compares the means between two groups of samples, was applied to variables presenting normality and homogeneity.

For all variables that did not meet the criteria for normality or homogeneity, the non-parametric Mann-Whitney U test was applied, which compares the medians between two groups. Statistical analysis was performed using IBM statistical package SPSS 21.0. 23 [29].

3. Results

3.1. Total Carbon, Total Nitrogen, Organic and Inorganic Carbon, Carbonates, and C/N Ratio

TC decreased significantly by depth, both in the control area ($t(27) = 3.22$, $p < 0.01$, $r = 0.53$) and in the post-fire area ($t(28) = 4.92$, $p < 0.001$, $r = 0.68$), but showed significantly higher levels in the post-fire area both at 0–5 cm depth ($U(28) = 21$, $p < 0.001$) and at 5–10 cm depth ($t(27) = -2.51$, $p < 0.05$, $r = 0.44$). TN decreased significantly by depth, both in the control area ($t(27) = 3.53$, $p < 0.01$, $r = 0.56$) and in the post-fire area ($U(28) = 10$, $p < 0.001$), but showed significantly higher levels in the burnt area both at 0–5 cm depth ($t(28) = -4.83$, $p < 0.001$, $r = 0.67$) and at 5–10 cm depth ($t(21) = -4.23$, $p < 0.001$, $r = 0.63$). OC decreased by depth both in the control area ($t(27) = 4.27$, $p < 0.001$, $r = 0.64$) and in

the post-fire area ($U(28) = 9$, $p < 0.001$), but showed slightly higher levels in the burnt area both at 0–5 cm depth ($U(28) = 56.5$, $p < 0.05$) and at 5–10 cm depth ($t(27) = -2.62$, $p < 0.05$, $r = 0.45$). IC increased slightly by depth both in the control area ($U(26) = 54$, $p < 0.05$) and in the post-fire area ($t(28) = -2.09$, $p < 0.05$, $r = 0.37$), but no statistically significant differences were detected between the control and post-fire areas. Carbonate content increased slightly by depth both in the control area ($t(27) = -2.69$, $p < 0.05$, $r = 0.46$) and in the post-fire area ($t(28) = -2.21$, $p < 0.05$, $r = 0.39$), but no statistically significant differences were detected between the control and post-fire areas. The C/N ratio increased significantly by depth both in the control area ($U(26) = 39$, $p < 0.01$) and in the post-fire area ($t(28) = -5.20$, $p < 0.001$, $r = 0.70$), but showed significantly lower levels in the burnt area both at 0–5 cm depth ($U(28) = 23$, $p < 0.001$) and at 5–10 cm depth ($U(27) = 27$, $p < 0.001$) (Table 2).

Table 2. Descriptive statistics for total carbon (TC), total nitrogen (TN), organic carbon (OC), inorganic carbon (IC), Carbonates, and C/N ratio. Mean at 95%; N = 60. C (Control) and F (Fire).

Parameter		Mean	SD	Median	Variance	Min	Max
TC (%)	C (0–5)	11.07	1.16	10.79	1.35	9.42	13.10
	C (5–10)	9.62	1.22	9.88	1.49	7.96	12.04
	F (0–5)	13.52	1.94	13.26	3.77	10.06	18.57
	F (5–10)	10.71	1.11	10.68	1.24	9.35	12.86
TN (%)	C (0–5)	0.40	0.09	0.40	0.01	0.22	0.52
	C (5–10)	0.29	0.08	0.30	0.01	0.16	0.39
	F (0–5)	0.63	0.16	0.61	0.03	0.40	0.93
	F (5–10)	0.38	0.05	0.37	0.00	0.34	0.51
OC(%)	C (0–5)	7.86	1.50	8.01	2.25	5.91	10.34
	C (5–10)	5.58	1.33	5.77	1.77	3.57	8.68
	F (0–5)	9.91	3.14	9.44	9.87	7.05	19.25
	F (5–10)	6.64	0.69	6.46	0.48	5.37	8.17
IC (%)	C (0–5)	5.08	0.57	5.04	0.32	3.88	5.96
	C (5–10)	5.57	0.82	5.57	0.67	4.62	7.98
	F (0–5)	4.74	1.06	4.79	1.13	2.62	6.16
	F (5–10)	5.45	0.96	5.47	0.91	4.04	7.54
CaCO ₃ ⁻ (%)	C (0–5)	24.13	3.43	23.91	11.74	18.74	29.43
	C (5–10)	27.39	3.47	27.17	12.07	22.04	36.28
	F (0–5)	23.33	5.25	24.13	27.56	12.31	30.52
	F (5–10)	27.02	4.72	27.72	22.31	19.85	37.00
C/N	C (0–5)	28.42	5.85	27.29	34.25	23.25	45.68
	C (5–10)	35.15	8.60	32.25	73.94	28.39	56.89
	F (0–5)	22.13	3.37	22.60	11.36	17.10	29.24
	F (5–10)	27.97	2.55	27.38	6.48	23.05	31.66

3.2. pH, Electrical Conductivity, Major Cations, Total Potassium, Silicon, Available Sulphur

No significant differences in pH by depth were observed in either the control or post-fire areas. However, significantly lower levels were detected in the post-fire area than in the control area at both 0–5 cm depth ($t(28) = 3.33$, $p < 0.01$, $r = 0.53$) and at 5–10 cm depth ($t(27) = 2.84$, $p < 0.01$, $r = 0.48$). EC did not present significant differences by depth in the control area, but did decrease by depth in the post-fire area ($U(28) = 60$, $p < 0.05$). Nevertheless, EC showed significantly higher levels in the post-fire area both at 0–5 cm depth ($U(28) = 6$, $p < 0.001$) and at 5–10 cm depth ($U(27) = 7.5$, $p < 0.001$) (Tables 3 and 4).

Ca²⁺ content showed no statistically significant differences by depth in the control area, but did do so in the post-fire area ($t(28) = -3.08$, $p < 0.01$, $r = 0.50$). The amount of Ca²⁺ in the control area at 0–5 cm depth was higher than in the post-fire area ($t(28) = 3.29$, $p < 0.01$, $r = 0.53$), but no statistically significant differences were observed at a depth of 5–10 cm. Neither Mg²⁺ nor exchangeable Na⁺ content presented any statistically significant differences. K⁺ decreased significantly by depth, both in the control area ($t(27) = 2.956$, $p < 0.01$, $r = 0.50$) and in the post-fire area ($t(28) = 2.85$, $p < 0.01$, $r = 0.47$). Nevertheless,

K⁺ showed significantly higher levels in the post-fire area both at 0–5 cm ($t(28) = -3.24$, $p < 0.01$, $r = 0.52$) and at 5–10 cm depth ($t(27) = -3.695$, $p < 0.001$, $r = 0.58$). Available Si only presented statistically significant differences between the control and post-fire areas at a depth of 0–5 cm ($U(28) = 59$, $p < 0.05$), being slightly higher in the post-fire area. Available S did not differ significantly by depth in either of the two areas, but it did show slightly higher levels in the post-fire area than in the control area, both at 0–5 cm depth ($U(28) = 55$, $p < 0.05$) and at 5–10 cm depth ($U(27) = 52$, $p < 0.05$) (Tables 3 and 4).

Table 5 shows the correlations between soil properties. Total carbon content showed a very high and positive correlation with total nitrogen and organic carbon, and a high correlation with electrical conductivity, pH (–) and total potassium. There was a very high correlation between total nitrogen and organic carbon content, and TN was also highly correlated with inorganic carbon (–), carbonates, pH (–), electrical conductivity, and K⁺. Organic carbon content presented a high correlation with electrical conductivity, pH, inorganic carbon (–) and carbonates (–), while inorganic carbon was very highly correlated with carbonates and highly with the C/N ratio. Of particular note was the high and negative correlation between pH and EC (–). Exchangeable calcium was moderately correlated with sodium and exchangeable magnesium.

Table 3. Descriptive statistics for pH, electrical conductivity (EC), major cations (Ca²⁺, Mg²⁺, Na⁺), total potassium (K⁺) and available silicon (Si) and sulfur (S). Mean at 95%; N = 60. C (Control) and F (Fire).

Parameter		Mean	SD	Median	Variance	Min	Max
pH	C (0–5)	8.13	0.25	8.21	0.06	7.61	8.44
	C (5–10)	8.21	0.29	8.29	0.08	7.51	8.51
	F (0–5)	7.83	0.25	7.77	0.06	7.23	8.28
	F (5–10)	7.92	0.24	7.98	0.06	7.49	8.25
EC (μS/cm)	C (0–5)	178.66	73.32	165.70	5375.89	104.40	345.00
	C (5–10)	159.81	60.02	162.50	3602.31	96.60	336.00
	F (0–5)	787.19	561.78	632.00	315,600.21	212.00	2060.00
	F (5–10)	443.52	273.73	367.00	74,927.35	200.00	1158.00
Ca ²⁺ (ppm)	C (0–5)	27,790.39	4797.77	26,434.72	23,018,591.39	22,355.81	39,979.59
	C (5–10)	27,212.48	6762.72	27,388.90	45,734,374.45	14,151.24	43,021.04
	F (0–5)	21,976.01	5179.54	20,534.78	26,827,636.72	15,439.06	31,805.93
	F (5–10)	29,499.61	7885.68	29,211.73	62,184,010.81	17,757.63	44,099.98
Mg ²⁺ (ppm)	C (0–5)	1252.18	392.30	1231.86	153,899.78	750.59	2150.59
	C (5–10)	1194.49	319.51	1145.93	102,089.03	706.04	1842.90
	F (0–5)	1248.67	361.78	1201.69	130,882.94	827.62	2110.92
	F (5–10)	1254.22	409.05	1032.27	167,320.68	811.79	2022.35
Na ⁺ (ppm)	C (0–5)	242.82	108.55	213.26	11,783.32	85.32	519.31
	C (5–10)	246.53	140.87	222.23	19,844.30	72.91	479.61
	F (0–5)	211.41	93.40	193.91	8723.98	103.84	431.93
	F (5–10)	274.67	125.67	249.15	15,792.17	131.55	534.37
K ⁺ (ppm)	C (0–5)	358.38	95.17	349.70	9057.69	219.66	553.67
	C (5–10)	260.05	84.47	239.29	7135.83	149.20	412.66
	F (0–5)	507.96	144.65	476.44	20,923.6	240.76	735.19
	F (5–10)	377.66	88.72	377.14	7871.92	238.48	587.72
Si (ppm)	C (0–5)	60.84	72.92	51.42	5316.67	18.09	312.28
	C (5–10)	41.58	26.14	38.83	683.37	5.84	104.21
	F (0–5)	115.43	68.10	107.19	4638.25	29.13	237.68
	F (5–10)	49.93	32.87	37.94	1080.58	12.15	101.67
S (ppm)	C (0–5)	99.19	44.18	77.23	1951.74	45.28	172.12
	C (5–10)	79.33	43.87	72.99	1924.29	28.56	160.42
	F (0–5)	204.57	216.76	209.95	46,984.69	49.27	867.91
	F (5–10)	126.06	101.57	113.40	10,316.98	41.82	480.75

Table 4. Summary of significant differences (Student’s *t*-test and Mann–Whitney U test) between groups. “ns” indicates that differences were not statistically significant. ↓ = decreased by depth or the level was lower in the post-fire area than in the control area. ↑ = increased by depth or the level was higher in the post-fire area than in the control area. N = 60. C (Control) and F (Fire).

	Depth				Control—Post-Fire			
	C (0–5)–C (5–10)		F (0–5)–F (5–10)		C (0–5)–F (0–5)		C (5–10)–F (5–10)	
	t	U	t	U	t	U	t	U
TC	↓	3.22 **	↓	4.92 *	↑	21 *	↑	2.51 ***
TN	↓	3.53 **	↓	10 *	↑	4.83 *	↑	4.23 *
OC	↓	4.27 *	↓	9 *	↑	56.5 ***	↑	2.62 ***
IC	↑	54 ***	↑	2.09 ***	ns		ns	
Carb.	↑	2.69 ***	↑	2.21 ***	ns		ns	
C/N	↑	39 **	↑	−5.2 *	↓	23 *	↓	27 *
pH		ns		ns	↓	3.33 **	↓	2.84 **
EC		ns	↓	60 ***	↑	6 *	↑	7.5 *
Ca ²⁺		ns	↑	3.08 **	↓	3.29 **		ns
Mg ²⁺		ns		ns		ns		ns
Na ⁺		ns		ns		ns		ns
K ⁺	↓	2.96 **	↓	2.85 **	↑	3.24 **	↑	3.67 *
Si		ns		42 **	↑	59 ***		ns
S		ns		ns	↑	55 ***	↑	52 ***

* Statistically significant differences at $p < 0.001$. ** Statistically significant differences at $p < 0.01$. *** Statistically significant differences at $p < 0.05$.

Table 5. Spearman’s non-parametric correlation matrix (R) for chemical variables in the control and post-fire areas; N = 60.

Parameter	OC	TC	TN	IC	CaCO ₃ [−]	C/N	pH	EC	Ca ²⁺	Mg ²⁺	Na ⁺
OC (%)											
TC (%)	0.770 **										
TN (%)	0.852 **	0.904 **									
IC (%)	−0.598 **	−0.114	−0.341 **								
CaCO ₃ [−] (%)	−0.602 **	−0.139	−0.374 **	0.961 **							
C/N	−0.804 **	−0.711 **	−0.931 **	0.481 **	0.512 **						
pH	−0.441 **	−0.536 **	−0.575 **	0.126	0.153	0.558 **					
EC (μS/cm)	0.436 **	0.638 **	0.677 **	−0.032	−0.010	−0.619 **	−0.721 **				
Ca ²⁺ (ppm)	−0.332 *	−0.250	−0.311 *	0.178	0.236	0.308 *	0.278 *	−0.150			
Mg ²⁺ (ppm)	−0.062	−0.023	−0.072	−0.033	0.003	0.148	0.248	0.102	0.480 **		
Na ⁺ (ppm)	−0.086	0.086	0.041	0.357 **	0.356 **	−0.004	−0.083	0.197	0.439 **	0.290 *	
K ⁺ (ppm)	0.616 **	0.697 **	0.709 **	−0.160	−0.159	−0.599 **	−0.474 **	0.654 **	−0.040	0.301 *	0.216

** The correlation is significant at the $p < 0.01$ level. * The correlation is significant at the $p < 0.05$ level; Spearman’s R. TC: total carbon; TN: total nitrogen; OC: organic carbon; IC: inorganic carbon; EC: electrical conductivity; Ca²⁺: exchangeable calcium; Mg²⁺: exchangeable magnesium; Na⁺: exchangeable sodium; K⁺: total potassium.

4. Discussion

Statistically significant changes in TC and OC content were observed according to depth [30,31]. The difference in TC content by depth was greater in the burnt area, and significantly higher levels of both OC and TC were observed between the control and post-fire areas at 0–5 cm depth. These higher OC and TC levels were probably due to the presence of charred material on the surface layer of the post-fire area [32,33]. Charred material on the soil may come from the incompletely combusted organic horizon or from

aerial vegetation parts (15 Almendros and González-Vila. 2012). The results indicate the presence of a low to moderate intensity fire, because black carbon is produced by incomplete combustion of wood at temperatures of 250 to 500 °C [34]. The negligible or absent alteration of inorganic carbon also indicates that the soil temperature did not exceed 550 °C [28]. It is more difficult to determine whether TC varies in a moderate intensity fire, since different studies have reported that TC content may increase or decrease [35,36]. At high intensity, in contrast, there is a steep reduction in soil organic matter and soil organic carbon [35,37].

In the long term, soil OC content is expected to increase with respect to pre-fire levels [38]. There are three reasons for this: the incorporation of unburnt residues that are more resistant to biochemical decomposition; the transformation of fresh organic materials into more recalcitrant forms; and the influx of nitrogen-fixing species into burnt areas [38]. An increase in soil organic content enhances moisture retention, thus increasing the water reserve in the soil [14]. However, other studies have reported following low-intensity fires in the long term. TC content decreases to levels lower than before the fire [39].

The extreme climatic conditions, to which Mediterranean ecosystems are subjected, are unfavorable to humification processes, but the high levels of dehydration caused by long periods of drought and fires favor the mineralization of organic matter, forming more stable compounds in the soil [15]. Three months after the fire the mineralization of organic matter (IC) in the study area was not as high as the values reported in other studies [14]. The variability of data was also observed in TC, OC, and TN content, and was probably due to the uneven spatial distribution of the fire and latent combustion of the organic layer [40].

Carbonate content did not vary significantly between the control and post-fire areas because these compounds are very resistant to high temperatures [13]. Variation in soil carbonate content occurs at temperatures of 900–1000 °C [27].

TN decreased by depth and was higher in the burnt area than in the control area. These results agree with those of other studies which have reported that low-intensity fires induce changes in soil nitrogen content [13,14,32]. In recently burned areas, increases in nitrogen concentration are observed, mainly due to the accumulation of ash. In the long term, these concentrations are decreasing, due to the washing and the germination of herbaceous plants [12]. However, it was not possible to determine which nitrogen compounds had changed or formed after the fire. Ammonium and nitrate are the inorganic forms of nitrogen that originate during the burning. Ammonium is a direct product of the combustion, while nitrate forms from ammonium some weeks or months after fire as a result of biochemical reactions called nitrification [13]. In contrast, the C/N ratio decreased significantly after the fire in the study area. This decrease has also been reported in other studies [35,36], and is probably due to the formation of recalcitrant nitrogen compounds [41].

pH was significantly lower in the burnt area, in both the 0–5 cm and 5–10 cm samples. This result contrasts with the findings of other studies of low-moderate intensity fires [32,42,43], but is in line with the other studies of fires of the same intensity [36,44]. In soils with high pH, some authors have not observed significant increases in pH after the passage of fire, especially when these have been low intensity fires [42]. Another possible cause could be the presence of low pH ash burnt at low intensity, since this facilitates the solubility of metals [43,44].

The concentration of soluble salts, measured by electrical conductivity, was significantly higher in the burnt area at both 0–5 and 5–10 cm depth, and was a consequence of the solubilization of compounds from the ashes [42,43]. Although electrical conductivity was higher, it was not as high as that observed in the studies mentioned above. This is probably because the low intensity of the fire generated a lower concentration of black carbon and therefore less release of cations [45]. The high variability in the concentration of soluble salts in the burnt area, which reflects variability in the presence of black carbon, is another indication of the uneven spatial distribution of the combustion of the organic layer and aerial parts in the study area.

The exchangeable cation Ca^{2+} was the most abundant cation in the study area due to the calcareous character of the soil. Statistically significant differences were observed between the burnt and the control areas at the shallowest depth (0–5 cm) and also by depth in the burnt area. This was probably due to solubilization of this cation by ash on the soil and its subsequent drainage to lower layers [33]. Mg^{2+} and Na^+ cations did not vary significantly between areas or depths.

Total potassium (K^+) increased significantly after burning in both the shallowest (0–5 cm) and deepest (5–10 cm) layers. The high potassium levels in the surface layer were due to the presence of burnt wood and ash [43,46,47]. This increase occurs when the soil temperature does not exceed 400 °C [48]. After one year, potassium content decreases considerably [32].

As a consequence of limited forest management over the past 70 years in the study area *Pinus halepensis* Mill. has dominated the tree layer, developing into a mature forest without much vertical continuity. This favors low-intensity fires, which can enhance nutrient recycling [15]. The existence of a stable forest ecosystem has increased soil organic matter, which in turn has enhanced the soil's water retention capacity and fertility [13].

However, where forest management is lacking, fuel accumulation and continuity must occur before mature forest ecosystems can be established, and in the event of a fire, this would generate severe impacts on the territory [49]. The geographical distribution of human settlements in the Mediterranean is another factor that renders non-forest management highly inadvisable [50]. Although natural Mediterranean ecosystems show resistance and recovery mechanisms in the face of environmental and socio-economic change, the current situation of global change exceeds the resilience capacity of these natural strategies [51].

This raises the need to adopt an adaptive management strategy until an effective fire regime is re-established, as in the case study, in order to prevent serious impacts on human activities and the ecosystem. Forest management techniques such as prescribed burning and extensive livestock farming help to reduce surface fuel, encroachment, preventing forest fuel accumulation, and continuity and thereby effectively preventing LFFs [39,52,53] while preserving soil's quality.

As with the low-intensity fire in the study area, prescribed burning increases more recalcitrant forms of carbon in the soil, helping to fix it [15]. As regards the use of livestock in Mediterranean forested areas, this generates an accumulation of organic matter in the soil and influences its vertical distribution, because it is distributed to a greater depth than in ungrazed areas [54]. In addition, the bulk density of organic matter is increased due to trampling, which in turn enhances the water retention capacity of the soil and retards decomposition [52].

5. Conclusions and Final Remarks

The results of the present study demonstrate several significant differences between chemical parameters according to the depth of the mineral soil. Total carbon, organic carbon, total nitrogen, and total potassium decreased significantly by depth in both the control and post-fire areas. As regards the concentration of soluble salts, this only decreased significantly in the post-fire area. Meanwhile, carbonate content, inorganic carbon, and the C/N ratio increased significantly by depth. However, no significant differences according to soil depth were observed for pH, exchangeable calcium, magnesium, or sodium cations or available silicon or sulfur.

The results for soil properties in the control and post-fire areas indicate a significant increase in the post-fire area compared to the control area in total carbon, total nitrogen, organic carbon, soluble salt concentration and total potassium. In addition, an increase was also observed in exchangeable calcium cations and available silica and Sulphur in the uppermost layers of the mineral soil (0–5 cm). In contrast, the pH and C/N ratio decreased significantly. With regard to the content of inorganic carbon, carbonates and exchangeable magnesium and sodium cations, no statistically significant differences were found between the two areas.

The partial combustion of the organic substrate, the significant increase in TC, OC, TN, EC, and K⁺ and the slight decrease in pH in the post-fire area with respect to the control area together demonstrate that the fire was of low intensity and did not generate significant short-term negative impacts for either the organic layer or the mineral soil; on the contrary, its effect was rather the opposite. Soils of this type, with a well-defined organic horizon and high organic matter content in the uppermost 5 cm of soil, tend to maintain their structure after a low-intensity fire and retain the nutrients necessary for ecosystem recovery and resilience. Therefore, it is important to implement forest management practices that maintain this type of soil structure in *Pinus halepensis* Mill. ecosystems, such as extensive livestock farming or prescribed burning, because the intensity of the fire in the latter case would be similar to that of the fire studied, and both strategies would help prevent large forest fires. Nevertheless, it should be noted that the present study has only determined the short-term effects. The long-term effects have been extrapolated from the results of other studies and can therefore only be considered an approximation of what might happen in this type of forest.

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