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Post-fire assessment of soil physicochemical properties in Tamgout Forest, Northern Algeria

Karima Sebki [(1)],
Zine Eddine Chekired [(2)],
Brahim Mehdi [(3)],
Ayoub Allam [(4)],
Ouahid Zanndouche [(2)],
Boussad Metna [(1)],
Rachid Meddour [(1)]

Understanding how fires affect forest ecosystem components is crucial for predicting vegetation recovery and guiding forest management. Yet information on wildfire consequences for soil properties remains limited in Algeria. This study investigated the impact of wildfire on the physicochemical and structural properties of forest soil in the Tamgout area, northern Algeria. Soil samples were collected along a post-fire chronosequence (2, 10, and 18 years) and compared to an unburned soil (control). ANOVA analysis revealed significant fire-induced changes in key soil properties, including moisture content (M), texture, electrical conductivity (EC), total Nitrogen (TN), organic carbon (OC), organic matter (OM), and mineral content (K^+, Ca^{2+}, Na^+, Fe, and Mn). In contrast, no significant differences were observed in pH, $CaCO_3$, and Mg^{2+} contents. The Fourier transform infrared spectroscopy (FTIR) showed marked spectral shifts in mineral bands, particularly in the mid-infrared region, distinguishing burned from unburned soils. X-ray diffraction (XRD) analysis further demonstrated progressive crystallographic alterations, including peak broadening, reduced intensity, and microstructural degradation in fire-affected soils, indicating mineral disorder and reduced crystallinity. These findings highlight the long-term effects of fire on soil composition, structure, and other parameters that play a critical role in forest resilience, ecosystem recovery, and biodiversity conservation in Mediterranean woodland environments.

Keywords: After-fire, FTIR, XRD, Tamgout Forest, Soil

Introduction

Forest fires (FF) play a crucial role in altering soil properties and landscapes, influencing forest ecosystem dynamics and regeneration potential (Sharma & Kumar 2025). Fire-induced soil property alteration depends on both the temperatures reached at different soil depths and the tolerance of soil nutrients to heat (Agbeshie et al. 2022). FF-related disturbances in the Mediterranean region are receiving more attention due to frequent prolonged dry seasons and high temperatures, which trigger wildfires at short intervals, devastating large areas. In addition to FF, soils are exposed to clearing, overgrazing, trampling by herds, and human activities (Sari 2023). Consequently, these factors significantly degrade soil quality and accelerate erosion. Other abiotic factors such as topography and climate change also significantly affect soil properties (Barmpoutis et al. 2023). However, FF impacts vary across ecosystems in space and time, considering pre-fire vegetation conditions and post-fire vegetation recovery (Spatola et al. 2023). Moreover, Santorufo et al. (2021) claimed that soil properties such as pH, water content, organic matter, organic carbon, and total nitrogen concentrations are significantly influenced by FF. These authors reported that total and available concentrations of Ca^{2+}, K^+, Mg^{2+}, Na^+, P, and trace elements such as Fe and Mn are also affected after a fire. These findings showed that temporal changes in soil element concentrations occurred at different rates, suggesting a comprehensive alteration of soil conditions.

In this context, Doblas-Miranda et al. (2015), Hrelja et al. (2020), and Kastridis et al. (2024) highlighted the immediate and short-term impacts of FF on soil, noting that FF effects on soil properties return as a function of time since FF. These insights support adapting management of burned areas, particularly under climate change scenarios that make recurrence more frequent (Goltas et al. 2024). Although extensive research worldwide has investigated FF impacts on soil characteristics, findings cannot be readily generalized because they usually focus on specific contexts based on emphasis, environment, and methodology (Moussaoui et al. 2022).

In the Mediterranean region, numerous studies have examined the positive and negative impacts of FF on soil properties (Gillon 1990, Parro et al. 2019, Fontúrbel et al. 2024). Algeria is one of the main hotbeds of FF in the southern Mediterranean region because of high FF activity along its northern coastal fringe (Curt et al. 2020, Guit & Nedjimi 2021). However, only a few studies in Algeria have reported mineralogical changes in forest soils after fires (Bekdouche 2010, Allam et al. 2020, Moussaoui

(1) Department of Biology, Faculty of Biology and Agronomy, Mouloud Mammeri University, Tizi Ouzou, 15000 (Algeria); (2) Soil Science Laboratory, National Forest Research Institute, Bainem, Algiers (Algeria); (3) Materials Physics Laboratory, Faculty of Physics, University of Science and Technology, University of Houari Boumediene - USTHB, Bab-Ezzouar, B.P. 32.16111 Algiers (Algeria); (4) Department of Biology, Faculty of Sciences and Technology, University of Relizane, Relizane (Algeria)

@ Karima Sebki (karima.sebki@ummto.dz)

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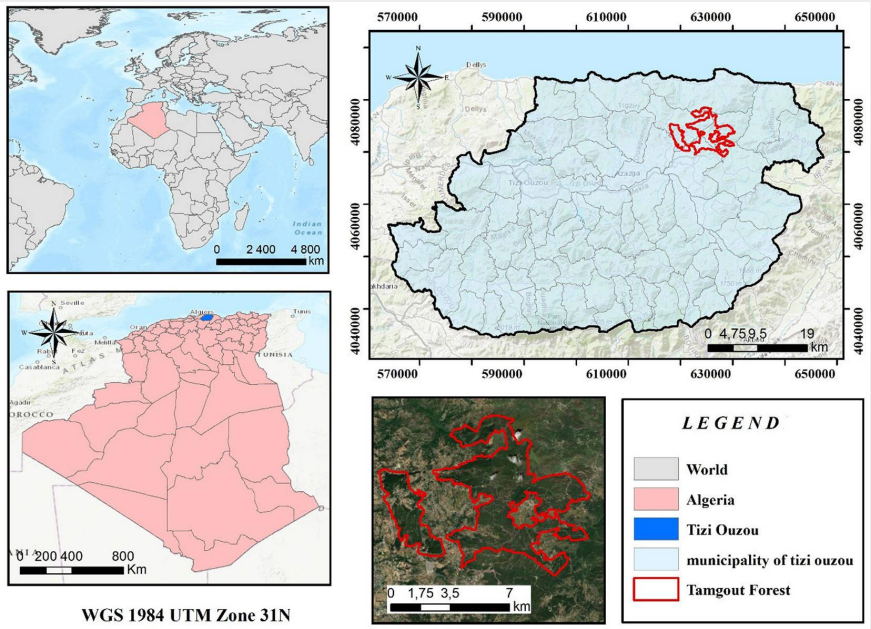


Fig. 1 - Geographic location of the study site in the Tamgout Forest, Algeria.

et al. 2022). Sustainable management of Algerian forest services requires a thorough assessment of the physicochemical properties of burned soils and ecosystems' vulnerability to soil disturbances. Any rehabilitation or regeneration program for burned forest ecosystems must account for FF impacts on soils (Borsali 2013).

This study investigated the effects of fires on the physicochemical characteristics and nutrient dynamics of soils in the Tamgout forest area, considered fairly representative of forest formations in the sub-humid climate zone challenged by increasingly frequent forest fires. The main objective was to compare the short- and long-term recovery dynamics of burnt and unburnt (control) sites, focusing on both macro- and micronutrients, soil texture, and mineralogy.

Materials and methods

Study area

The Tamgout forest is located in the Tizi Ouzou department, part of the Kabylia coastal chain. It is located on a ridge 5 km from the sea (Azeffoun) to the north, between 04° 19′ 15″ and 04° 27′ 40″ East longitude and 36° 45′ 30″ and 36° 50′ 40″ North latitude (Fig. 1). With a surface area of 3,800 ha, it overlaps four municipalities, namely Akerrou (East) and Aghrib (West). Tamgout forest is divided into 18 forest provinces managed by the Forest Management Directorate of Tizi Ouzou. The region's climate is typically Mediterranean, with mild, wet winters and hot, dry summers, with average annual rainfall of 1,053 mm and average annual temperatures of 15.59 °C. The vegetation is mainly composed of cork oak (*Quercus suber*), with 33% pure stands and mixed patches of cork oak, zeen oak (*Q. canariensis*), and afares oak (*Q. afares*). We chose the site because it contains two areas: the first was burnt in different years, while the second area has not burned. This allows us to observe the effect of FF on the physicochemical properties of burnt and unburnt forest soil. Fig. 1 shows the geographical location of the study site.

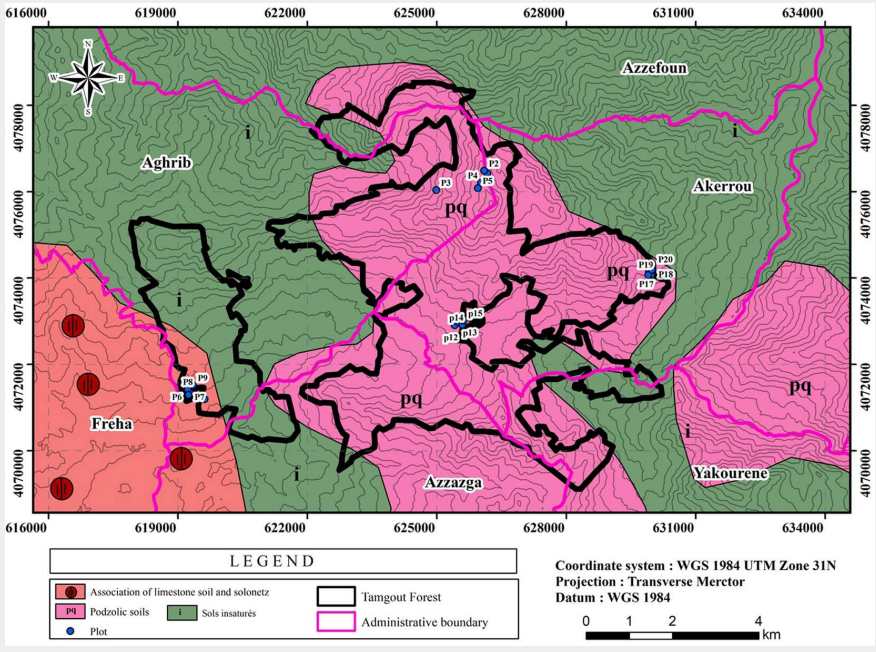


Fig. 2 - Localization of sampling sites on Tamgout forest soil type map.

Data collection

The sampling was performed in summer. Fig. 2 shows the sample locations on a map of soil types in the Tamgout forest.

The undergrowth is dense, and the tree formation is dominated by cork oak in the three fire strata, and is clear and dominated by zeen oak in the control fire stratum (C). Tab. 1 provides additional information on the four strata.

We determined sampling locations within the plot as randomly as possible by walking through the entire plot in a zigzag pattern. We took samples using an auger at depths of 0-10 cm, corresponding to the organo-mineral surface horizon A, because this layer is the first and most intensely impacted by fire (Mayor et al. 2016, Curt et al. 2020). Twenty study plots of 400 m² (5 plots/fire strata) were selected from four fire strata. Each plot was randomly sampled at 6 points after total litter removal (Vennetier et al. 2008). Fire strata were named according to fire recurrence period: 2 years (P1), 10 years (P2), 18 years after the fire (P3), and control (C).

The samples were mixed to obtain a composite sample of 1 kg per plot. Each composite sample was placed in a hermetically sealed bag and identified by origin, sample, plot, and fire strata.

In the laboratory, part of each sample was sieved after air-drying. The remaining part was kept in a refrigerator, awaiting further analyses carried out a few days after sampling. Fig. 3 shows photos of the different fire layers taken during sampling.

Physical and chemical analysis

Soil analysis enables the monitoring of soil fertility. Prior to analysis, soil samples were spread out and air-dried for 72 hours, then crushed and passed through a 2 mm sieve. After homogenization, the fine soil samples were kept in airtight boxes. Physicochemical analyses, pH, and soil EC were measured separately in deionized water at soil/water ratios of 1:5 and 1:2.5, according to McLean (1982). Soil MC was determined by taking 5 g of wet soil samples.

The samples were weighed before and after oven drying at 105 °C for 24 h. Total limestone was determined by the calcimeter Bernard method (Aubert 1978). This method measures the CO_2 volume released by the soil samples in the presence of hydrochloric acid (HCl). TN was measured by the Kjeldahl method (Mathieu & Pieltain 2003). The OC was determined using a wet oxidation technique (Walkley & Black 1934). We obtained the OM rate by multiplying the OC value by 1.724. Available P in soil was measured using the Olsen method (Olsen 1954). The quantity of P in the form of orthophosphates (mg kg^{-1} of dry soil) in the extracts was measured using spectrocolorimetry.

The exchangeable cations K^+, Ca^{2+}, Mg^{2+}, and Na^+ were determined by the Knudsen et al. (1982) method, by extraction with ammonium acetate (1 N NH_4OAc) at pH 7.0. These operations were followed by atomic absorption spectrometry for Ca^{2+} and Mg^{2+}, and by atomic emission spectrometry (flame or ICP-OES) for K^+ and Na^+.

Trace element content of sampled soils was determined via ICP-MS analysis, which allows for the detection and quantification of trace elements. Measurements were performed following the analytical methodology described by Bennour et al. (2020). Extraction of mineral elements was carried out via hot nitric o-perchloric acid $HNO_3/HClO_4$ with V/V 4/1 attack. The trace-element fraction was measured directly after mineralization or after dilution using a Perkin Elmer atomic absorption spectrophotometer in flame mode.

Fourier transform infrared spectroscopy

We used this analytical method in soil assessment, aiming to identify functional groups in soil materials *via* characteristic absorption bands of chemical bonds linked to soil chemical and physical properties (Ge et al. 2024). FTIR analyses were performed using a Shimadzu IRAffinity-1S® (Shimadzu Scientific Instruments, Columbia, MD, USA). Soils were dried and then deposited on an attenuated total reflection (ATR) cell equipped with a diamond crystal. Raw data were processed with Origin® 2015 software (OriginLab Corp., Northampton, MA, USA).

Soil mineralogy measurement by XRD

X-ray spectra were recorded using a D2 Phaser X-ray diffractometer (Bruker Corp., Billerica, MA, USA), with Co-Kα radiation (λ = 1.78) on all samples. A scan step of 0.02 and a 2θ range varying from 5° to 90° were used.

Statistical analysis

We analyzed the collected data using MiniTab v.17 (Minitab, LLC, PA, USA). Before performing ANOVA, we verified normality and homogeneity using the Shapiro and Levene tests. For variables for which we did not verify normality and homogeneity, we used the Kruskal-Wallis test. An ANOVA test was performed to determine significant differences between the fire strata studied, using a 5% threshold to compare means.

We also used a multivariate statistical technique based on principal component analysis (PCA) to examine relationships among variables that showed significant differences and the explanatory variables (age, elevation, slope, aspect, and vegetation cover density) between four strata. Data processing was carried out in Rstudio® (Posit PBC, MA, USA), enabling both statistical computation and graphical visualization.

Tab. 1 - Characteristics of the sampled strata of the Tamgout forest.

Samples	P1	P2	P3	C
Canton name	Ihmamouchene	Ait Lader	Tala Ghanim	Tamgout
Sampling date	June 23, 2019	June 20,2019	June 23, 2019	June 13, 2019
Last fire (yrs)	2	10	18	Control
Climate	Temperate subhumid	Temperate subhumid	Temperate subhumid	Temperate subhumid
Elevation (m)	680	401	530	1100
Slope (%)	12.5-25	12.5-25	12.5-25	3-12.5
Aspect	South-West	North-East	North-East	North-East
Vegetation cover (%)	Dense	clear	Very dense	Very dense
Dominant tree species	Cork oak	Cork oak	Cork oak	Cork oak and Oak zeen
Understory dominant species	*Rubus ulmifolius, Erica arborea, Cistus salviifolius, Calicotome spinosa, Genista tricuspidata*	*Rubus ulmifolius, Erica arborea, Cistus salviifolius, Calicotome spinosa, Genista tricuspidata*	*Rubus ulmifolius, Erica arborea, Cistus salviifolius, Calicotome spinosa, Genista tricuspidata*	*Cytisus villosus, Erica arborea*

Results

Physical characteristics and macro/microelements content

Tab. 2 shows the results for the physicochemical parameters of the soil analyzed. The results revealed statistically significant differences in 11 parameters: M, EC, TN, OC, sand, Ca^{2+}, K^+, Na^+, P, Fe, and Mn. However,



Fig. 3 - Fire strata identified in Tamgout forest: P1, P2, P3, and C.

Tab. 2 – Means ± standard deviation of all soil parameters from fire strata. Different letters indicate significant (p<0.05) differences after ANOVA test (n = 5). (ns): non-significant.

Group	Parameters	P1	P2	P3	C	Prob
Chemicals parameters	pH	5.48 ± 1.50	5.81 ± 0.23	5.98 ± 0.24	5.88 ± 0.78	ns
	$CaCO_3$ (%)	0.90 ± 0.32	0.63 ± 0.24	1.08 ± 0.24	0.90 ± 0.55	ns
	EC (dS m^{-1})	0.09 ± 0.01 ^{bc}	0.06 ± 0.01 ^{c}	0.12 ± 0.01 ^{b}	0.17 ± 0.03 ^{a}	<0.001
	TN(%)	1.68 ± 0.29 ^{ab}	0.87 ± 0.43 ^{b}	1.81 ± 0.85 ^{ab}	2.38 ± 0.46 ^{a}	<0.01
	OC(%)	3.44 ± 0.66 ^{c}	2.41 ± 0.18 ^{c}	5.75 ± 0.85 ^{b}	6.95 ± 1.38 ^{a}	<0.001
	OM (%)	5.92 ± 1.15 ^{c}	4.15 ± 0.32 ^{c}	9.89 ± 1.46 ^{b}	11.95 ± 2.34 ^{a}	<0.001
	P_2O_5 (ppm)	13.16 ± 1.88 ^{b}	17.02 ± 2.69 ^{b}	18.02 ± 2.51 ^{b}	22.46 ± 5.16 ^{a}	<0.01
Physical parameters (%)	M	2.77 ± 0.60 ^{a}	0.80 ± 0.13 ^{b}	2.34 ± 0.30 ^{a}	2.81 ± 0.63 ^{a}	<0.001
	Granulometry	Silty	Sandy-silty	Silty	Silty	-
	Clay	22.11 ± 9.45	16.48 ± 3.90	20.07 ± 4.87	22.90 ± 11.01	ns
	Silt	46.50 ± 10.16	34.09 ± 3.27	44.11 ± 6.86	43.01 ± 8.27	ns
	Sand	32.39 ± 4.59 ^{b}	49.35 ± 2.69 ^{a}	35.82 ± 6.61 ^{b}	34.04 ± 5.23 ^{b}	<0.001
Exchangeable cations (ppm)	Ca^{2+}	14.12 ± 0.23 ^{c}	13.60 ± 0.72 ^{c}	16.14 ± 1.07 ^{b}	17.56 ± 0.88 ^{a}	<0.001
	Mg^{2+}	7.37 ± 0.15	7.55 ± 0.84	7.58 ± 0.25	7.56 ± 0.64	ns
	Na^{+}	14.07 ± 1.51 ^{a}	13.59 ± 0.52 ^{ab}	14.46 ± 0.42 ^{a}	11.76 ± 2.52 ^{b}	<0.05
	K^{+}	5.54 ± 0.34 ^{c}	3.17 ± 0.31 ^{d}	9, 64 ± 0.63 ^{a}	8.12 ± 1.15 ^{b}	<0.001
Trace elements (ppm)	Fe	3.10 ± 0.75 ^{a}	2.11 ± 0.35 ^{b}	1.68 ± 0.4 ^{b}	1.16 ± 0.04 ^{c}	<0.001
	Mn	0.50 ± 0.06 ^{b}	0.03 ± 0.02 ^{c}	0.66 ± 0.03 ^{a}	0.55 ± 0.06 ^{b}	<0.001

no statistically significant effects were found for 6 remaining parameters: pH, total limestone $CaCO_3$, clay, silt, Mg^{2+}, and K^{+}.

All soils analyzed had very similar pH values, ranging from 5.48 (P1) to 5.98 (P3); this pH is generally favorable for *Quercus suber*, as it prefers acidic to neutral soils. According to international standards, the soils studied do not contain limestone, given their $CaCO_3$ content. The general trend showed that variability in TN content between the burned strata was similar to that of OC content and, therefore, OM, with a decrease in P2 and an upturn in P3. The highest values were recorded in C content (2.38 ± 0.45%, 6.95 ± 1.38% and 11.95 ± 2.34%, respectively). Regarding available P, the four strata showed significant differences after the fire, with P levels increasing over time; however, the values were lower than those recorded in C. Fluctuations were observed, with EC showing highly significant differences among the four fire strata. EC decreased in P2, then increased in P3, and the highest value was recorded in C. Ca^{2+}, Na^{+}, and K^{+} levels decreased significantly in plot P2, then increased in P3, indicating higher K^{+} levels *versus* lower Ca^{2+} and Na^{+} contents. For trace elements, Mn follows the same trend as Ca^{2+} and Na^{+}, while Fe shows a different trend and decreases over time. The highest value was recorded in P1 (3.10 ± 0.75 ppm), and the lowest in C (1.16 ± 0.04 ppm).

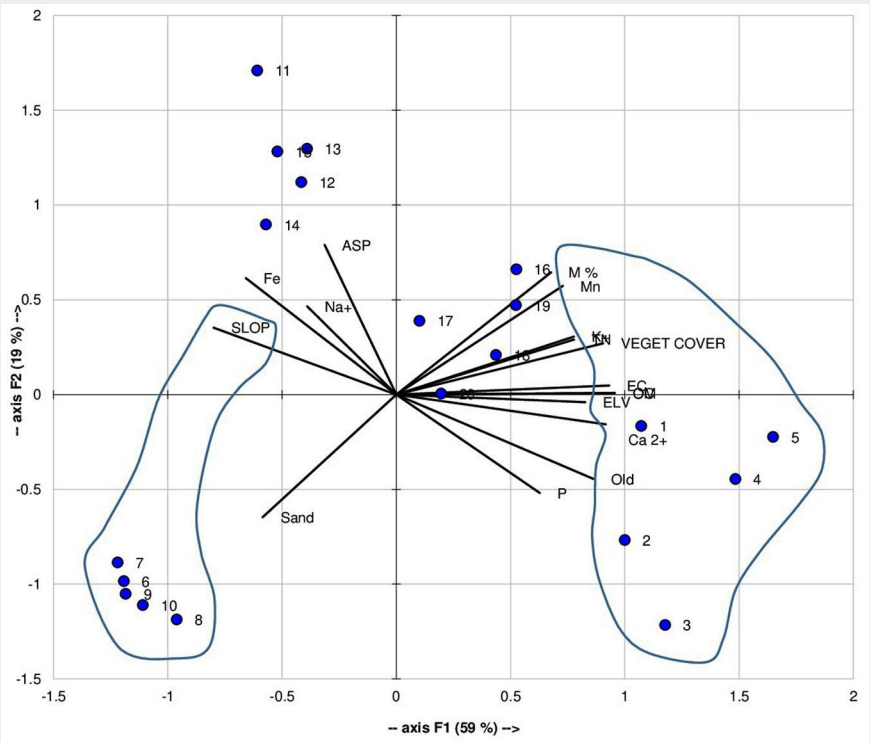


Fig. 4 - PCA graphs of individuals (fire strata) and variables (analytical data) providing an overview of correlations between physicochemical parameters measured in soils from Tamgout forest. Individuals: 11, 12, 13, 14, 15 (P1); 6, 7, 8, 9, 10 (P2); 16, 17, 18, 19, 20 (P3) ; 1, 2, 3, 4, 5 (C)

Regarding soil particle size, clay and silt did not differ greatly among the soils studied. Slight fluctuations were recorded between the four plots, but the sites did not differ significantly. However, sand differed significantly, with a high value of 49.35 ± 2.69% in P2. Therefore, the soil texture is silty for P1, P2, and C, and silty-sandy for P2.

PCA performed on edaphic, topographic, and biophysical variables revealed a clear data structure (Fig. 4). The two axes explain 78% of the total inertia, with a dominant contribution from axis F1 (59%) and a secondary contribution from axis F2 (19%). This high cumulative inertia reflects a strong representation of the initial information on the F1-F2 factor plane.

Axis F1 is strongly positively correlated with variables related to soil fertility and quality, in particular M, OC, OM, EC, TN, exchangeable Ca^{2+}, K^{+}, Mn, and vegetation

cover (VEGET COVER). Topographic variables such as elevation (ELV) and the number of years since the last fire (Old) also contribute significantly to this axis. Conversely, sandy texture (Sand) and slope (SLOPE) showed marked negative correlations with F1. Axis F2 is mainly structured by the explanatory variable exposure (ASP), which does not show significant correlations with any variables; therefore, it is useful to exclude this axis from the interpretation.

FTIR spectroscopy results

The FTIR spectra of the analyzed soil samples exhibit several absorption bands associated with both mineral and organic components. All samples showed a weak but persistent band at 464 cm^{-1}, indicating the presence of silicate minerals (Fig. 5). The band at 780 cm^{-1}, characteristic of quartz, showed variable intensity among samples and was more pronounced in P3, suggesting a higher relative quartz contribution. Absorption bands between 905 and 915 cm^{-1} displayed variable intensities across samples, with strong signals in the control (C) and P3 soils and moderate to low intensities in P1 and P2. A pronounced band at 1030 cm^{-1} was also detected, being particularly intense in the control and P3 samples and less marked in P1 and P2. The spectral region between 1600 and 1650 cm^{-1} showed a moderately intense band related to organic matter and/or adsorbed water; in the control sample, a distinct band appeared at 1620 cm^{-1}. A weak, very low-intensity band at 1997 cm^{-1} was observed in all spectra and strata, except P2. In contrast, an intense absorption band at 2109 cm^{-1}, mainly observed in the control soil, and the band around 2340 cm^{-1} were identified as non-soil-related signals. Finally, bands in the 3650-3700 cm^{-1} range, corresponding to hydroxyl stretching vibrations, demonstrated variable intensities among samples, with a general decrease in burned soils. Fig. 5 shows the FTIR transmittance spectra of four soil samples (P1, P2, P3, and C) as a function of wavenumber (cm^{-1}).

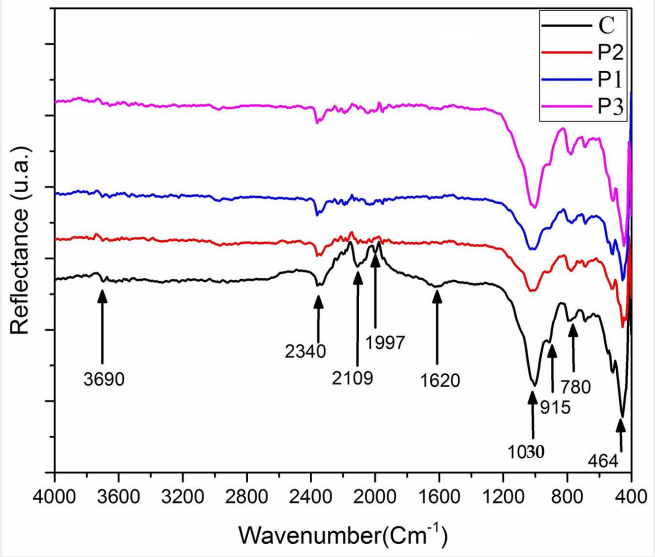


Fig. 5 - FT-IR spectral signature of soil samples.

Tab. 3 - XRD-derived microstructural parameters of soil samples with and without forest fire exposure.

Samples	Position	FWHM	D-spacing	Crystallite size	Microstrain %
P1	24.567	0.127	4.204	722.39	0.288
	31.317	0.145	3.314	891.64	0.184
P2	24.75	0.122	4.181	930.88	0.224
	31.505	0.242	3.302	484.39	0.340
P3	24.509	0.172	4.214	667.70	0.135
	31.257	0.187	3.320	658.21	0.252
C	24.810	0.161	4.163	1231.32	0.170
	31.580	0.149	3.287	962.31	0.172

Soil mineralogy

The XRD analysis was conducted on four soil samples collected at different intervals following a wildfire: P1, P2, P3, and C. We performed phase identification using the "diffraction material analysis software" X'Pert HighScore Plus with the PDF4/2022 database. Fig. 6a shows the XRD spectra of the control sample C compared with samples P1, P2, and P3. Tab. 3 presents the cor-

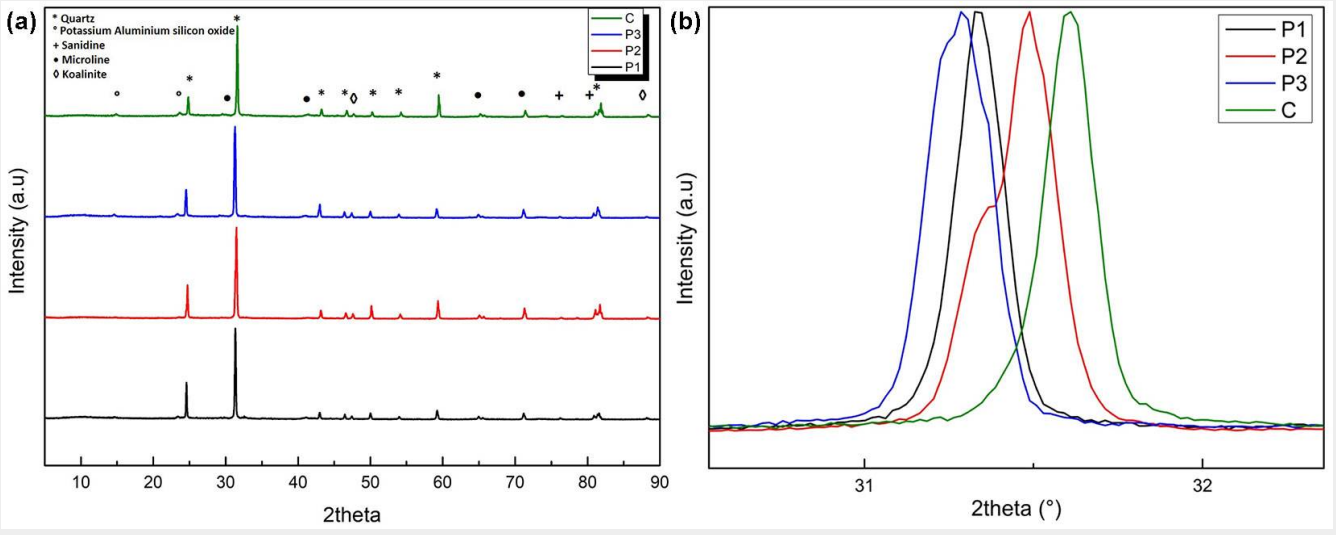


Fig. 6 - XRD spectra of the control sample C compared with samples P1, P2, P3 (a). Magnified views and comparison of the main diffraction peaks (b).

responding microstructural and crystallographic parameters for the representative intense peaks. The XRD results showed clear, measurable differences in the mineralogical structure of the soils depending on exposure to FF and the time elapsed since the event. These differences were observed in changes in peak width (FWHM), interplanar spacing (Fig. 6b), crystallite size, and microstrain.

Discussion

The effect of FF on OC and, therefore, on OM may depend on fire duration, soil type, topography, soil M, vegetation type, and vegetation cover (Erkovan et al. 2016). OC stocks increase with the number of years after the fire (P1, P2, and C). High OC and OM levels in C samples are attributed to greater living above-ground biomass than in burned soils (Mirzaei 2016, Alcañiz et al. 2018). However, the low OM content at site P2 may be explained by high nutrient exports and by relatively light textures that cannot accumulate a significant stock of organic matter (Sene et al. 2014). Opinions differ on changes in soil TN content after a forest fire. Some authors estimated that total nitrogen decreases after a forest fire due to volatilization (Kumar et al. 2013, Mirzaei 2016). Others reported that soil TN levels increase (Muqaddas et al. 2015). Our observations are consistent with those reported by Jacquet & Cheylan (2008) and Caon et al. (2014) in the Mediterranean forest, who stated that the amount of TN volatilized during a FF is proportional to the amount of OM lost. Indeed, long-term TN recovery or loss in plots P1, P2, P3, and C was proportional to that of OM and, therefore, OC. P availability in soils increased over time, with the highest value in C, likely due to improved vegetation and soil quality (Alcañiz et al. 2018) and increased OM mineralization. In contrast, other authors (Borsali et al. 2012, Parlak 2022) have reported decreased P content due to vegetation uptake and the difficulty of replenishing it. However, Scharenbroch et al. (2012) and Valkó et al. (2016) found no change in P level over time. It has been reported that EC tends to increase immediately after forest fires, due to the release of soluble ions during the combustion of soil and OM, and the incorporation of ash into the soil (Alcañiz et al. 2018). This nutrient availability, which was observed shortly after the fire, can persist long after the ash has settled (Jacquet & Cheylan 2008). In addition, EC is positively correlated with soil nutrients such as OM, TN, Ca^{2+}, K^{+}, and Na^{+}. Indeed, the increase in nutrients and exchangeable cations, and therefore in EC, in P1 is due not only to enrichment of the soil by deposited ash residues (Gillon 1990, Guit & Nedjimi 2021), but also to vegetation growth and emergence, which increases soil nutrient content. The decrease in EC at site P2 was driven by reduced nutrient content, likely lost through export and drainage into deeper layers (Vennetier 2004, Brye 2006). The dominance of the sandy fraction at site P2 explains the poor quality of these soils, as shown by nutrient leaching (Bouka et al. 2019). Sandy material has a low water-retention capacity; however, sandy material behavior could be influenced by the intensity and severity of the fire (Alcañiz et al. 2018), resulting in the collapse of the crystalline structure of clay lattices (*e.g.*, through the loss of hydroxyl ions or dehydration), resulting in the cementation of clay particles and the formation of either silt- or sand-sized new particles (Jacquet & Cheylan 2008, Heydari et al. 2017). We could not test this property in our case because we lack information on the history of local fires. Different cations undergo different changes. According to Verma & Jayakumar (2012), Mg^{2+} is relatively less sensitive to FF, which can be explained by its high threshold temperatures. The slight decrease in K^{+}, Na^{+}, and Mn stocks observed at site C is probably due to emergent plants using these nutrients (Moussaoui et al. 2022). The high concentrations of trace elements in recently burned sites are attributed to suspended ash (Parlak 2022). This shows how forest fires affect Fe forms in forest soils (Burton et al. 2016). Consequently, plants use them over time, reducing their mineral fraction in the soil (Parlak 2022).

PCA highlighted soil maturity and stability, showing a major soil gradient and contrasting mature soils. This indicated enhanced organic matter, greater chemical fertility, and developed vegetation cover, while sandy soils on steeper slopes were exposed to erosion and had low nutrient-retention capacity. Discrimination was evident between topographically more active areas, exposed to erosion and remobilization processes, and older, relatively stable areas.

Correlations showed a strong association between edaphic and abiotic ecological factor associated with soil fertility. Overall, soil maturity and vegetation cover were the main factors modulating the spatial dynamics of edaphic properties.

The persistent band at 464 cm^{-1} in the FTIR results confirmed the dominance of silicate minerals, particularly clay minerals, within the soil matrix, while the band at 780 cm^{-1} indicated the presence of quartz. The enhanced intensity of this quartz-related band in sample P3 suggested relative quartz enrichment, commonly attributed to post-fire concentration effects driven by OM loss and thermal alteration of fine soil fractions (Madejová 2003, Virji et al. 2002). High absorptions between 905 and 915 cm^{-1}, together with the pronounced band at 1030 cm^{-1} in the control and P3 samples, indicated a greater contribution from organic compounds, notably polysaccharides. However, this spectral region overlaps with silicate stretching vibrations, making mineral interference likely in soils with significant clay content. The reduced intensity of these bands in P1 and P2 suggested fire-induced degradation or transformation of labile OM (Madejová 2003, Nocita et al. 2015, Robinson et al. 2015). The absorption features in the 1600-1650 cm^{-1} region are commonly associated with aromatic C=C structures of soil OM and/or the bending vibration of adsorbed water. The moderate intensity of the 1620 cm^{-1} band in the control soil reflects higher moisture content or a greater proportion of aromatic organic compounds. Such bands typically decrease after fire due to dehydration and thermal decomposition of OM (Robinson et al. 2015). The very weak band at 1997 cm^{-1} corresponds to a minor overtone of quartz and has limited interpretative significance compared with the more pronounced fundamental Si-O vibrations at ~1100 or 460 cm^{-1} (Virji et al. 2002). Finally, the decrease in intensity of hydroxyl stretching bands between 3650 and 3700 cm^{-1} in burned soils revealed the loss of structural and adsorbed water, as well as the degradation of hydroxyl-bearing organic compounds. This behavior is consistent with fire effects on soil moisture and OM pools, as reported in previous studies (Robinson et al. 2015, Dai et al. 2023). Thus, the FTIR analysis indicated that FF hinders the short-term recovery of OM quality (Guénon 2010).

The C sample, used as the unburned reference, showed relatively sharp diffraction peaks with low FWHM values (0.149°-0.161°), large crystallite sizes (about 962-1231 Å), and moderate microstrain (0.17%). Together, these parameters indicate a well-preserved crystalline structure, typical of soil minerals unaffected by significant thermal stress. In contrast, the P1 sample, collected two years after the forest fire, showed noticeable peak broadening, accompanied by reduced crystallite size and increased microstrain. FWHM values reached up to 0.145°, while crystallite sizes decreased to approximately 722-892 Å. These changes indicate fire-induced microstructural damage, reflected in internal lattice distortion and increased residual stress within the mineral framework. The P2 sample exhibits intermediate but more variable behavior. Some diffraction peaks remain relatively narrow, whereas others are strongly broadened (FWHM up to 0.242°), with a marked decrease in crystallite size (down to ~484 Å) and the highest microstrain values observed (up to 0.340%). This variability suggested that, although partial structural relaxation may occur with time, significant residual strain and disorder persist in certain crystallographic domains. By comparison, the P3 sample, collected from a site that has not been exposed to forest fire for approximately 18 years, showed stable diffraction peaks with moderate FWHM values (0.172-0.187°), relatively uniform crystallite sizes (~658-668 Å), and lower microstrain than those measured in P1 and P2. These characteristics are close to those of reference sample C, indicating that natural aging without fire allows soil

minerals to retain a more stable and coherent crystalline structure. Overall, the quantitative XRD parameters demonstrated that forest fire exposure produced long-lasting microstructural changes in soil minerals. While some recovery is observed over time, the data indicate that crystallographic restoration remains incomplete even at the decadal scale.

Conclusion

Comparison between burned and control soils in the Tamgout forest demonstrated that fires hinder the short-term recovery of soil quality, with trajectories strongly controlled by time after fire, soil texture, and vegetation regeneration. Furthermore, results indicated that soil carbon and organic matter stocks generally increase with post-fire age, but their recovery remains limited in sandy soils due to reduced stabilization capacity and enhanced nutrient leaching. Post-fire nutrient availability showed element-specific responses: electrical conductivity and exchangeable cations increase shortly after fire due to ash inputs, then decline due to leaching, while phosphorus availability tends to improve as the ecosystem recovers. Mineralogy in both aged burned soils and controls showed persistent mineral signatures dominated by silicates and quartz, alongside marked alterations in organic functional groups in burned soils, indicating degradation of labile organic matter and loss of hydroxyl-associated water.

This study provided the first data allowing insight into how FF impacts local forest soils. The information provided is necessary to improve forest fire prevention strategies, especially on rough terrain. Therefore, we recommend increasing the number of replicates across strata in future work to better confirm our observations.

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