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Spatio-temporal assessment of soil properties immediately and eight months after a high intensity-controlled burn in the south of Spain

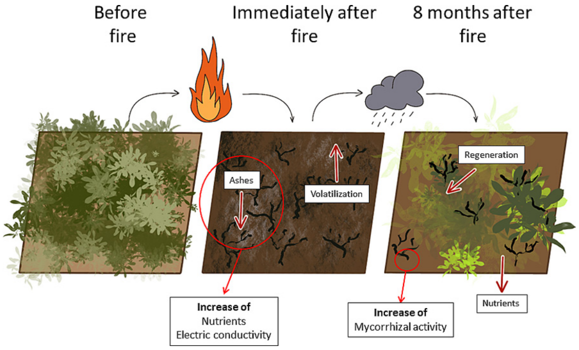
Elisa Vega-Martínez [a,b,*], Juan Ramón Molina [b], Vidal Barrón [a], Francisco Rodríguez y Silva [b], María del Carmen del Campillo [a], Antonio Rafael Sánchez-Rodríguez [a]

[a] *Unidad de Edafología, Departamento de Agronomía, Universidad de Córdoba, Córdoba, Spain*
[b] *Laboratorio de Defensa contra Incendios Forestales, Departamento de Ingeniería Forestal, Universidad de Córdoba, Córdoba, Spain*

HIGHLIGHTS

- Soil physical, chemical and biological indicators were assessed in a high intensity-controlled burn.
- Eight months after the burn, the microbial community structure remained altered.
- Soil nutrient availability was positively affected immediately after the burn.
- Putative arbuscular mycorrhiza was increased eight months after the burn.
- Fire behaviorbehaviour had a key role on spatial-temporal soil properties alteration.

GRAPHICAL ABSTRACT



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ABSTRACT

In recent years, the use of fire as a means by which to manage forest ecosystems has become more frequent in Europe. Fire has a significant impact on the soil, and it is therefore necessary to understand how controlled burns affect this invaluable resource. The purpose of this study was to evaluate the main alterations in the physical-chemical and biological properties of the soil because of a high intensity-controlled burn in "Los Boquerones" area (Villaviciosa de Córdoba, Spain). Additionally, we assessed the spatial heterogeneity of the alterations of different soil properties. A grid of 12 points was established on a hillside in Sierra Morena (Córdoba). Thermocouples were placed at each point, and soil samples were collected at two depths (0–2 cm and 2–5 cm) before burning, immediately after burning and eight months later. Soil pH, electrical conductivity, nutrient content and/or availability, among others, and their spatio-temporal variations were analysed. Soil pH, increased in the first centimetres of the soil (0–2 cm) immediately after burning up to >2 units, and the increase was maintained eight months following the burn. Additionally, the high-intensity burn had a positive short-term effect on some of the soil properties, such as nutrient availability for plants, which was considerably increased. The magnitude of the alterations in the soil indicators assessed was spatially explained by the behaviour of the fire during the controlled burning. The burn also had both direct and indirect effects on soil microorganisms. In conclusion, the possible immediate and short-term effects of burning on the soil resource should be considered for a more holistic management of fire in forest ecosystems, as its functionality and capacity to provide ecosystem services is largely altered by these events as a function of their intensity.

1. Introduction

The planet is undergoing a process of continuous change that is accelerated at a certain extent by human influence, which implies alterations in

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* Corresponding author at: Unidad de Edafología, Departamento de Agronomía, Universidad de Córdoba, Córdoba, Spain.
E-mail address: o62vemae@uco.es (E. Vega-Martínez).

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climatic and ecosystem conditions. These changing conditions not only intensify the severity of wildfires but also increase the frequency of such events even in areas that are not typically prone to them, like Northern Europe and certain parts of Asia. (Prichard et al., 2017; Pechony and Shindell, 2010). Together with climate change, another factor affecting the frequency and severity of wildfires is land-use change. In recent decades, many rural areas traditionally used for agricultural activities have been abandoned as a consequence of migration to cities (Alcañiz et al., 2018). Land abandonment in rural areas traditionally used for agriculture has been linked to an increase in wildfires in many parts of the world, particularly in the Mediterranean region (Mantero et al., 2020). This abandonment often leads to a recovery of scrubland and forests, which in turn replace open habitats and increase wildfire events (Moreira and Russo, 2007). In the Mediterranean region, most studies on wildfires have focused on land abandonment, disturbances, and the resulting changes in vegetation communities. The abandonment of land in southern Europe has led to a higher frequency of large wildfires, impacting both human populations and vegetation communities (Mantero et al., 2020). The abandonment of land in southern Europe has led to a higher frequency of large wildfires, impacting both human populations and vegetation communities (Mantero et al., 2020). Furthermore, land abandonment is a big deal as around 30 % (56 million ha) of agricultural areas in the European Union are at moderate risk of abandonment and this percentage is even greater in half of the Member States (Dax et al., 2021).

In terms of prevention in different parts of the world, the main objective is to raise awareness and educate people on the impacts of fire and its proper use (FAO 2006). Fire is a key tool in agricultural and forestry management, and a total ban on its use is, therefore, inadequate due to its role in clearing land, maintaining ecological processes, and promoting biodiversity. (Pérez Salicrup et al., 2018; Rodrigues et al., 2020). Although prevention and suppression methods are necessary in order to prevent wildfires, there is a counterpart to their application: the so called “fire paradox” (Rego and Rigolot, 2011). This paradox explains that with the current suppression policies, fire events do not occur at all, resulting in an accumulation of significant quantities of fuel in areas that need fire for their natural dynamics, which ultimately leads to potentially more severe wildfires when they do occur (United Nations, 2021). A possible way to address this paradox would be the use of fire as a tool of forest and fuel management (Arévalo and Naranjo-Cigala, 2018).

According to Urbieta et al. (2019), wildfire activity has decreased in the last decades in Spain as a whole and in most provinces. The study found that the number of fires, burned area, mean fire size, and largest fire size have all decreased. However, fire risk factors have increased, with weather conditions becoming more severe and landscapes more hazardous due to greater forest cover. In addition, the proportion of large forest fires, which are those affecting >500 ha, has increased (Urbieta et al., 2019). This trend can also be identified in other countries, such as the United States (Parks and Abatzoglou, 2020). The extension of these fires complicates their suppression, resulting in a major impact not only on the environment, including forests and rural areas, but also on urban areas. The most effective strategy is to act in order to prevent them from occurring or spreading out of control by raising public awareness, urban planning, or fuel treatments to avoid fuel continuity (Cochrane et al., 2012; Fox et al., 2018).

Given the current situation of the environment and forest fires, we must identify and evaluate the tools that can be applied at different scales in order to mitigate or minimize this issue. These tools include forest management at a certain level of specificity, i.e., knowledge of the characteristics and vulnerability of each specific forest system is crucial in terms of making the right decisions. Preventive silviculture is a forest management approach aimed at reducing the continuity of fuel horizontally and vertically to minimize the risk of wildfires. It involves creating discontinuities in combustible matter through various techniques, such as mechanical and manual clearance, manual pruning, restricted burning, controlled pasturage, and the use of phytocides (Ameray et al., 2021). Horizontal fuel continuity refers to the uninterrupted distribution of fuel particles across the landscape, which affects the ability of a fire to spread horizontally (Drury, 2019). Vertical fuel continuity, on the other hand, refers to the connection of biomass fuels from the mineral soil/duff interface to the needles on the top of the trees (Drury, 2019). In this context, the use of prescribed fire plays a very important role. Prescribed fire is a form of preventive silviculture in which fire is intentionally applied to vegetation under specific conditions to achieve predetermined objectives, such as restoring fire regimes in adapted ecosystems or limiting the amount of dry brush in an area prone to wildfires (Grebner et al., 2013). There are two types of prescribed fire: controlled and prescribed burns. While controlled burns are generally used in rural areas for recovery purposes, such as recovering pastures or eliminating agricultural and forestry residues (Eales et al., 2018), prescribed burns are applied with a more planned and controlled approach. Prescribed burns require the evaluation of specific climatic conditions and the involvement of experts in wildfire management (Drury, 2019). Prescribed burns can be carried out before the fire season as a preventive measure or during the suppression of a large wildfire to prevent its spread (Miller et al., 2020).

Wildfire and prescribed burning affect the functionality of forest ecosystems, including the water cycle (changing runoff dynamics, water solute composition), the carbon cycle (affecting carbon sequestration pools and gaseous exchanges) and other nutrients, habitats and biodiversity (changes in the distribution of plant species and the dominance of some over others, as well as affecting fauna and their distribution), containing soil as a support and development of life in the ecosystems (Alcañiz et al., 2018; Caon et al., 2014). According to Volkova et al. (2021), prescribed burning has limited potential for reducing net greenhouse gas (GHG) emissions, but there are no significant emission penalties for changing burn management. The study developed an ecosystem carbon model to investigate the implications of prescribed fire management on total net ecosystem carbon balance, including both emissions and carbon storage, and concluded that land managers can adopt prescribed fire regimes to target specific management outcomes without significantly impacting these two variables over the long term. Another study carried out by Tangney et al. (2022), a meta-analysis of field-based studies across different vegetation types and climate regions, found that fires outside of the historical fire season may lead to decreased post-fire recruitment, particularly in obligate seeding species. Conversely, there was a general increase in post-fire survival in resprouting species. Changes in the occurrence of fire can alter seed germination, resulting in delayed or failed emergence, and decreased recruitment processes have the potential to cause the abrupt local loss of obligate seeding species. These findings suggest that understanding the complex interactions between climate change, fire regimes, and plant species distribution is critical for the management of ecosystems impacted by wildfires.

As soil is the base of most of the life on Earth, understanding how it reacts to disturbances such as forest fires is necessary in order to determine their impacts on the natural environment (Alcañiz et al., 2018). Fire has direct impacts on physical, chemical and biological soil properties due to the processes that take place during the temperature rise and soil organic matter combustion (Alcañiz et al., 2018; Certini, 2005). Maksimova and Abakumov (2017) conducted a study on the impact of fire on soil chemistry and found that the addition of ash following complete or partial burning of biomass and organic matter, and their incorporation into the soil, significantly modified soil chemistry. During a forest fire, soil temperatures higher than 200 °C incinerate organic matter and produce char compounds, leading to ash formation and increased pH. Additionally, fire not only affects soil properties while it is occurring, but also has (indirect) effects after the fire has ceased (Santín and Doerr, 2016). In general, fire has a greater impact on the surface soil horizon (Abakumov et al., 2020a; Alcañiz et al., 2018; Francos et al., 2018) due to the low thermal conductivity of soils. However, the top centimetres of soils are fundamental for soil health (water retainment capacity, C sequestration, soil fertility, soil biodiversity) and forest ecosystems due to the limited depth of forest soils.

High temperatures during wildfires can lead to the fragmentation or cracking of parent material, which increases weathering and, consequently, nutrient availability, similarly to when rock gelifraction occurs (Santín and Doerr, 2016). Consequently, this leads to an increase of soil bulk density

(Giorgis et al., 2021), although this effect is unclear, as different authors have obtained different results (Alcañiz et al., 2018). Soil structure is affected both by the combustion of the soil organic matter and alterations in soil aggregates that are favoured by both soil organic matter content and clay minerals. Organic matter generally accumulates to a greater extent on the soil surface, and is thus directly affected by high fire temperatures, reaching total combustion at 450 °C to 500 °C (Alcañiz et al., 2018). The high temperatures reached in the soil during a wildfire could lead to the alteration of iron (Fe) oxides; for example, formation of hematite and maghemite (depending on soil organic matter content), the latter with magnetic properties and produced by fires of greater intensity (Jordanova et al., 2019b).

The accumulation of ash, resulting from the combustion of vegetation and organic matter on the soil surface, leads to changes in the chemical properties of the soil. After a fire, a temporary nutrient enrichment of the soil can lead to an increase in electrical conductivity and pH, as well as in the concentration of available nutrients such as nitrogen (N) and phosphorus (P), and certain exchange cations can generally be observed (Ca, Mg, K and Na; Caon et al., 2014; Coates et al., 2018; Francos et al., 2018; Majder-łopatka et al., 2019). Furthermore, the increase in soil pH together with the high temperatures reached on the soil surface impact nitrogen (N) availability, increasing the amount of dissolved organic N and inorganic nitrogen forms (NH_4^+, NO_3^-) (Caon et al., 2014; Múgica et al., 2018). At the biological level, plant roots, fungi, bacteria, seed banks and any form of life present in the soil are drastically impacted when soil temperature exceeds 50 °C, and particularly when it reaches 150 °C (Adkins et al., 2020; Santín and Doerr, 2016). These effects are dependent on the characteristics of the burn or fire, the amount of fuel, the microtopography and soil moisture (Alcañiz et al., 2018).

Soil functionality encompasses the processes that take place in the soil and facilitate the provision of ecosystem services (Bünemann et al., 2018). Soil must be considered a multifunctional resource, given its complexity and the wide variety of processes that take place in it. In most cases, actions undertaken in soil have a direct consequence on its functionality, as well as on the ecosystem services provided by the soil itself (Bünemann et al., 2018).

Fire intensity is a crucial concept in understanding the combustion process of energy release from forest fuel during various phases of a fire (Rossi et al., 2018). It is defined as the energy output rate per unit length of fire front and is directly related to flame size (Alexander, 1982). However, fire intensity has been criticized for its incorrect usage in evaluating fire impacts on vegetation, as it is sometimes restricted to a single measure of energy output, such as fireline intensity (Rossi et al., 2018). Fireline intensity is a more useful metric to understand fire behaviour in forests, but it is too narrow to fully capture the multitude of ways fire energy affects ecosystems (Alexander, 1982). Therefore, the concept of fire severity is related to fire intensity, as it describes how fire behaviour affects ecosystems.

In forest management, prescribed fire is a common practice to manage vegetation and reduce the risk of wildfires. Prescribed fire and controlled burns are often used with forest management and training purposes, but they are also very useful in terms of research regarding ecosystem regeneration, or specifically the impact on the soil system, as in this case. The purpose of this study is to analyse the effects that a high intensity-controlled burn (flame length is higher than 2.5 m) has on the properties of the soil and assess the evolution of these changes over time and throughout the profile of the soil. Additionally, we assessed the spatial heterogeneity of the alterations of different soil properties. The main alterations are expected to occur in the uppermost 2 cm of soil and in relation to the accumulation of ashes immediately after the fire.

2. Materials and methods

2.1. Study area

The experimental plot selected for this study is located in the south of the Iberian Peninsula, in an area called “Los Boquerones”, in the province of Córdoba (Fig. 1A). The study area had an altitude of 402.4 m and a mean slope of 49.7 %. The climate of the area is characterised by high temperatures and lack of precipitation during summer (Fig. 1B), with a mean annual precipitation of 621.6 mm and a mean annual temperature of 15.4 °C for the 2003–2021 period. More details regarding the climate are included in Table S1 (Supplementary material). The soils in this area exhibit predominantly siliceous substrate (slates, schists and quartzites) and shallow depths. The area is dominated by Eutric Regosols, Lithosols and Eutric Cambisols, greyish-brown or reddish-brown in colour, with a medium to coarse texture and stoniness (Andalusia Regional Government, 2011). The presence of stable vegetation in the area produces a layer of leaf litter in the top centimetres of the soil.

The vegetation is mainly dominated by pine trees (*Pinus pinea* L.) as a result of reforestation and kermes oaks (*Quercus coccifera* L.), which grow naturally. Eucalyptus trees (*Eucalyptus camaldulensis* Dehnh) are also located in watercourses or in the edges of firebreaks and woodlands. The plant composition of the experimental plot is mainly shrub, the most abundant species being *Genista hirsuta* Vahl, *Cistus ladanifer* L. and *Salvia rosmarinus* Spenn.

2.2. Controlled burn

The controlled burn was conducted by INFOCA (forest firefighting brigade in Andalusia, Spain) and the University of Córdoba Forest Fire Laboratory. It was developed on a forest plot of 1.4 ha on 25th October 2019. The main objective of the controlled burn was the evaluation of the working conditions on a firebreak line, located on a ridge, in the event of a topographic fire progressing from the lower part of the slope. Based on significative differences between the spread rate, fire-line intensity, heat per unit area, flame length and flame residence time, three different fire behaviours were established along the plot, represented in Fig. 2. These measures were collected by using thermocouples installed on the soil's surface and at 2 cm soil depth, radiometers, thermic cameras and drones [more details in Molina et al., 2021]. During the controlled burn, flame lengths of around 9 m were reached, thus making it an example of high intensity burn. This controlled burn can be considered high-intensity due to the relationship between the fireline intensity and the flame length established by Byram's empirical equation (Byram, 1959). This relationship indicates that higher flame lengths are related to to higher fire intensities, which means a more intense energy output from the fire. The maximum temperature reached on the topsoil surface ranged between 521 °C and 1032 °C. As for the residence time, the maximum value recorded was 530 s, and the minimum 47 s (University of Córdoba Forest Fire Laboratory, internal report, 2019; Table S2).

2.3. Soil sampling and laboratory analysis

Soil samples were collected at three different times; (i) the day before the burn, (ii) immediately after (2 h after the burn took place), and (iii) eight months after the controlled burn, at 12 points along three transects and along four lines running perpendicular to the central transect (Fig. 1A). Composite soil samples (1 kg) were collected at two different depths, the first from 0 to 2 cm soil depth, and the second one at a depth of 2 to 5 cm, in an area of 2.5 m^2 around each of the 12 sampling points. Therefore, the total amount of samples was 72 considering all depths (2) and sampling times (3). Before the burn, thermocouples were installed in the sampling points in order to record the temperature reached during the controlled burn in the soil surface and at a 2 cm depth. The distance between the transects was 40 m and each transect had a length of 60 m with a distance between each of the four points within each transect of 20 m.

A subsample of fresh soil was then sieved to 2 mm and used to determine soil ammonium (NH_4^+), nitrate (NO_3^-) and dissolved organic carbon (DOC) content, in addition to phospholipid fatty acids (PLFAs). Five g of fresh soil were weighed and 25 ml of 0.5 M K_2SO_4 solution [1:5 (*w:v*)] added, the mix shaken for 30 min and centrifuged to maintain the supernatant.

The remaining soil was air-dried at room temperature (≈25 °C) and passed through a 2 mm sieve and used for other analysis as follows. The

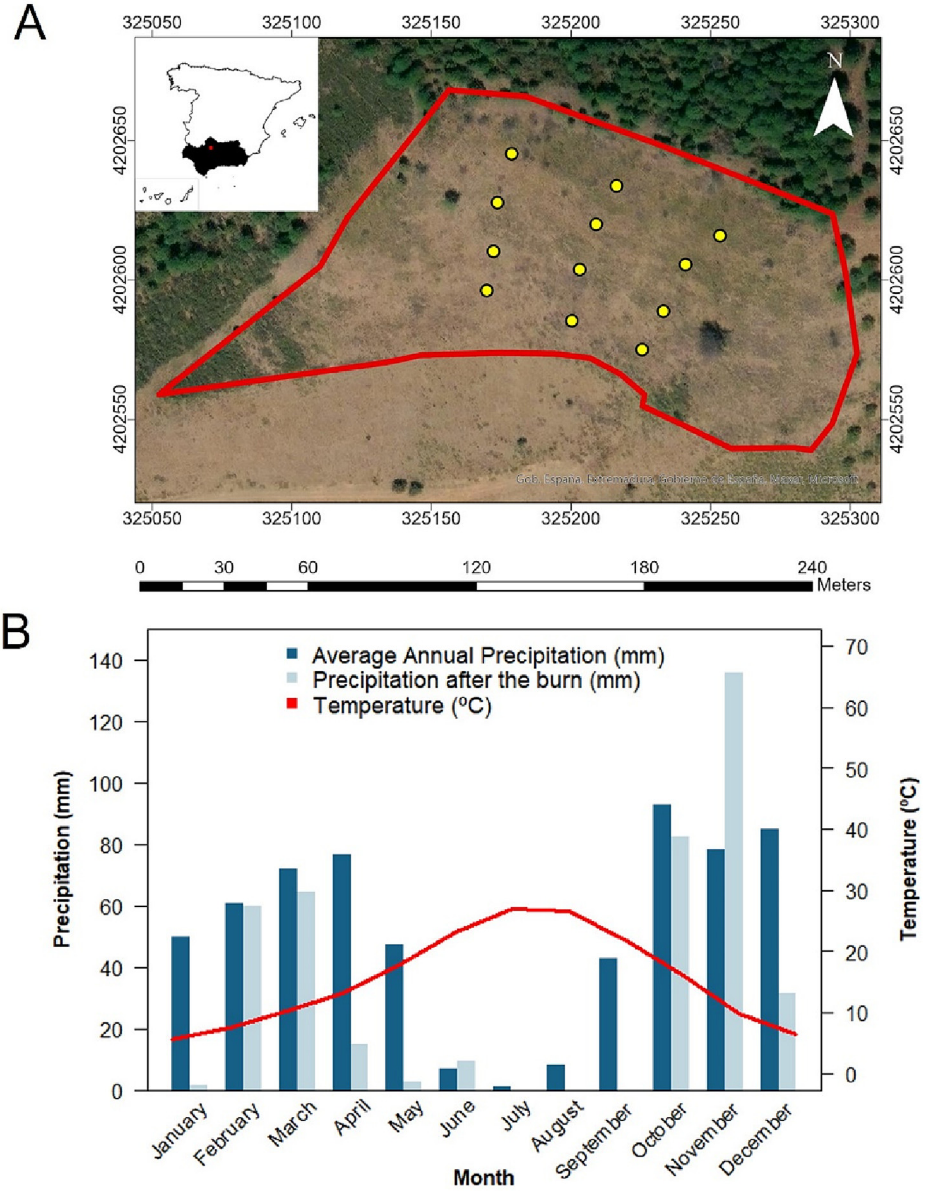


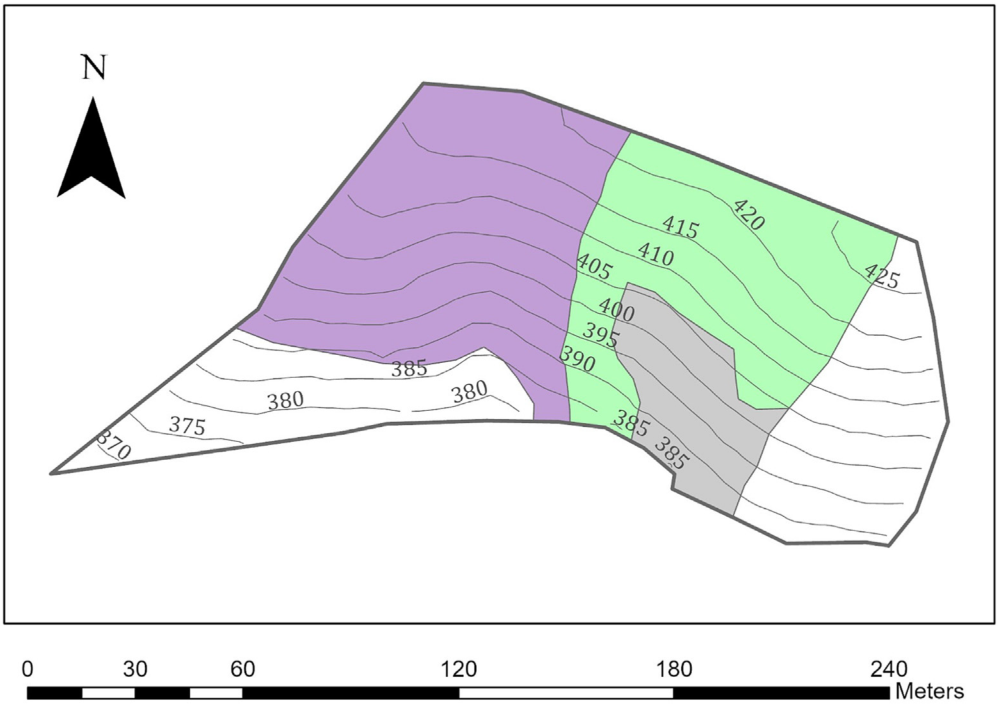
Fig. 1. A) Location of the area of study and sampling points (coloured in yellow); B) Average monthly temperatures and precipitation of the Agroclimatic Station of Espiel for the period 2003–2021 (Source: http://www.uco.es/grupos/meteo/), the closest station to the study area.

magnetic susceptibility of each sample (χ_{fd} %) and the specific mass magnetic susceptibility (χ_{lf}) were measured using the MS2 Magnetic Susceptibility Meter (Bartington Instruments, Oxon, UK). Soil colour was measured by grinding the samples to a fine powder and using the Cary 5000 UV–Vis-NIR spectrophotometer (Varian), in which a wavelength scan from the ultraviolet (380 nm) to the near infrared (750 nm) was performed. Then, soil colour was expressed according to the Munsell colour system (S. Cochrane, 2014).

Soil pH was determined potentiometrically in a 1:2.5 soil:water suspension (pH meter GLP 21, Crison Instruments SA) and electrical conductivity (EC) of the 1:5 (*w*/*v*) soil:water suspension, with a conductivity meter (micro CM 2200, Crison Instruments SA). Exchangeable cations (Ca, Mg, K, Na) and the cation exchange capacity (CEC) were determined using 1 M NH_4OAc buffered at pH 7.0. Exchangeable Ca and Mg in NH_4OAc-extract were analysed using an atomic absorption spectrometer (AANALYST 200, PerkinElmer) and K and Na using a flame photometer (PFP7, Jenway). Acid oxalate-extractable Fe (Fe_{Ox}; Schwertmann, 1964) and citrate/bicarbonate/dithionite-extractable Fe (Fe_{Di}; Mehra and Jackson, 2013) were determined in order to estimate the content in poorly crystalline Fe oxides (Fe_{ox}) or in both poorly crystalline and crystalline Fe oxides (Fe_{di}).

NH_4^+ and NO_3^- were determined colorimetrically according to Mulvaney (1996) and Miranda et al. (2001), respectively, using a PowerWave-XS microplate reader (BioTek Instruments Inc., Winooski, VT), and DOC in a Total Organic Carbon Analyzer (Total Organic Carbon Analyzer, Shimadzu). Available soil P (P_{Olsen}) was extracted according to Olsen (1954) and measured by using the Molybdate Blue method (Murphy and Riley, 1962). Labile Fe (Fe_{DTPA}), Cu (Cu_{DTPA}), Mn (Mn_{DTPA}) and Zn (Zn_{DTPA}) were extracted with X.Y M diethylenetriaminepentaacetic acid (DTPA) at 25 °C (1:2 soil/DTPA suspension; Lindsay and Norvell, 1978) and measured by atomic absorption spectrophotometry.

Phospholipid fatty acids (PLFAs) and neutral lipid fatty acids (NLFAs) were determined on 25 g soil samples according to Bartelt-Ryser et al., 2005a,Bartelt-Ryser et al., 2005b. In the case of the NLFAs, the determination was made only in 6 samples, corresponding to the points in the uppermost line (sampling points with more altitude) at both soil depths. Briefly, after sieve to pass 2 mm and dried by freeze-drying. Fifty-six different fatty acids were detected in the soil samples used for PLFAs. These fifty-six fatty



Characterization of fire parameters across the plot

Behaviour	Spread rate (m min^{-1})	Fire-line intensity (kW m^{-1})	Heat per unit area (kcal m^{-2})	Flame length (m)	Flame residence time (s)
▨	10.5	5116	6930	3.83	65.0
🟩	11.3	5495	7035	5.76	160
🟪	29.8	18185	8877	8.52	200

Fig. 2. Fire behaviour along the study plot. The white areas correspond to the surface where none of the behaviour scenarios were applied. (Source: Informe preliminar elaborado en relación con el fuego experimental realizado en la finca Los Boquerones (Córdoba) el 25 de octubre de 2019, Laboratorio de Gestión del Paisaje Forestal y Defensa contra incendios; Personal communication).

acids were classified per putative taxonomic group: (gram+ bacteria) 14:0 iso, 15:0 iso, 15:0 anteiso, 16:0 iso, 16:0 anteiso, 17:0 iso, 17:0 iso 3OH, 18:0 iso, 19:0 anteiso, 17:0 anteiso, 15:1 anteisoω9c, 15:1 isow6c and 17:1 isoω9c; (gram− bacteria) 15:1 w6c, 16:1ω7c, 16:1ω9c, 17:1ω8c, 18:1ω5c, 18:1ω7c, 18:1ω9c, 19:1 w8c,20:1 w6c, 20:1 w8c, 20:1 w9c, 21:1 w3c, 21:1 w6c, 17:0 cycloω7c and 19:0 cycloω9c; (actinomycetes) 17:0 10 methyl, 17:1ω7c 10 methyl, 18:0 10 methyl, 18:1ω7c 10 methyl, 19:1ω7c 10 methyl and 20:0 10 methyl; (saprotrophic fungi) 18:2ω6c; (biomarker for putative arbuscular mycorrhizal fungi) 16:1ω5c; (bacteria) 12:0, 14:0, 15:0, 16:0, 17:0, 20:0, 22:0 and 24:0; (eukaryote - protozoa) 15:4 w3c, 20:4 w6c, 18:3 w6c, 19:4 w6c, 20:5 w3c; (not assigned to a specific putative taxonomic group) 21:0 and 23:0 (Bartelt-Ryser et al., 2005b; Bédard and Knowles, 1989; Bossio and Scow, 1998; Bowman et al., 1991, 1993; Griffiths, 1997; Kieft et al., 1994; Kujur and Patel, 2014; Niklaus et al., 2003; Olsson et al., 1999; Ratledge, 2008; Veum et al., 2019; Zelles, 1999). Certain PLFAs ratios were also considered to assess potential alterations in soil microbial communities (protozoa/bacteria or predator/prey, fungi/bacteria, gram+/gram−, saturated/unsaturated fatty acids, mono/polyunsaturated fatty acids, and GNeg Stress, which is an indicator of hight stress based on 16ω/17 cyclo and 18ω/19 cyclo precursor/cyclopropane fatty acids (Knivett and Cullen, 1965).

2.4. Spatial monitoring of selected properties

A selection of soil properties (mainly chemical) was done, based on their significance and spatial heterogeneity, in order to study their spatial alteration both immediately and 8 months after the controlled burn (regarding the former values, before the burning). ArcGIS Desktop 10.8© was used to produce maps to assess potential alterations in pH, P_{Olsen}, Fe_{DTPA}, Fe_{ox}, CEC, DOC, NO_3^- and NH_4^+ in the uppermost 2 cm of soil (where most differences occurred), and an interpolation according to the Cokriging method (Han et al., 2003) was used, considering the behaviour of fire along the study area, the slope, and the slope aspect.

2.5. Statistical analysis

A Principal Component Analysis (PCA) was undertaken in order to study how the samples were grouped according to the sampling time and soil depth, as well as their relationship with the measured variables. In addition, those variables that met the requirements for a parametric test (normality by Shapiro's test and homogeneity of variance by Levene's test) were subjected to a factorial analysis of variance (ANOVA) to determine the effect of time (called time; before burning, immediately and 8 months after the prescribed fire) and soil depth (0–2 cm and 2–5 cm), as well as to study possible interactions between both factors. In the cases where the results of the ANOVA showed a non-significant interaction between the two factors evaluated, the Tukey's test (with 5 % significance) was applied. An additional one-way ANOVA was done to find significant differences between the three sampling times. Additionally, the response ratio was utilized as a statistical measure to quantify the relative change in the observed variables of the study. The response ratio (lnRR) was calculated as the natural logarithm of the ratio of the means of the treatment group (sampling time) and the control group(Hedges et al., 1999). A positive response ratio suggests a higher mean in the treatment group compared to the control, while a negative value indicates a lower mean. Uncertainty was quantified by calculating 95 % confidence intervals around the mean response ratio. Regression trees were then performed in order to obtain prediction models of the different putative taxonomic groups based on sampling and fire characteristics. To study how properties varied across the experimental plot, we used interpolation according to the Cokriging method (Han et al., 2003), a geostatistical method that allows to use information on several layers. This method was chosen over other deterministic methods (based only on distances), because it allows to consider other variables such as the fire behaviour, the slope, and the slope aspect in the plot. In order to demonstrate the viability of the models (Regression trees and prediction maps), the root-mean-square error (RMSE) and mean absolute error (MAE) were used. Moreover, permutational analysis of variance (PERMANOVA) on Bray-Curtis dissimilatory matrices as well as redundancy analysis (RDA) were undertaken to assess the relationship between sampling times, depths and PLFAs.

All statistical analyses were undertaken using R' software (R Core Team, 2020) and the packages: *tidyverse* (Wickham et al., 2019), *stringr* (Wickham, 2022), *devtools* (Wickham et al., 2022), *dplyr* (Wickham et al., 2023), *car* (J. Fox and Weisberg, 2019), *ggpubr* (Alboukadel Kassambara, 2023a), *rstatix* (Alboukadel Kassambara, 2023b), *vegan* (Oksanen et al., 2023), *rpart* (Therneau et al., 2017) and *ggplot2* (Wickham, 2016).

3. Results

3.1. Relationships between soil properties

The PCA (Fig. 3A) showed that the samples were well grouped according to both sampling time and soil depth, with the exception of the control samples (before the burn) in which the soils belonging to both soil depths shared similar characteristics. The 0–2 cm and 2–5 cm soil samples collected immediately after the burn and eight months later were clearly differentiated according to the first principal component (PC1), which explained the 46.3 % of the total variance. The second principal component (PC2) explained the 17.9 % of the total variance and was able to group the soil samples in relation to the factor time, with the control and immediately after the fire samples closer than the samples taken eight months after the fire. The variables used in the biplot analysis are shown in Fig. 3B. In the case of the PC1, the variables that contributed the most were DOC, P_{Olsen}, CEC, Zn_{DTPA} and soil pH in one direction, and chroma and value in the opposite direction. Additionally, PC2, Fe_{Di}, Fe_{Ox}, χ_{fd} % (SM), χ_{lf} in another direction and Fe_{DTPA} in the opposite direction. The PCA also showed that the control (both soil depths) and 2–5 cm burned samples were related to higher soil contents of NO_3^- and high chroma and value, while 0–2 cm burned samples to DOC, P_{Olsen}, CEC, hue, soil pH, Zn_{DTPA}, Mn_{DTPA}, NH_4^+ and total PLFAs (between other variables; Fig. 3B). Moreover, the fire had an instant effect as regards reducing Fe_{Di}, Fe_{Ox}, χ_{fd} and χ_{lf} at both soil depths. The samples collected eight months after the burn partially returned to similar values to the ones observed on the first sampling regarding the PC1 but behaved in the opposite way with respect to PC2 and were related to high soil Fe_{DTPA} contents (Fig. 3B). Additionally, a difference between the samples collected at the two soil depths remained.

3.2. Physical-chemical soil properties and nutrient cycling

Focusing individually on each soil property independently (Table S3; Fig. S1), the χ_{fd} % and χ_{lf} were significantly reduced ($p < 0.0001$) with the burn (from $1.09 \cdot 10^{-7} \pm 3.05 \cdot 10^{-10}$ m^3 kg^{-1} to $1.07 \cdot 10^{-7} \pm 2.09 \cdot 10^{-10}$ m^3 kg^{-1}, and from 8.53 ± 0.3 % to 6.54 ± 0.2 %, respectively) and it was maintained eight months later ($1.07 \cdot 10^{-7} \pm 6.04 \cdot 10^{-10}$ m^3 kg^{-1} and 6.18 ± 0.5 %, respectively). However, these two soil physical indicators were unaffected by soil depth ($p = 0.7793$ and $p = 0.6629$, respectively). Initial soil colour (not included in tables or figures) was uniform both on the soil surface (0–2 cm) and at a greater depth (2–5 cm). These values significantly varied only in the first cm of the soil (0–2 cm) immediately after burning ($p < 0.05$), from 7.97 YR 5.84/3.62 to 8.27 YR 5.37/2.90 and to 8.21 YR 5.48/3.10, immediately and eight months after the controlled burn, respectively (Y indicates yellow and R, red).

Soil pH (Fig. 4A and Table S3) was significantly affected by the interaction sampling time and soil depth ($p < 0.0001$). This chemical indicator increased immediately after burning (from 6.4 ± 0.1 to 7.4 ± 0.1), reaching its higher mean value at this point. Eight months later, the pH dropped and

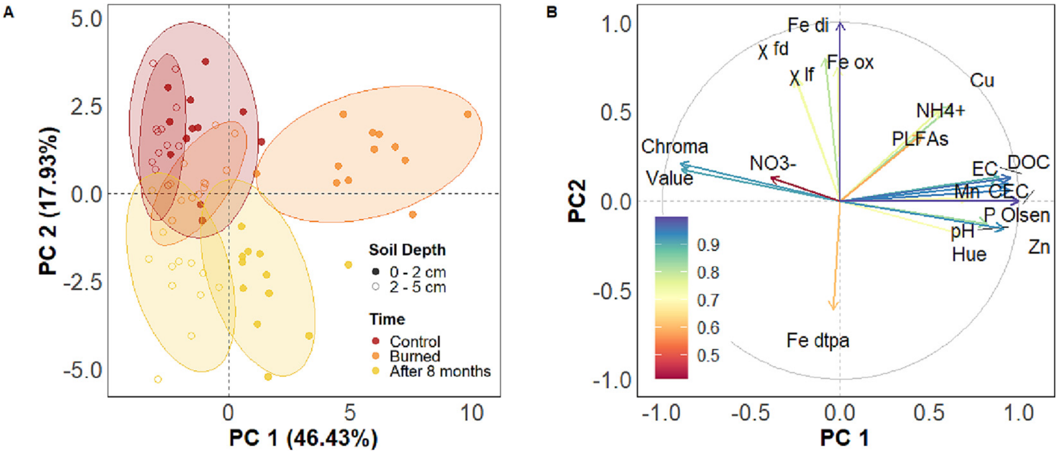


Fig. 3. Principal Component Analysis (PCA) performed on the soil samples ($n = 72$) as a function of the time and soil depth (A) and the variables used for that (B). The ellipses represent the 95 % confidence interval for the combination of each treatment and soil depth. The colour of the samples and ellipses indicates the different sampling times: Red-Control samples (before the burn), Orange-Burned (2 h after the burn), and Yellow-8 months after the burn. Filled points are used for soil samples collected at 0–2 cm depth and empty points for soils collected at 2–5 cm depth. The colour used for the variables indicate how they are represented in the PCA from red (worst) to blue (best).

reached intermediate values between the former and immediately after the burn (7.1 ± 0.1, significantly higher than before the burn). This was similar at both soil layers assessed (Fig. 4A). Likewise, a similar pattern to that which has been mentioned for soil pH occurred in $EC_{1:5}$, CEC, P_{Olsen} and NH_4^+ (Figs. 4B, C and D), being significant the interaction between sampling time and soil depth in all of them (Table S3). It should be highlighted

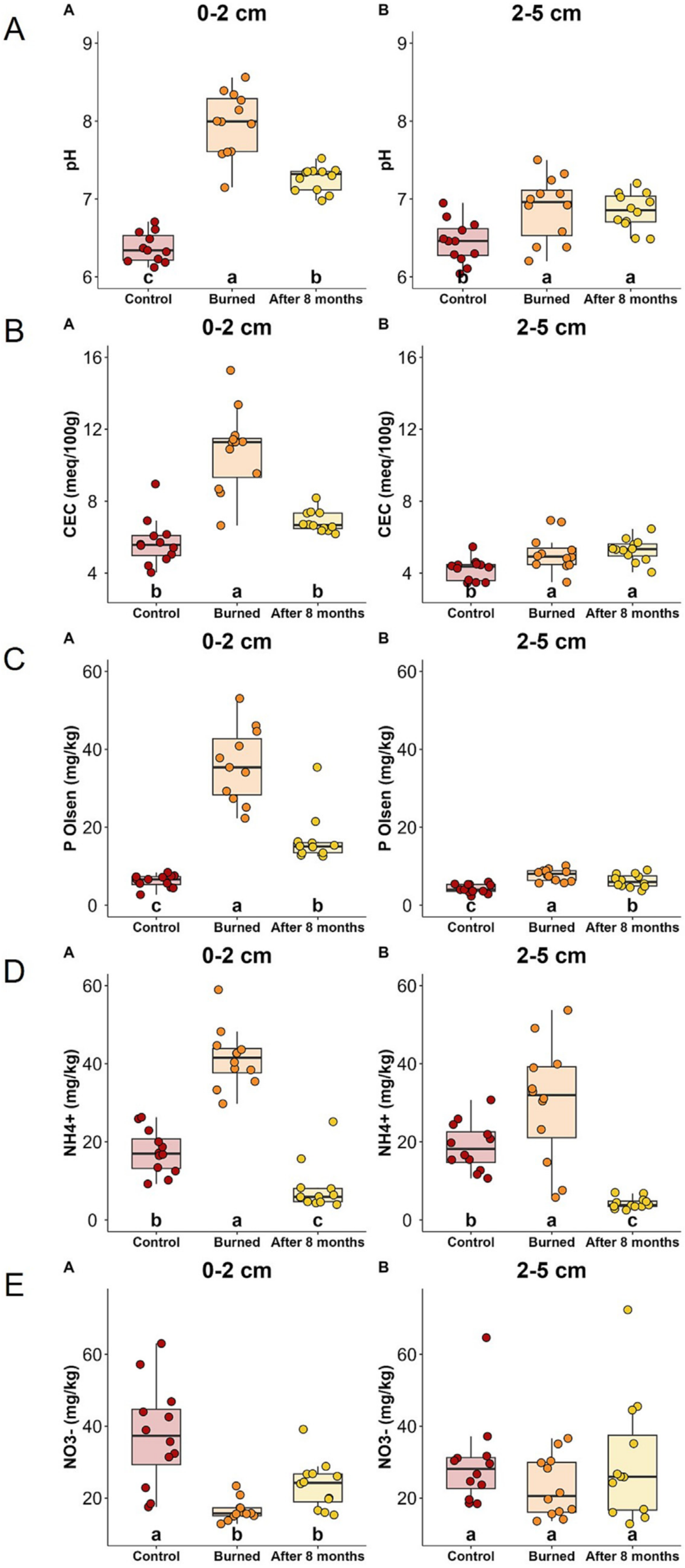


Fig. 4. Soil pH (A;soil:water, 1:2.5), cation exchange capacity (B; CEC), P_{Olsen} (C), NH_4^+ (D) and NO_3^- (E) as a function of time [control (before burning), burned (immediately after burning) and 8 months after burning; $n = 12$] for the different soil depths. Different letters indicate significant differences between sampling time according to the Tukey's HSD test.

the considerable increase observed in P_{Olsen} (mg kg^{-1}) from 5 ± 0.4 to 23 ± 4, immediately after the burn, which was still significantly higher 8 months later (12 ± 1; Table S3). Additionally, the decrease observed eight months after the burn for NH_4^+ (from 36 ± 3 mg kg^{-1}, immediately after the burn, to 18 ± 1 mg kg^{-1}) produced lower values than those obtained previously at both soil depths (6 ± 1 mg kg^{-1}, mean values; Fig. 4D). DOC also followed a similar pattern as soil pH (Fig. S2A; Table S3). However, this was not the case for soil NO_3^- (Fig. 4E), which although reduced after the burn (from 34 ± 3 mg kg^{-1} to 20 ± 1 mg kg^{-1}), was increased 8 months later (27 ± 3 mg kg^{-1}, especially at 0–2 cm; Fig. 4E).

Fe_{ox} and Fe_{di} (g kg^{-1}, Table S3) were significantly reduced over time ($p < 0.05$; from 1.52 ± 0.06 to 1.29 ± 0.10 and finally, 0.92 ± 0.03 in the case of Fe_{ox}) but unaffected at different soil depths ($p > 0.05$). With the exception of Fe_{DTPA}, which demonstrated a great increase in soil after 8 months of the burn (> 115 % of the initial content), soil micronutrients' availability (Mn_{DTPA}, Zn_{DTPA}, Cu_{DTPA}) peaked after the burn in the first 2 cm of soil. However, the availability of micronutrients was reduced eight months later (reaching lower values than at the beginning of the experiment for Cu_{DTPA} and between those which were measured at the beginning and immediately after the burn for Mn_{DTPA} and Zn_{DTPA}; Fig. S2B). Cu_{DTPA}, Mn_{DTPA} and Zn_{DTPA} at 2–5 cm followed a similar pattern as that which has been explained for 0–2 cm (Fig. S2C, D and E).

3.3. Microbial communities and structure

The total PLFA were significantly reduced as regards time and soil sampling, reaching the lowest values 8 months after the controlled burn for both factors (factorial ANOVA in Table S3, and Fig. 5A). According to the PERMANOVA (Table S4), the fatty acids type (%), the ratios of PLFA and total PLFA were significantly affected by both time and soil depth in all cases ($p < 0.05$), while the interaction between the two assessed factors was significant for the putative taxonomic groups and total NFLA ($p < 0.05$) only. However, the model explained a reduced percentage of the variability (small R^2 values in all cases, ranging from 0.066 obtained for PLFAs ratios to 0.119 for fatty acids type in the case of the variable sampling time, and from 0.301 for total PLFAs to 0.454 for taxonomic groups in the case of soil depth).

The RDA for the different putative taxonomic groups (Fig. 5B) show that most of the 0–2 cm soil samples were grouped in the left of the ordination plot, whereas the 2–5 cm soil samples were on the right; RDA 1 explained 45.36 % of the total variance. Additionally, the burned soil samples at 0–2 cm were more related to a high content in fungi, immediately after the burn, but they were related to high contents in AM fungi, gram negative bacteria and eukaryote (protozoa) eight months after the burn (Fig. 5B). In comparison with soil samples before the burn, RDA 2 explained <5 % of the total variance. The effect of the fire on the 2–5 cm soil samples did not have

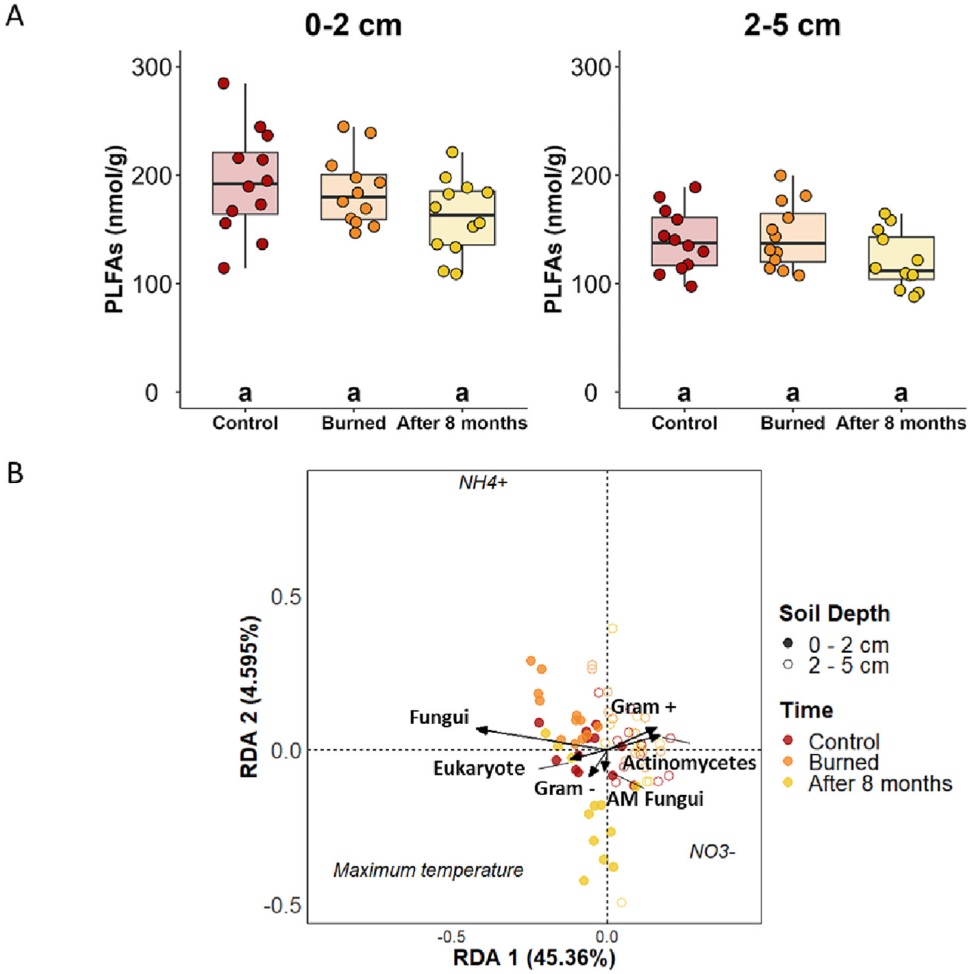


Fig. 5. A) Phospholipid fatty acids as biomarkers of different taxonomic groups as a function of sampling time and soil depth [control (before the burn), burned (2 h after the burn) and 8 months after the burn; $n = 12$ for each combination sampling time × soil depth]. Different letters indicate significant differences between sampling time according to the Tukey's HSD test (A). B) Redundancy Analysis (RDA) of the different putative taxonomic groups; Distribution of the 72 soil samples used along the two RDA axes, variables (arrow showing putative taxonomic groups) used in the RDA and main correlated soil properties (NH_4^+, NO_3^- and maximum soil temperature reached during the burn). The colour of the samples indicates the different sampling times [Red-Control samples (before the burn), Orange-Burned (2 h after the burn), and Yellow-8 months after the burn]. Filled points are used for soil samples collected at 0–2 cm depth and empty points for soils collected at 2–5 cm depth.

a clear effect on putative taxonomic groups. Regarding the relationships between the different putative taxonomic groups of microorganisms and the environmental factors, fungi were related to higher soil contents in NH_4^+, and inversely related to NO_3^- content, while eukaryote (protozoa), gram negative bacteria and AM fungi were mostly affected by the maximum temperature and NO_3^- content in soil. On the other hand, gram positive bacteria and actinomycetes behaved in the opposite direction to AM fungi, gram negative bacteria and eukaryote. Similar conclusions were reached by using regression trees, which are shown in Fig. S3.

3.4. Spatial variation of the main soil properties – Prediction maps

The viability of each prediction map has been tested by using RMSE and MAE, the values of which are shown in Table S5. The magnitude of the differences in soil pH had an inverse relationship with fire behaviour (Fig. 2), with greater variation occurring in the south-eastern corner of the study area (Fig. 6A), matching with the area where the fire had lower spread rate, fire-line intensity, heat per unit area, flame length and flame residence time values. The western part of the area showed smaller differences in both comparisons, corresponding with the areas where the fire was more intense.

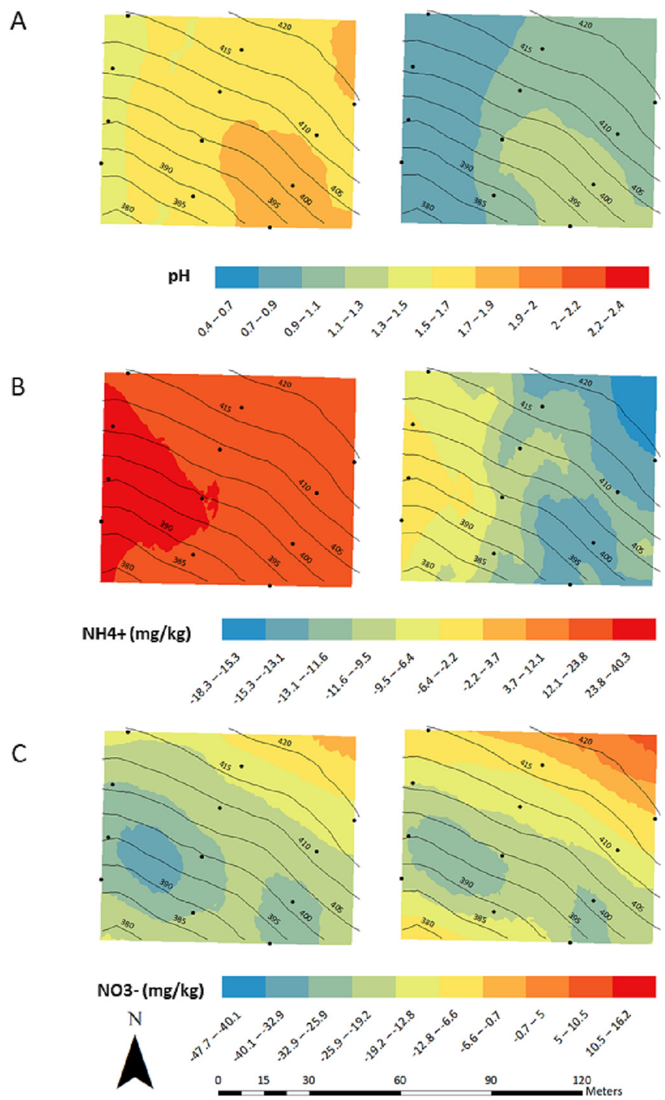


Fig. 6. Prediction map for the difference of pH (A; soil:water, 1:2.5),), NH_4^+ (B; mg kg^{-1}) and NO_3^- (C; mg kg^{-1}) in the uppermost two cm of soil. (Left) Differences between control and burned samples; (Right) Differences between control and after eight months samples.

Ammonium was homogeneously increased along the plot immediately after the fire, with smaller changes identified on the north-eastern corner (Fig. 6B). On the other hand, the behaviour was the opposite, with a more heterogeneous decrease in terms of the difference between the former values and the contents after 8 months of soil recovery. In this case, the biggest differences occurred in the north-eastern corner of the plot and the smallest in the areas where the fire was more severe. The behaviour of soil NO_3^- (Fig. 6C) content was similar when comparing control samples with both, immediately after and eight months after the fire; the bigger decreases were observed in the southern part of the study area. The alterations followed a pattern similar to that of the level curves, showing a relationship between altitude and the alterations.

Poorly-crystalline Fe oxides (Fe_{ox},Fig. 7A) variations demonstrated greater values when comparing control samples with those collected immediately after the burn than when comparing control samples with those collected 8 months after the burn. The areas with more significant differences were those in which the area was affected by the most severe fire behaviour, and the alterations in the other two scenarios were more homogeneous. The spatial behaviour of the variations in the content of total Fe (Fe_{di}, Fig. 7B) was very similar to that of the Fe_{ox}, where in the case of the comparison between control samples and samples taken immediately after the burn, the variation was more heterogeneous, with smaller differences in those areas where the burn was less severe. When comparing control samples and samples collected after 8 months, the variation was homogeneous, and a significant decrease was observed. The spatial behaviour of labile Fe (Fe_{DTPA},Fig. 7C) was more homogeneous for the difference between the control values and those from immediately after the burn than for the difference between former values and the contents after 8 months of soil recovery. When comparing control and immediately after the burn values, a significant increase can be observed in the areas corresponding to those in which the fire behaved less severely, while in the areas where the fire was more intense the decrease was of a lower magnitude. On the other hand, the areas where the fire was more severe were those in which the increase was greater with respect to the control sampling.

4. Discussion

The variability in topographic and vegetation conditions caused the fire to have different behaviours along the study plot, significantly impacting the properties in the uppermost 2 cm of soil. The fact that the alterations occurred only in the first layers of the soil is related to its low thermal conductivity (Abakumov et al., 2020b; Enninful and Torvi, 2008), reaching higher temperatures only in these layers as opposed to in deeper ones. The significant thermal increase that occurs during a fire event, in this case a high intensity-controlled burn, gives rise to different processes related to the alteration of different soil properties, i.e., the volatilisation of some elements, accumulation of ashes, mineralisation and the subsequent washing of the soil and ashes (Badía et al., 2014; Caon et al., 2014; Giorgis et al., 2021). These processes take place both simultaneously during and immediately after burning, and more progressively with the passage of time after the fire. This explains the tendency of some elements such as P, which, despite losing a certain amount through volatilisation, an increase in the amount of P in the soil is observed after burning due to the accumulation of ashes and mineralisation.

The prediction maps (Figs. 6 and 7) showed that there was a direct relationship between the alterations observed in soil pH, NH_4^+, and the different forms of Fe measured (labile Fe or Fe_{DTPA}, poorly crystalline Fe oxides or Fe_{ox} and total Fe in soil or Fe_{di}) and fire behaviour (Fig. 2; spread rate, fire-line intensity, heat per unit area, etc.). The greatest alterations in soil pH (increase) and labile Fe (decrease) were observed in the areas in which the intensity of the burn was less severe. Conversely, poorly crystalline Fe oxides and total Fe in soil exhibited less differentiation in areas where fire intensity was lower. Thus, the response of these soil indicators to the different intensity of the burn measured demonstrates the intricate relationship between fire intensity and geochemical changes in the soil.

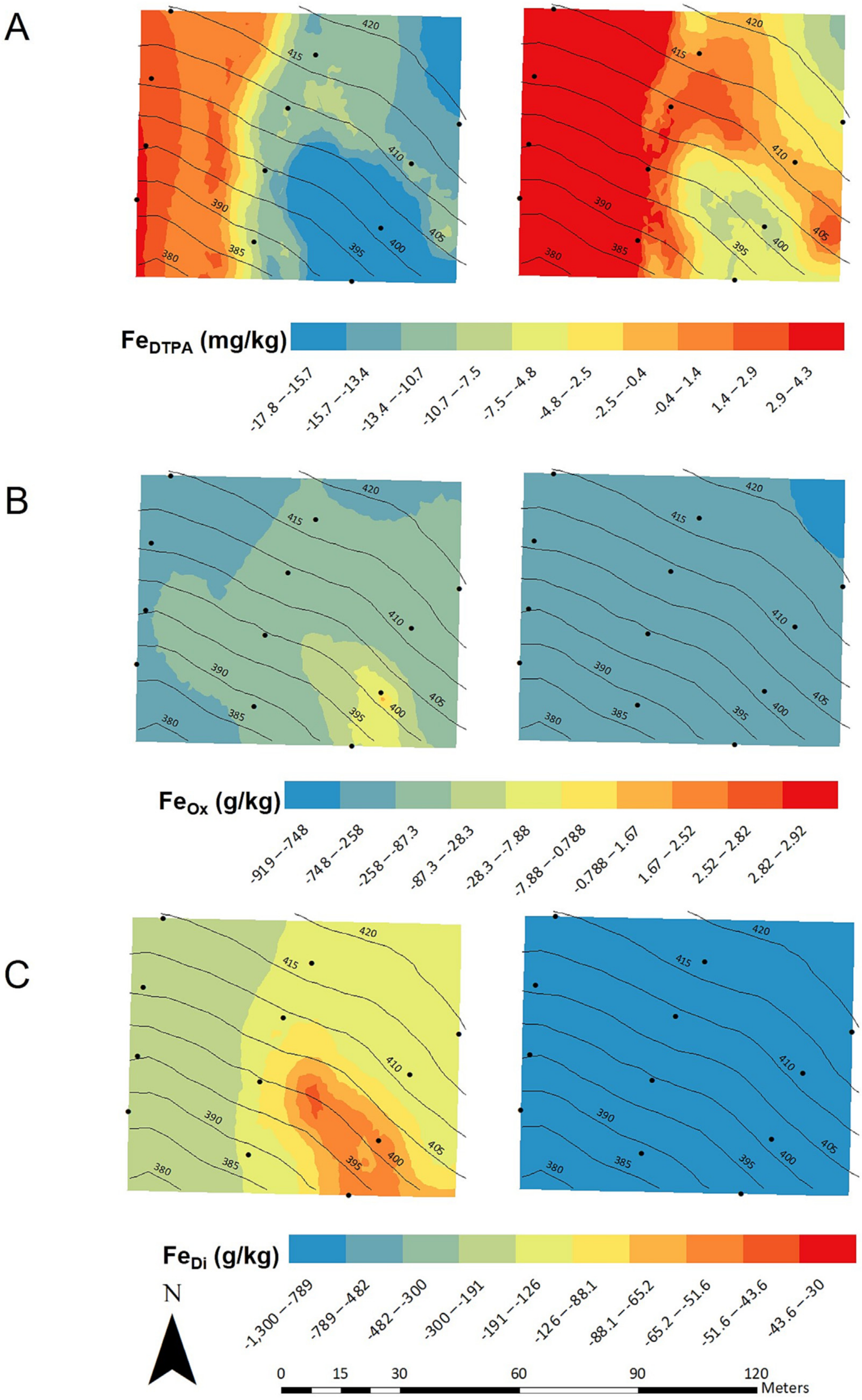


Fig. 7. Prediction map for the difference of Fe_{DTPA} (A; mg kg^{-1}), Fe_{ox} (B; g kg^{-1}) and Fe_{di} (C; g kg^{-1}) in the uppermost two cm of soil. (Left) Differences between control and burned samples; (Right) Differences between control and after eight months samples.

Fire behaviour should had been influenced by other factors such as: the residence time of the flame, related to the possible partial or total combustion of organic matter and vegetation; and the maximum temperature reached, which determines the occurrence of different processes in the soil related to alterations in the physical, chemical and biological properties of the soil; the effect of slope, which affects both fire behaviour and post-fire ash runoff and entrainment; the effect of precipitation that occurred just after the burn (around 140 mm in November, higher than the mean value, 80 mm) could have washed and/or entrained ash and the corresponding ash nutrients, especially in combination with the high slope of certain areas of the experimental field (mean slope around 50 %).

The alteration in soil carbon and organic matter in the top layer depends on the fire severity, volatilisation of organic matter and oxidation processes. Incomplete consumption of vegetation can bring organic matter to the soil in the form of semi-pyrolyzed ash (Doerr et al., 2018), which protect organic matter from bio-decomposition processes (Johnson & Curtis, 2001). As the soil temperature increases, organic matter decomposes. This includes nutrient mineralisation and the death of soil microorganisms that have immobilised nutrients, for example, N inside (Yevdokimov & Blagodatsky, 1994) and inorganic forms of N, i.e., NH_4^+ and NO_3^- are released, increasing nutrient availability in the short term. However, part of the total N and other nutrients will be lost by way of volatilisation (of NH_4^+), with this process being proportional to the temperature (the higher the temperature, the more N and other nutrients will be lost). After the fire, mineralisation could increase, as solar radiation is easily absorbed due to the decrease in the albedo caused by the darkening of soil as a consequence of fire and the accumulation of charred plant debris and ash (Dadi et al., 2013; Ulery and Graham, 1993). Soil microorganisms 'work better' at higher temperatures and the NO_3^- in the soil will increase (mineralisation) while a decrease in NH_4^+ is expected (DeLuca et al., 2002), as observed in our results.

The combustion of both the vegetation and organic matter during the burn led to the accumulation of ash on soil's surface, which plays a fundamental role in the alteration of some soil properties such as soil pH (Arocena and Opio, 2003; Giorgis et al., 2021), electrical conductivity (Alcañiz et al., 2016; Certini, 2005), dissolved organic carbon (Revchuk and Suffet, 2014), cation exchange capacity (Úbeda et al., 2005), available P (Badía et al., 2014; Caon et al., 2014; Romany, 1993), and micronutrients availability (Parra et al., 1996). In general, the pattern observed for these soil properties was similar, increasing immediately after the fire, linked to the deposition of ashes, and decreasing after some time due to events of precipitation, which cause a surface overflow that trawls the ash away (or to deeper soil layers with infiltration), among other reasons (Hung et al., 2005; Notario del Pino et al., 2008; Úbeda et al., 2005; Vila-Escalé et al., 2007). In the case of this study, the burn took place in October, and during the month of November the precipitation was higher than in other months. This could perhaps be one of the main influencing factors for the decrease observed in some of these properties eight months after the burn.

It could be of interest to contextualize our findings with those of Allen et al. (2011) and Arunrat et al. (2023), both of which shed light on different facets of fire's impacts on soil properties. Allen et al. (2011), who assessed the effect of fire and invasive species on desert soil, demonstrated that both fire and invasive species can induce alterations in biological, chemical, and physical soil properties. Our study is in line with their findings, in which high intensity fire leads to substantial changes (soil pH, Fe forms in soil), especially under conditions of high temperature, substantial fuel buildup, and soil moisture that enables heat to penetrate deeper into the soil. Contrastingly, Arunrat et al. (2023) observed a negligible impact of fire on soil organic carbon, soil total nitrogen, and other soil properties in the context of rotational shifting cultivation in Northern Thailand. Instead, the duration of the fallow period emerged as a more significant factor for alterations in soil properties (organic carbon, total nitrogen and even clay). The discrepancy between our findings and those shown in Arunrat et al. (2023) could be due to differences in ecological settings and fire conditions. Meanwhile, our study highlights the effect of a single high intensity burn event without the benefit of lengthy fallow periods, underscoring the potential long-term consequences of such an event on soil properties as shown by Allen et al. (2011) and Arunrat et al. (2023). Further research may help elucidate the range and variability of fire's impacts on soil across diverse ecosystems and conditions.

The content in soil available nutrients after a fire usually increases due to the accumulation of ash enriched and the release of basic cations from the soil organic matter (Badía et al., 2014; Caon et al., 2014; Romany, 1993). However, this effect normally persists only in the short or medium term, as with the washing of ash (water, wind and even the effect of gravity), the availability of P and other nutrients will be drastically reduced (Ferreira et al., 2016; Pereira et al., 2012), and may reach lower values than those initially recorded. Consequently, it would have a negative impact on soil fertility (in the short or medium term depending on precipitation events, location of the area that has suffered the burn or fire, etc.). Furthermore, the conditions reached during the burn affected soil P, favouring its mineralisation from soil organic matter and even the release from the vegetation, releasing inorganic phosphorus into the soil solution. Then, this P can be absorbed by plants, microorganisms and be adsorbed on the surface of Al, Fe and Mn oxides and hydroxides (in acid soils), or the formation of calcium phosphates (in alkaline or neutral soils) (Badía et al., 2014; Ferreira et al., 2016), decreasing its availability in the soil and depleting reserves. Phosphorus plays a significant role in soil fertility, being one of the most limiting macronutrients for the regeneration of vegetation, and fire can cause the transformation of organic P into inorganic P, which is labile and bioavailable. It means that the controlled burn had a positive effect on the fertility of soil regarding P availability (Elser et al., 2007; Schaller et al., 2015) and will contribute to the regeneration of the burned area, at least in the first eight months under similar conditions to those of this study. A similar study to ours, except for the intensity of the burn, conducted by Akburak et al. (2018) aimed to understand the impacts of low-intensity prescribed fire on the chemical (and biological) properties of the topsoil. In that study, soil pH increased slightly in the burned plots and had a significantly positive correlation with the availability or certain nutrients. Although this in line with our results, the higher intensity of the burn in our study would explain that increases of up to 2 units in soil pH were reached after the burn (immediately and 8 months later) and could partially explain the higher availability of P and micronutrients measured in our study.

As regards the magnetic properties of soil, the variation in the magnetic susceptibility measured at low frequency (χ_{lf}) does not correspond to that which has been observed in previous studies. Jordanova et al. (2019b) identified an increase in the magnetic susceptibility measured at low frequency (χ_{lf}) in the first centimetres of the soil after natural forest fires in Bulgaria. There is a relationship between magnetic susceptibility and soil organic carbon, meaning the magnetic susceptibility of a soil can be considered as an estimator of soil organic carbon Jordanova et al. (2019a). Therefore, the higher the magnetic susceptibility, the higher the organic carbon content is expected in the soil. This relationship can be explained based on the behaviour of organic matter when combustion occurs, as when organic carbon undergoes this process, it is converted into its more pyrogenic form, which has a reducing character with great importance in the process of transformation of soil Fe oxides to more magnetic forms (magnetite, maghemite, pyrrhotite or magnetic pyrite) (Bautista et al., 2014; Jordanova et al., 2019b). Therefore, we could hypothesise that the unexpected results regarding magnetic properties of our soil after the burn could be due to a low organic carbon content in this soil, which is typical of Mediterranean areas.

The increase in soil pH after fire is related to the dispersion and promotion of small particles (Nørnberg et al., 2004). It explains the results obtained by Norouzi and Ramezanpour (2013) in which both forms of Fe oxides, amorphous iron oxides (Feox) and total iron oxides (Fedi), were increased slightly after fire. The opposite was observed in our study for both Fe forms. The content of amorphous iron oxides (Feox) is related to the solubility and availability of Fe in the soil (Campillo and Torrent, 1992) and a decrease in its content, as observed in our results, is expected because they could be transformed to more crystalline Fe oxides at high temperatures (Terefe et al., 2008) during the high intensity burn.Microbial communities and structure.

Biological properties of soils are related directly and indirectly to the effect of controlled burns and/or fires by means of the different processes that occur after them, such as combustion of the soil organic matter, the accumulation of ash and the changes of physic-chemical properties of soils, in addition to climatic events such as temperature or precipitation that influence soil moisture (Longo et al., 2014). According to the results of this study, soil microbial communities were also affected by different soil properties, such as soil pH and nutrient availability (Hart et al., 2005). The main putative taxonomic groups, in addition to the different fatty acid types, were related to soil inorganic N forms (NO_3^- and NH_4^+) and to the maximum temperature reached on soil's surface. Similar results were found in Cobo-Díaz et al. (2015), where a significant relationship was found between the alteration of bacterial communities and the N cycle. This indicates the dependency on these variables between themselves and their potential influence in nutrient cycling.

In this study, it was clear that the soil microbial community was affected by the fire and that this community differed from the former one eight months after the fire. We could say that the structure of the topsoil microbial community at 0–2 cm was different to the initial structure, especially 8 months after the burn. Nevertheless, the differences were minimum between 2 and 5 cm soil depth (Fig. 5) probably due to a reduced impact with depth of the high temperature. The development of this soil microbial community, and consequently, the ecosystem services that will be provided by the forest system, will depend on precipitation events, the postfire management and the vegetation that will cover the soil.

Partially in line with Chanda (2020) and Köster et al. (2021), we found that the monitored taxonomic groups in the first layer of soil varied depending on the sampling time due to their different sensitivity to the effect of fire and heating, and organic matter content in soil. Bacteria and actinomycetes have a high resistance to the effects of controlled burns due to their adapting capacity to the burned environment, with the actinomycetes being the most resistant group (Chanda, 2020). As regards eukaryotes, their advantage resides in their recovery time after a fire event, which is shorter than in the case of the other putative taxonomic groups (Certini et al., 2021), so, they were also related to the burned samples (immediately after the burn). Akburak et al. (2018) aimed to understand the impacts of low-intensity prescribed fire on chemical and biological properties of the topsoil and they observed that microbial activity was affected even one year after the burn. Whitman et al. (2019) investigated the response of soil bacterial and fungal communities to wildfires in the Canadian boreal forest across a burn severity gradient, which was related to the alterations produced in the bacterial and fungal communities and the effect was persistent for two years. These findings, including ours after 8 months of the burn, suggest that wildfires have significant medium-lasting effects on soil microbial communities, with potential implications for ecosystem resilience and recovery.

4.1. Forest ecosystems management

This study demonstrated that the use of controlled burns has effects on soil properties, which can be useful from a forest ecosystem management perspective. The persistent rise in pH could help in terms of the management of species such as *Cistus ladanifer*, which needs to be controlled due to their invasive and allelopathic tendencies (Du Plessis et al., 2018), and which does not tolerate basic soil conditions (Núñez-Olivera et al., 1995). Additionally, it has also been shown that the accumulation of ash after the burn leads to a rise in fertility in the short-term, which, in combination with the control of certain undesirable species, can benefit the fast recovery of the vegetation cover (Úbeda et al., 2005). In addition, the controlled burn benefits the growth of pasturelands and tender buds, increasing its livestock and hunting potential.

The use of controlled burning has both positive and negative aspects in terms of soil condition. Some of the negative effects include increased susceptibility to erosion, runoff, and consequent soil loss (Fonseca et al., 2017), which have not been addressed in this study. However, considering the results of this research, the low costs and the possible effects of controlled burns, their use and application for the management of forest ecosystems can be of great interest for certain areas.

5. Conclusions

The use of controlled burning for different purposes (manage forest ecosystems, control specific plant species, training firefighter teams) has implications on soil conditions in both the short and medium term. In this study, physical, chemical, and biological properties of the 0–2 cm and 2–5 cm were directly influenced by the burn, both immediately after the fire and also 8 months later. The burn increased the differences in soil properties and microbial community structure between the two assessed soil depths. All these changes conditioned soil health and had implications on the functionality of the soil and its capacity to provide ecosystem services. For this reason, the effects in the soil described in this study related to a high intensity and prescribed burn should be considered when planning the use of fire as a means by which to manage forest ecosystems. The postfire management and regeneration of the affected area will be a function of the positive and negative impacts of the burn. Further research in the long-term and under different soil and meteorological conditions is required to fully understand the effects of these burns on physical, chemical, and biological properties of soil and to consider this information for a holistic management of fire and forest ecosystems.

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CRediT authorship contribution statement

Elisa Vega-Martínez: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Visualization. **Juan Ramón Molina:** Methodology, Writing – review & editing, Funding acquisition. **Vidal Barrón:** Formal analysis, Writing – review & editing, Supervision. **Francisco Rodríguez y Silva:** Methodology, Supervision, Funding acquisition. **María del Carmen del Campillo:** Formal analysis, Writing – review & editing, Supervision. **Antonio Rafael Sánchez-Rodríguez:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – review & editing, Supervision, Visualization.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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