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EFFECT OF PRE-FIRE LAND USE ON RECOVERY OF SOIL CHEMICAL PROPERTIES AFTER A PRESCRIBED FIRE. A SHORT-, MEDIUM- AND LONG-TERM CASE STUDY IN THE NE IBERIAN PENINSULA

MARCOS FRANCOS [1]*, SEBASTIÁN ALFARO [2], LUÍS OUTEIRO [3, 4], XAVIER ÚBEDA [2]

[1] *Department of Geography, Faculty of Geography and History, University of Salamanca, Cervantes s/n, 37002 Salamanca, Spain.*

[2] *GRAM (Grup de Recerca Ambiental Mediterrània), Department of Geography, Faculty of Geography and History, University of Barcelona, Montalegre, 6. 08001, Barcelona, Spain.*

[3] *Centro FONDAP de Investigación Dinámica de Ecosistemas Marinos de Altas Latitudes (IDEAL), Universidad Austral de Chile, 5090000 Valdivia, Chile.*

[4] *Instituto de Ciencias Marinas y Limnológicas, Facultad de Ciencias, Universidad Austral de Chile, 5090000 Valdivia, Chile.*

ABSTRACT. Rural land abandonment means that some rural areas fall into disuse or are taken over by forest stands. In this context, prescribed burning is a widely used forest management tool, but few studies have analyzed the influence of pre-burn land use on post-burn soil recovery. This study seeks to determine the impact of prescribed burning on soil chemical properties and to examine any differences in these parameters based on prior land use. The study is conducted in two plots – one, a forest plot (TV2); the other an abandoned agricultural terrace (TV3) – located in Tivissa (southern Catalonia), both dominated by *Pinus halepensis Mill*. and *Quercus ilex L*., and situated on Lithic Calcixerept soils. The plots, located 3 km apart, share a similar topography, exposure, and vegetation structure. Low-intensity prescribed burns were conducted in 2001, and soil samples (0–5 cm depth) were collected in five campaigns: just before the fire (BPF), immediately after the fire (APF), and at 1-, 3-, and 13-years post-burn (1YAPF, 3YAPF, and 13YAPF, respectively). In each sampling period, 30 samples were collected from an experimental plot of 72 m^2 (4 x 18 m). The soil properties analyzed included total carbon (TC), total nitrogen (TN), pH, electrical conductivity (EC), and extractable calcium (Ca), magnesium (Mg), potassium (K), and available phosphorus (P) concentrations. In TV2 soil, TC and TN increase at short and medium term, soil pH increases after fire and decreases gradually, EC decreases at short and medium term, and increases at long-term, and extractable major cations increase until medium term and are reduced at long-term. In TV3 soil TC decreases and TN increases gradually over time, pH increases at short and decreases at long-term, EC decreases from short to long-term with a slight increase at medium-term, and extractable major cations (except P which decrease over time) increase until long-term. Changes caused by different pre-fire land use and consequently differences caused by different vegetation cover minor over time. Despite differences in soil properties in the short and medium term due to land use prior to prescribed fire, after 13 years, soil conditions had largely stabilized, and there was no evidence of horizontal or vertical continuity in plant fuel. These findings suggest that prescribed burning does not result in long-term soil degradation and, thus, remains a viable tool for sustainable forest management under different land uses.

Efecto del uso del suelo previo al fuego en la recuperación de las propiedades químicas del suelo tras una quema prescrita. Estudio de caso a corto, medio y largo plazo en el noreste de la Península Ibérica

RESUMEN. El abandono de las áreas rurales implica que algunas zonas caen en desuso o son ocupadas por la masa forestal. En este contexto, las quemas prescritas son una herramienta de gestión forestal muy utilizada, pero pocos estudios han analizado la influencia del uso del suelo antes de la quema en la recuperación del suelo después de la quema. El presente estudio tiene como objetivo determinar el impacto de la quema prescrita en las propiedades químicas del suelo y examinar las diferencias en estos parámetros en función del uso anterior del suelo. El estudio se lleva a cabo en dos parcelas, una forestal (TV2) y otra agrícola abandonada (TV3), situadas en Tivissa (sur de Cataluña), ambas dominadas por *Pinus halepensis* Mill. y *Quercus ilex* L. y situadas en suelos de tipo calcixerept lítico. Las parcelas, situadas a 3 km de distancia, tienen una topografía, exposición y estructura vegetal similares. En 2001 se realizaron quemas prescritas de baja intensidad y se recogieron muestras de suelo (0-5 cm de profundidad) en cinco campañas: justo antes del fuego (BPF), inmediatamente después del fuego (APF) y 1, 3 y 13 años después del fuego (1YAPF, 3YAPF y 13YAPF, respectivamente). En cada periodo de muestreo, se recogieron 30 muestras de una parcela experimental de 72 m² (4 x 18 m). Las propiedades del suelo analizadas incluyeron el carbono total (CT), el nitrógeno total (NT), el pH, la conductividad eléctrica (CE) y las concentraciones extraíbles de calcio (Ca), magnesio (Mg), potasio (K) y el fósforo (P) disponible. En el suelo de la zona TV2, el TC y el TN aumentan a corto y medio plazo, el pH del suelo aumenta después del fuego y disminuye gradualmente, la EC disminuye a corto y medio plazo y aumenta a largo plazo, y los cationes principales extraíbles aumentan hasta el medio plazo y se reducen a largo plazo. En el suelo de TV3, el TC disminuye y el TN aumenta gradualmente con el tiempo, el pH aumenta a corto plazo y disminuye a largo plazo, la EC disminuye de corto a largo plazo con un ligero aumento a medio plazo y los cationes extraíbles (excepto el P, que disminuye con el tiempo) aumentan hasta el largo plazo. Los cambios causados por los diferentes usos del suelo antes de la quema prescrita y, en consecuencia, las diferencias causadas por la diferente cobertura vegetal fueron cada vez menores con paso del tiempo. A pesar de las diferencias en las propiedades del suelo a corto y medio plazo debido al uso de suelo previo a la quema, después de 13 años, las características del suelo de ambas zonas se habían equiparado en gran medida y no había evidencia de continuidad horizontal o vertical en el combustible vegetal. Estos hallazgos sugieren que las quemas prescritas no provocan una degradación del suelo a largo plazo y, por lo tanto, siguen siendo una herramienta viable para la gestión forestal sostenible en diferentes usos de suelo.

Keywords: soil nutrients; forest management; fire ecology; soil recovery; wildfire risk.

Palabras clave: nutrientes del suelo; gestión forestal; ecología del fuego; recuperación del suelo; riesgo de incendio forestal.

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***Corresponding author:** Department of Geography, Faculty of Geography and History, University of Salamanca, C/ Cervantes s/n, 37002, Salamanca, Spain. E-mail: mfq@usal.es.

1. Introduction

Forest fires are a common phenomenon in ecosystems such as the ecological communities of the Mediterranean (Neary *et al*., 2005), where high intensity and high severity fire events cause major disturbances to the physical, chemical, and microbiological soil properties (Certini, 2005; Santín and Doerr, 2016). Indeed, these soils can take several decades to recover, and, in some instances, they may never completely recover (Francos *et al*., 2018). However, the impact of large natural forest fires should not be confused with the outcomes of the application of prescribed fire (PF) for land management. The latter has been a valuable tool for thousands of years for achieving a range of goals that include scaring away predators, creating space for cultivation, fertilizing soils, and, in general, shaping a territory (Ryan *et al*., 2013). In fact, in recent years, prescribed burning has become one of the most widely used forestry tools (Alcañiz *et al*., 2018) since it promotes sustainable land management at a reasonable cost and can be tailored to meet different goals (Francos and Úbeda, 2021).

Several studies have analyzed the impact of these low-intensity fire events on soil properties (Wienhold and Klemmedson, 1992; Choromanska and DeLuca, 2001; Úbeda *et al*., 2005; Murphy *et al*., 2006; Fonseca *et al*., 2017; Carra *et al*., 2022; Zema *et al*., 2022; Diniz *et al*., 2023; Rai *et al*., 2023), but only a few have analyzed the long-term effects of PF on soil chemical properties applying the latest techniques (Muqaddas *et al*., 2015; Alcañiz *et al*., 2016; Coates *et al*., 2018; Francos *et al*., 2019a; Úbeda *et al*., 2019). In short, while PF is an increasingly prevalent tool, its long-term effects on soil properties are far from clear.

The effects of fire on soil are highly diverse and depend on multiple factors, including soil type and texture, pre-fire conditions (e.g., moisture content), vegetation type and structure, fire intensity, post-fire weather conditions, and topography (Certini, 2005; Caon *et al*., 2014; Francos *et al*., 2019a). At the same time, the main impacts of PF on soil chemical properties include, most notably, an increase in (or a non-significant effect on) soil pH (Granged *et al*., 2011) and an increase in electrical conductivity (EC) and nutrient availability attributable to the incorporation of ash from the low, partial combustion of organic matter in the soil (Outeiro *et al*., 2008). The soil degradation attributable to PF events results from the volatilization of nutrients, while the soil's biodiversity has been identified as a key factor in mitigating this impact and promoting recovery (Gómez-González *et al*., 2018). However, the effects are usually short-lived, and within 1 to 4 years, the soil recovers its pre-PF values. In this regard, one of the most salient determinants is a territory's pre-fire land use, since the greatest environmental, economic, and social damage tends to be recorded in areas where there was no prior management or where there were large swathes of monospecific plantations (e.g., industrial pine and eucalyptus) (Pereira *et al*., 2018).

Likewise, in the case of PF, only a few studies have evaluated the influence of land use before the fire on the recovery of the soil's chemical properties. For example, on abandoned terraces, slight, ephemeral increases in pH, EC, total carbon and total nitrogen, and extractable cations were recorded, with values returning to their pre-fire levels just two years after the burn (Úbeda *et al*., 2019). The same authors report that if the same plot is to be subject to a repeat PF, a wide time window is preferred to allow the soil to recover. Other studies report the recovery of pre-PF values after three years (Alcañiz *et al*., 2020). In this particular instance, the PF did not significantly affect soil properties, and in the long-term, soil chemical properties fully recovered. However, these two studies were conducted on a forested plain that had been abandoned a few years before the PF, while typically most studies of this nature are conducted in native forest areas, where burning results in a slight, ephemeral increase in pH, EC and extractable cation concentrations, though pre-fire levels are recovered between 1 and 3 years after the event (Scharenbroch *et al*., 2012; Fonseca *et al*., 2017). In fact, in some instances, post-fire soil values are even lower than those recorded before burning, albeit that the situation normalizes two years after the PF. In studies conducted on grasslands, no negative effects were recorded following PF, although the annual application of this management tool was associated with a deterioration in soil conditions (Úbeda *et al*., 2005; Valkó *et al*., 2016). All in all, however, this pre-fire land use seems to ensure the prompt recovery of soil after fire. In short, prior land use is critical in determining whether PF should be used as a recurring tool for land management and whether systematic prescribed burns should be applied over time.

To the best of our knowledge, the number of studies that have actually addressed the long-term impact of PF is scarce. To address this gap, this study seeks to investigate the long-term effects of PF on soil chemical properties and to determine any differences in this regard according to prior land use. We hypothesize that a PF does not have any long-term impacts on soil properties and that while the pre-fire land use gives rise to short- and medium-term differences, these disappear in the long term.

2. Materials and methods

2.1. Study area

The study area lies in the Tivissa mountain range in the province of Tarragona (NE Iberian Peninsula) (Fig. 1) at an altitude of between 200 and 300 m.a.s.l. The area has a Mediterranean climate with a mean annual precipitation of 581 mm and a mean temperature of 15.7 °C. Its soil is classified as a Lithic Calcixerepts (Soil Survey Staff, 2022), lying on a calcareous bedrock (Alcañiz *et al*., 2020). The study was conducted at two sites – a forest plot (TV2) and an abandoned terrace (TV3). The slope on both is gentle, and the PF was set to burn from the base of each at a low-to-moderate intensity, given that three crowns were not combusted and the soil was partially covered with black ashes (Moreno and Oechel, 1989). In both cases, only herbs and partially some shrubs were burned. The two sites share the same soil parent material, southerly aspect and climate characteristics; however, their land use histories differ significantly. TV2 can be considered representative of a primary vegetation succession on bare rock. It was exposed to PF in 2001, at a time when the area presented a predominance of *Pinus halepensis, Ulex parviflorum, Pistacea lentiscus, Erica arborea, Juniperus oyxcedrus, Quercus coccifera,* and *Lonicera implexa*. As such, TV2 represents a natural forest area without human perturbation until the first PF event. TV3, in contrast, is representative of a secondary succession following anthropogenic disturbance (Boixadera *et al*., 2016). In 2001, at the time of the PF, the site was an abandoned terrace colonized by *Rubus ulmifolius*, *Salvia rosmarinus*, and *Ulex parviflorum* with a grass matrix. Before this, the site had been covered by a rainfed almond (*Prunus dulcis*) plantation, last managed in 1994, and as such, is representative of an abandoned terrace left unmanaged for 7 years.

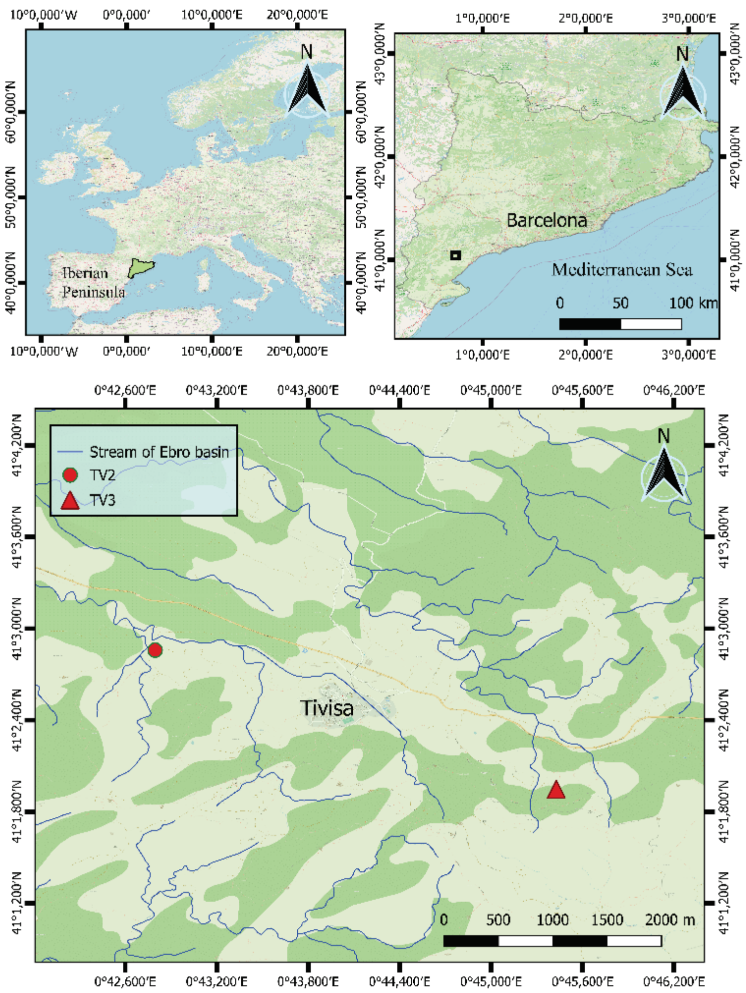

Figure 1. Location of the study area.

2.2. Methodology

A 72-m^2 experimental plot (18 × 4 m, consisting of a grid with 2-m spacing between sampling points) was designed within the burned area. A total of 30 soil samples (0–5 cm depth) were collected from this grid in line with the procedure described in Alcañiz *et al*. (2016) and Francos *et al*. (2019a, 2019b). Soil samples were taken from the top layer (0–5 cm) at each sampling point to record the direct and indirect effects of prescribed burning. There is a scientific consensus that has been shown to reach a depth of about two centimeters due to the soil's low thermal conductivity (see Badía *et al*., 2017), but this study also wanted to observe indirect effects and evaluate how the ecosystem recovers from prescribed fire, considering previous use and everything that this entails. Other studies on long-term burning and ecosystem recovery have been published in recent years using the same methodology, since the objective of evaluating these direct and indirect effects was similar (see Alcañiz *et al*. (2016) and Úbeda *et al*. (2019)). At each of the two sites (TV2 and TV3), five sampling campaigns were conducted: just before the fire (BPF), immediately after the fire (APF), one year after the fire (1YAPF), three years after the fire (3YAPF), and 13 years after the fire (13YAPF).

The laboratory methods employed are described in detail in Francos *et al*. (2018). Briefly, each sample was dried in the laboratory at 25 °C and sieved to obtain a <2 mm fraction. Soil pH and EC were analyzed following extraction with pure water (1:2.5). Total nitrogen (TN) and total carbon (TC) contents were analyzed in the pulverized samples using gas chromatography combustion-reduction with a thermal conductivity detector with a Flash EA 112 Series (Thermo-Fisher Scientific, Milan). Data acquisition and calculations were carried out using Eafer 300 software (Thermo-Fisher Scientific, Milan). Soil cations (calcium, magnesium, and potassium) were extracted from samples using ammonium acetate (Knudsen *et al*., 1982). The extractable cation content was analyzed by inductively coupled plasma mass spectrometry (ICP-MS), using a PerkinElmer Elan-6000 Spectrometer, and by optical emission spectrometry (OES), using a PerkinElmer Optima-3200 RL Spectrometer. The available phosphorus (P) was analyzed following the Olsen–Gray method (Olsen *et al*., 1954) due to the soil pH resulted higher than 7 (Perez *et al*., 2019).

Before data comparison, tests for data normality and the equality of variances were conducted using the Shapiro-Wilk and Levene tests, respectively. Statistically significant differences were identified at $p < 0.05$. A one-way ANOVA was used when the data met the Gaussian distribution and the equality of variances criteria. For data that did not meet the normality and homogeneity assumptions, the non-parametric Kruskal-Wallis ANOVA test was used. The Tukey post-hoc test was applied to identify differences at $p < 0.05$ for each sampling campaign. A redundancy analysis (RDA) was performed to determine the relationships between the variables using SPSS 23.0 and CANOCO for Windows software 4.5. The graphics have been created using R.

3. Results and Discussion

The forest area (TV2) registered significantly lower values of TC at the BPF and APF stages than those recorded at 1YAF, 3YAF, and 13YAF, as well as significantly lower TN values at 13YAF than at 1YAF. In the case of TC, significantly higher values were recorded at 1YAF and 3YAF than at BPF, APF, and 13YAF (Table 1).

The abandoned agricultural area (TV3) registered significantly lower values of TC at 3YAF and 13YAF than during the other sampling campaigns. TC values were also significantly lower at 1YAF than at BPF and APF, but significantly higher than at 3YAF and 13YAF. Significantly higher TC values were obtained at BPF and APF than during the other campaigns. In the case of TN, significantly lower values were obtained at BPF than at 13YAF (Table 2).

In TV2, soil pH registered significantly lower values at 3YAF than at the other sampling dates. Values at 13YAF were significantly higher than at 3YAF; yet, they were lower than those recorded at

BPF, APF, and 1YAF. Similarly, pH values were significantly higher at BPF and 1YAF than at 3YAF and 13YAF, but still lower than those at APF. The highest pH values were observed at APF, being significantly greater than at all other time points. In the case of EC at this site, significantly lower values were recorded at BPF than at all other sampling points. EC values at APF and 1YAF were significantly lower than those at 3YAF and 13YAF, yet significantly higher than at BPF. The highest EC values were recorded at 3YAF and 13YAF, both significantly greater than those at earlier sampling dates.

In TV3, soil pH was significantly lower at 13YAF than at all other time points. Values at BPF, APF, and 3YAF were significantly lower than those at 1YAF but significantly higher than at 13YAF. The highest pH values were observed at 1YAF. In the case of EC at this site, significantly lower values were recorded at 1YAF and 13YAF than at the other sampling points. EC at 3YAF was significantly lower than at BPF and APF but higher than at 1YAF and 13YAF. The highest EC values in TV3 were observed at BPF and APF, both significantly greater than at the later sampling dates.

In TV2, extractable calcium (Ca) concentrations were significantly lower at BPF, APF, and 1YAF compared to later sampling periods. At 13YAF, Ca levels remained significantly lower than at 3YAF, which recorded the highest values across all time points. In the case of extractable magnesium (Mg), significantly higher values were observed at APF than at 1YAF and 13YAF. Extractable potassium (K) was significantly higher at BPF and APF than at 1YAF, 3YAF, and 13YAF. As for available phosphorus (P), significantly lower concentrations were found at BPF and APF compared to subsequent sampling dates. Phosphorus levels at 13YAF were significantly higher than at BPF and APF but lower than those at 1YAF and 3YAF, which exhibited the highest values (Fig. 2).

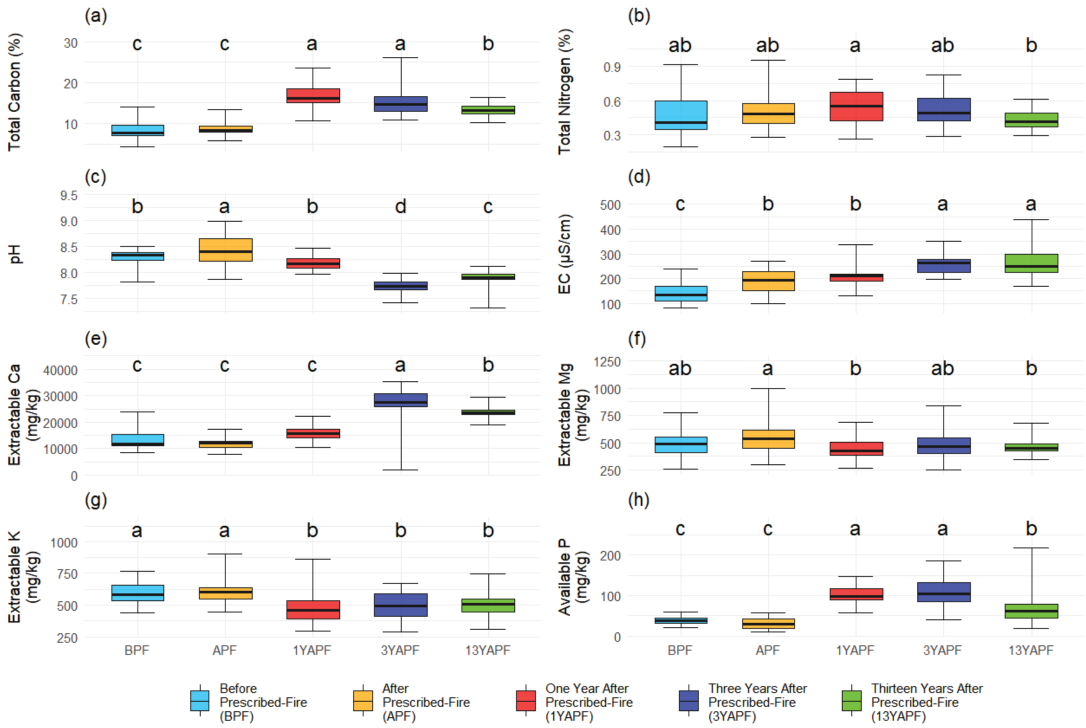

Figure 2. Boxplot of chemical soil properties in forest area (TV2) across sampling periods.

In TV3, extractable Ca concentrations were significantly lower at BPF, APF, and 1YAF compared to later samplings, with 3YAF showing the highest values. In the case of extractable Mg, concentrations were significantly lower at BPF, APF, and 1YAF than at 3YAF and 13YAF. Extractable K was significantly lower at BPF compared to 3YAF and 13YAF. Additionally, K levels were significantly lower at 3YAF than at 13YAF but remained higher than at BPF, with the highest values recorded at 13YAF. Finally, available P showed significantly lower concentrations at BPF and 13YAF relative to all other sampling periods. P levels at 1YAF and 3YAF were significantly lower than at APF but higher than at BPF and 13YAF, while the highest values were recorded at APF (Fig. 3).

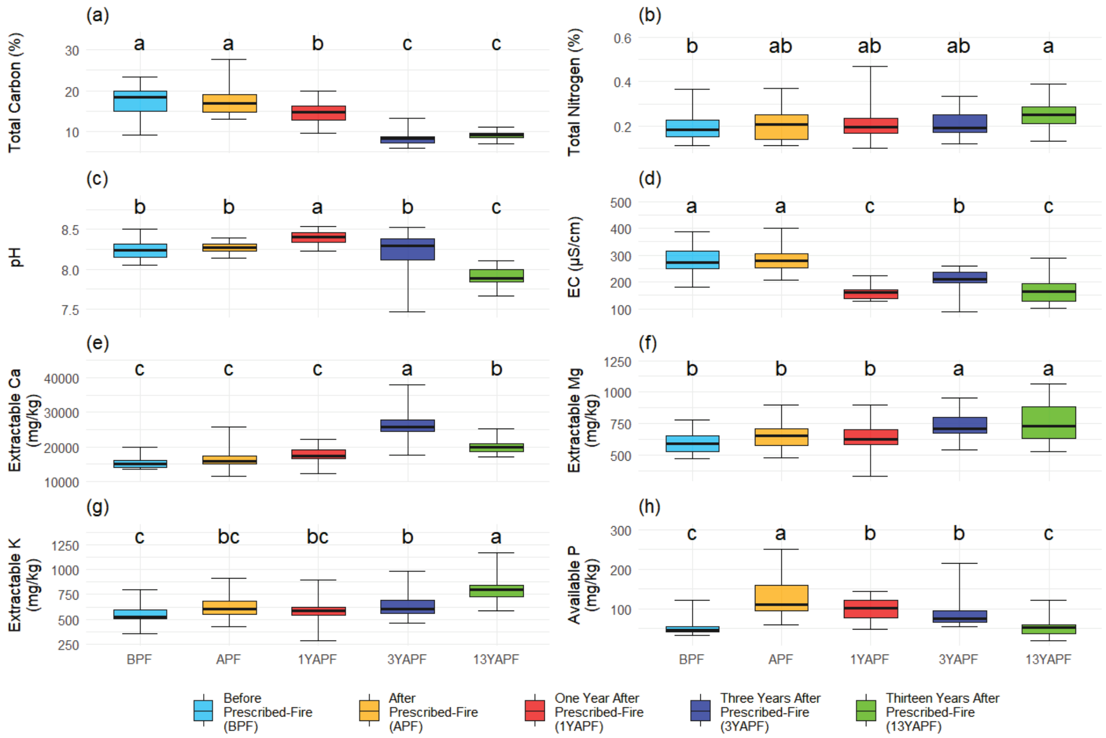

Figure 3. Boxplot of chemical soil properties in abandoned agricultural area (TV3) across sampling periods.

Although the short-term effects of fire on soil chemical properties are well-documented, there is limited research that simultaneously examines short-, medium-, and long-term changes within a single plot. Soil TC is a key indicator of carbon storage capacity and overall ecosystem health. Here, the PF did not significantly affect TC levels, likely due to its low intensity and combustion temperatures, an outcome that is consistent with earlier findings (Alcañiz *et al*., 2018). Over time, TC increased in the forest area (TV2), which can be attributed to the formation of black carbon under low-intensity fire conditions (<450 °C) (Alcañiz *et al*., 2016) and reduced oxidation of organic matter (OM) due to minimal heat exposure (Scharenbroch *et al*., 2012). Conversely, in the abandoned agricultural terraces (TV3), TC levels declined in the long term, likely due to shifts in vegetation composition and associated losses in soil organic matter (Agbeshie *et al*., 2022). These findings highlight the importance of land-use history: the prior use of the site as abandoned agricultural land affects post-fire vegetation recovery and, consequently, influences forest structure and soil health.

Soil TN is also affected by prescribed burning. Combustion can volatilize nitrogen as gaseous compounds, leading to significant losses (Certini, 2005). However, in this study, no immediate TN losses were observed due to the low intensity of the PF. In the long term, TN levels in the forested area showed a slight decline, likely due to the preferential immobilization of nitrogen during the charring process (Certini *et al*., 2011). In contrast, the abandoned agricultural area exhibited a long-term increase in TN. This may be attributed to the accumulation of vegetation, as a substantial portion of organic nitrogen can survive low-severity fires (Scharenbroch *et al*., 2012), along with the post-fire incorporation of incompletely combusted organic residues into the soil (Alcañiz *et al*., 2018).

Soil pH typically follows a predictable trajectory in response to prescribed burning, as observed in both TV2 and TV3. Numerous studies have reported an initial increase in soil pH immediately after a fire event, followed by a gradual decline over time (Alauzis *et al*., 2004; Granged *et al*., 2011). This pattern was evident here in both plots, with the increase being more pronounced in TV2, although final pH values were similar in the two areas (7.89 in TV2 and 7.90 in TV3). Comparable findings were reported by Muñoz-Rojas *et al*. (2016) in Australia, in a study based similarly on five sampling campaigns in which soil pH rose to 7.38 shortly after fire and then declined to 6.70 over 14 years in unburned control areas. The magnitude and persistence of pH increases are influenced by several factors, including fire intensity, the quantity of vegetation burned, and the amount of charred organic matter that is converted into ash (Pereira *et al*., 2012; Bodí *et al*., 2014). Additionally, post-fire processes such as ash incorporation into the soil or ash removal by wind or water can significantly affect the duration and extent of pH changes (Jordán *et al*., 2010).

EC increased in both TV2 and TV3, although the increase was only statistically significant in TV2. Over time, the two areas exhibited contrasting trends: while EC decreased in TV3, it continued to rise in TV2. A similar temporal pattern was reported by Alauzis *et al*. (2004) in a four-year study conducted in Chile, which included four sampling points. The differing behavior between the two sites may be attributed to variations in vegetation cover and soil exposure. In TV3, which consists of terraced, abandoned agricultural land, the soil tends to be more exposed to precipitation, potentially leading to greater leaching of soluble salts and, thus, lower EC over time (Outeiro *et al*., 2008). This trend was also observed here in other parameters related to EC response. Muñoz-Rojas *et al*. (2016) reported a more pronounced increase in EC following a natural wildfire in Australia. In their study, EC values rose from 0.38 dS/m to 2.92 dS/m over 14 years, ultimately returning to levels typical of unburned soils.

The most notable trend in phosphorus dynamics is the increase in available phosphorus in TV3 following the PF, whereas in TV2, this increase was more gradual. One explanation for the delayed response in TV2 may lie in the role played by ash and its slower incorporation into the soil (Pereira *et al*., 2012). In contrast, in TV3, where vegetation cover is sparser and soil is more directly exposed to precipitation, ash is more readily incorporated into the soil, accelerating the availability of phosphorus (Outeiro *et al*., 2008). Here, the historical use of phosphorus fertilization at the TV3 site is an additional factor. According to Stephens *et al*. (2004), phosphorus applied as fertilizer can persist in insoluble forms, which may become solubilized through fire-induced chemical transformations, thereby increasing its availability post-fire. Ekinci and Kavdir (2005) also emphasize the importance of understanding land-use history when interpreting soil chemical responses to fire events. Supporting these findings, Muñoz-Rojas *et al*. (2016) observed a significant post-fire increase in available phosphorus in a long-term study in Australia, with concentrations rising shortly after fire and then decreasing over 14 years.

Exchangeable cations (Ca^{2+}, Mg^{2+}, and K^{+}) did not exhibit significant changes immediately following the prescribed burn in either plot. However, a gradual increase in their concentrations was observed over time, which may be attributed to the progressive incorporation of ash into the soil and its gradual assimilability. Similar trends were reported by Lewis (1974) in a study conducted in California, where cation concentrations significantly increased post-fire, attributed to enhanced solubility following combustion. In contrast, Alauzis *et al*. (2004) observed an immediate increase in cations after fire, followed by a steady decline over four years. Meanwhile, Muñoz-Rojas *et al*. (2016) reported no significant variation in exchangeable cations across five sampling points over a 14-year post-fire period in Australia. The increase in available cations is usually due to the combustion of organic matter and tends to occur in medium- or high-intensity fires. In cases where this dynamic does not occur, it may be because the intensity has been low (Alfaro-Leranoz *et al*., 2023). Despite this, pre-fire values are usually recorded after one year and depend on the ashes' dynamic (Capogna *et al*., 2009). This suggests that the observed increases in TV2 and TV3 are aligned with the effects typically associated with low-to-moderate intensity burns.

Soil TC and TN did not exhibit significant changes immediately after the PF in either study plot. However, consistently higher concentrations of TC were observed in TV2, while a decline was recorded in TV3. Similar findings were reported by Muñoz-Rojas *et al*. (2016), who observed no significant changes in TC or TN concentrations across a 14-year post-fire monitoring period, nor any clear trend of increase or decrease attributable to fire. Likewise, Alauzis *et al*. (2004) reported stable values over a four-year period following fire.

An RDA was performed using the soil properties from both study areas: the forest site (TV2) and the abandoned agricultural terrace (TV3) (Fig. 4). This type of analysis makes it possible to establish relationships between the dynamics of different soil properties. Despite this, the variance explained is low, but it allows to see how the different variables are associated with each other around the samplings (factors). In TV2, the RDA explained 37.4% of the variance (22.2% by Factor 1 and 15.2% by Factor 2), with extractable Ca, TC, available P, and EC having the highest explanatory capacity and TN and extractable Mg contributing the least. Two clusters were identified: one including pH, K, and Mg near BPF and APF, and another comprising EC and extractable Ca near 3YAF and 13YAF. In TV3, the RDA explained 38.3% of the variance (21.9% by Factor 1 and 16.4% by Factor 2), with extractable Ca and TC as the most influential variables, and pH and available P the least. Two main clusters were observed: one formed by extractable Ca, Mg, and K, and another by TC, EC, and available P.

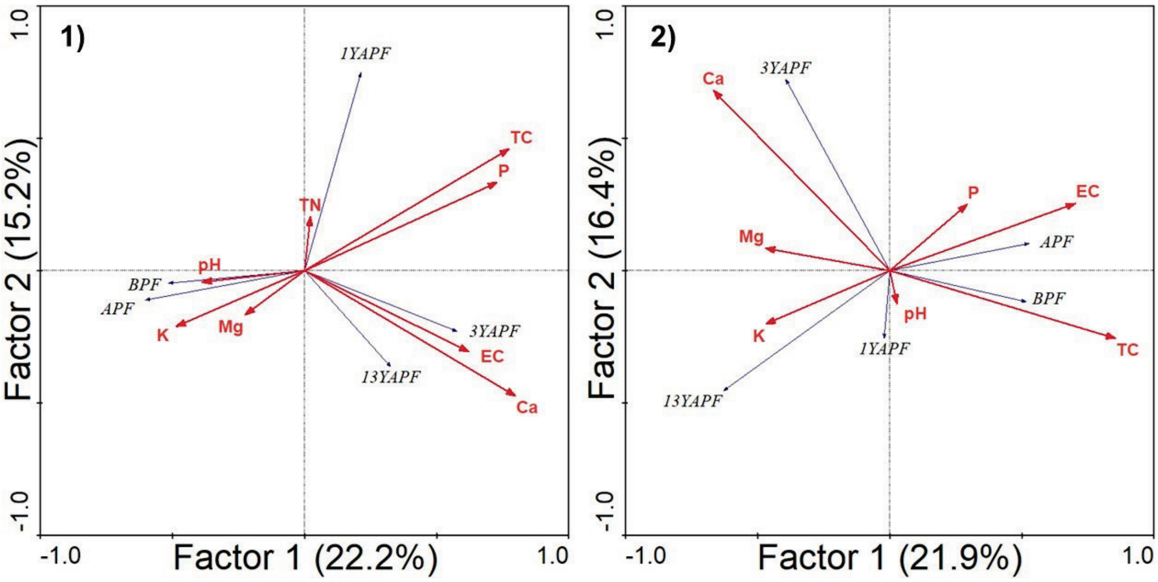

Figure 4. Redundancy analysis biplots showing the relationship between Factor 1 and Factor 2 for (1) the forest site (TV2) and (2) the abandoned agricultural terrace (TV3). Environmental variables include total carbon (TC), total nitrogen (TN), pH, electrical conductivity (EC), extractable calcium (Ca), magnesium (Mg), potassium (K), and available phosphorus (P). Sampling times at both sites: before prescribed fire (BPF), after prescribed fire (APF), and 1, 3, and 13 years after prescribed fire (1YAPF, 3YAPF, and 13YAPF, respectively).

In soils with a history of intensive agricultural use, fertilization and management practices significantly alter nutrient dynamics, with long-term effects. Even low-intensity prescribed burning can interact with these inputs, enhancing nutrient mineralization, though repeated or high-intensity burns may cause nutrient losses (Úbeda *et al*., 2019). Intensive agricultural practices often compromise soil organic matter and structure, increasing vulnerability to post-fire nutrient depletion, especially in soils with initially low fertility (Lal, 2004). In TV3, the variables appeared more dispersed, suggesting a greater influence of post-fire vegetation regrowth rather than the immediate effects of the temperature reached during ignition. Low-intensity fires likely spared the seed bank, allowing regeneration from fire-resistant or dormant seeds (Francos and Úbeda, 2021). The clustering of BPF and APF samples in the RDA suggests minimal short-term fire impact. Furthermore, in TV2, soil properties showed recovery within three years post-fire, with stability up to 13 years, indicating a rapid return to pre-fire conditions, in contrast to the longer recovery observed after wildfires (García-Braga *et al*., 2024). In the case of TV3, the same relationship is observed between the different sampling times; the greater variability shown by the soil properties may be attributed to pre-fire land use and the regeneration of the seed bank. Continued monitoring is recommended to evaluate the influence of land-use legacy and changes in plant diversity and density on soil properties. Such data can guide adaptive management strategies aimed at preserving soil fertility, preventing degradation, and reducing fuel loads when and where necessary (Francos *et al*., 2018; 2019b). In summary, while natural forest soils tend to recover from prescribed burns, former agricultural areas may remain more vulnerable due to altered structure and depleted organic matter. Prescribed burning plans must account for these differences to mitigate adverse impacts on soil fertility.

4. Conclusions

In our study, we report significant changes in soil chemical parameters after prescribed fire. Thirteen years after prescribed burns, the results reveal low values of pH and K in the area occupied by forest, and low values of TC, pH, and EC in the area occupied by terrace crops with respect to before each burn. Prescribed fires can have temporary positive effects on the availability of soil nutrients, but if sites are not properly managed, they can suffer long-term losses that impact soil fertility and soil health. As such, these results need to be taken into consideration in land management practices to ensure a proper balance of nutrients. Low-intensity fire management practices of this type do not significantly affect soils in the medium- to long-term, yet they can improve soil fertility and help boost ecosystem resilience. However, when analyzing the changes to a soil due to the passage of fire, it is critical to know the prior land use history, because the vegetation, organic matter, and the amount of ash produced are basic variables for understanding the effects. It is also important to know whether the land has previously been fertilized to boost productivity, since this also determines the post-fire evolution of soils. Finally, differences in vegetation coverage and slope are a further factor to be considered when conducting long-term studies, since they determine the amount of water reaching the soil during a rainfall episode and the associated incorporation of nutrients. Then the long-term results show a higher effect in the area previously occupied by crops, which leads us to consider that the effects caused by the use prior to prescribed burning can reach up to the long term, even in low-moderate intensity fires. In this sense, this land use must be considered in order to prioritize forest management for wildfire prevention in the areas where it is most necessary, such as historically abandoned agricultural terraces.

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