TERRA LATINOAMERICANA

Post-Fire Changes in Soil Chemistry of the Savannas of the Paraguayan Humid Chaco
Cambios Químicos Post-Incendio en Suelos de Sabanas del Chaco Húmedo Paraguayo

Ana Beatriz Candia-Díaz[1,2‡], William Jefferson Watler-Reyes[3], Jimmy Walter Rasche-Álvarez[1,4], Rafaela Laino-Guanes[5], and Larissa Karina Rejalaga-Noguera[4]

[1] Grupo de Investigación de Manejo de Suelo y Agua (GI-MSA), Campus Universitario de la Universidad Nacional de Asunción, Facultad de Ciencias Agrarias. Ruta Mariscal José Félix Estigarribia, km 11. 2160 San Lorenzo, Paraguay; (A.B.C.D.), (J.W.R.A.),
[2] Universidade Federal do Rio Grande do Sul, Faculdade de Agronomia, Programa de Pós-Graduação em Ciência do Solo. Av. Bento Gonçalves, 7712 Bairro Agronomia. 91540-000 Porto Alegre, Rio Grande do Sul, Brasil; (A.B.C.D.).
‡ Corresponding author: anacandia09@gmail.com
[3] Centro Agronómico Tropical de Investigación y Enseñanza. Carretera Turrialba–Siquirres, km 3, Distrito Santa Rosa. 30501 Turrialba, Cartago, Costa Rica; (W.J.W.R.).
[4] Universidad Nacional de Asunción, Facultad de Ciencias Agrarias. Ruta Mariscal Estigarribia, km 10.5. 2160 San Lorenzo, Central, Paraguay; (J.W.R.A.), (L.K.R.N.).
[5] Centro de Investigación del Chaco Americano. San José 365, Estancia Playada. 9000 Villa Hayes, Asunción, Paraguay; (R.L.G.).

SUMMARY

Contradictory results regarding the effects of fire on the chemical properties of soil are found in the existing literature. This study evaluated the effects of burning on the pH, organic matter (OM), phosphorous (P), calcium (Ca), magnesium (Mg) and potassium (K) in the soil of savannas in the Benjamín Aceval district of the Paraguayan Humic Chaco, over the medium term (two years after the wildfire event). The selection of sampling sites was based on the Fire Severity Index (dNBR). The treatment factors were the type of land cover (savanna and flooded savanna), burn condition (burned and unburned), and sample depth (0-3 and 3-6 cm). Regarding pH, no significance was found with any factor or their interactions. For OM, a significant interaction was found between burn condition and sampling depth. For P, the interaction between the type of cover and depth was significant. Concerning C, M, and K, a significant effect was observed based on sampling depth. Overall, the results indicate that two years after the fire, the effects of burning on the chemical properties of the soil were limited and dependent on the evaluated variable.

Index words: *burn intensity assessment, nutrient availability, vegetation recovery.*

RESUMEN

En la literatura existen resultados contradictorios sobre los efectos que genera el fuego en las propiedades químicas del suelo. El presente estudio evaluó los efectos de la quema en el pH, materia orgánica (MO), fósforo (P), calcio (Ca), magnesio (Mg) y potasio (K) en suelos de sabanas del distrito de Benjamín Aceval, Chaco Húmedo Paraguayo, en mediano plazo (dos años después del evento de incendio). La selección de los sitios de muestreo se basó en el Índice de Severidad de Fuego (dNBR). Los factores de tratamiento fueron el tipo de cobertura de tierra (sabana y sabana inundada), la condición de quema (quema y no quema) y la profundidad de muestreo (0-3 y 3-6 cm). Con relación al pH, no se encontró significancia con ningún factor ni sus interacciones, para MO se encontró interacción significativa de la condición de quema con la profundidad de muestreo, para P resultó significativa la interacción tipo de cobertura con profundidad de muestreo. En cuanto a Ca, Mg y K se observó efecto significativo de la profundidad de muestreo. En general, los resultados indican que dos años después del incendio, los efectos de la quema sobre las propiedades químicas del suelo fueron limitados y dependientes de la variable evaluada.

Palabras clave: *evaluación de la intensidad del incendio, disponibilidad de nutrientes, recuperación de la vegetación.*

Recommended citation:

Candia-Díaz, A. B., Watler-Reyes, W. F., Rasche-Álvarez, J. W., Laino-Guanes, R., & Rejalaga-Noguera, L. K. (2025). Post-Fire Changes in Soil Chemistry of the Savannas of the Paraguayan Humid Chaco. *Terra Latinoamericana, 43*, 1-13. e2256. https://doi.org/10.28940/terra.v43i.2256

Received: March 16, 2025.
Accepted: April 29, 2025.
Article, Volume 43.
September 2025.

Section Editor:
Dr. Esteban Sánchez-Chávez

Technical Editor:
M. C. Ayenia Carolina Rosales Nieblas

INTRODUCTION

Fires are part of the natural evolution of landscapes (Shlisky *et al.*, 2007), as opposed to the initial belief that the worldwide distribution of ecosystems was only influenced by climate and soil factors (Bond and Keeley, 2005; Pausas and Keeley, 2009). Nowadays, fires are perceived as threats to ecosystems since their regime (frequency, severity, intensity, seasonality, size) can be disrupted by human intervention (Cochrane and Barber, 2009; Doerr and Santín, 2016), and by climate change (Bento-Gonçalves, Vieira, Úbeda, and Martin, 2012; Budde *et al.*, 2017). The occurrence of extreme fire events in the southern hemisphere is projected to increase by 20% to 50% (Bowman *et al.*, 2017), particularly when favorable weather conditions combine, such as drought, high temperatures, and reduced precipitation (Devisscher, Anderson, Aragão, Galván, and Malhi, 2016; Harrison *et al.*, 2021).

The annual average number of fires in Latin America is one of the highest in the world (Andela *et al.*, 2017), being closely related to the use of fire in agricultural activities such as deforestation for agricultural expansion, pasture management, and clearance of agricultural land (Armenteras *et al.,* 2021; Barlow, Berenguer, Carmenta, and França, 2020; Souza-Alonso, Saiz, García, Pauchard, Ferreira, and Merino, 2022), causing significant changes in the natural configuration and composition of the landscape (Neary, Ryan, Debano, Landsberg, and Brown, 2005). In Paraguay, the use of fire is a deeply rooted practice in farming systems and is one of the main triggers of wildfires in the country (Kernan, Cordero, Macedo, and Villaba-Marín 2010).

In the short term, fires exert a significant impact on soil properties, with effects that are not always visible to the naked eye and tend to go unnoticed and are underestimated (Minervini *et al.*, 2018; Neary *et al.*, 2005). Indeed, most research has focused on evaluating the effect of fire on vegetation compared to research focusing on the effects on the soil (Agbeshie, Agbugre, Atta-Darkwa, and Awaah, 2022). In Latin America and the Caribbean, various studies have been carried out on fires and their impact (Armenteras *et al.*, 2021; Chen *et al.*, 2013; Drüke *et al.*, 2019; Giorgis *et al.*, 2021). For example, Lizundia-Loiola, Pettinari, and Chuvieco (2020) compared fire occurrence estimates in countries such as Brazil, Bolivia, Colombia, Argentina, Venezuela, and Paraguay in 2019, with data ranging from 2001 to 2018. They discovered that the Surface area burned in 2019 was 70% greater than for the same period in 2018, highlighting the significant increase in fire events, especially in countries such as Paraguay. Capulín, Mohedano y Razo (2010) in a study about changes in soil and vegetation in a pinus forest affected by fire concluded that the vegetation showed increases in species diversity and number of plants in the burned area compared with the control, indicating that the fire created favourable conditions for incoming pioneer plant species which formed a microclimate allowing natural regeneration of the original.

Despite an increase in research on the effect of fires on soil, Souza-Alonso *et al.* (2022) point out that research on these effects continues to be one of the least studied aspects in Latin America and the Caribbean. The existing literature on the effects of fire on soil properties reveals variable and sometimes contradictory results (Mataix-Solera, Cerdà, Arcenegui, Jordán, and Zavala, 2011; (Ondik, Bennell, Davies, Ooi, and Muñoz-Rojas, 2022), probably due to the diversity and complexity of existing soils (Minervini *et al.*, 2018).

Fires cause effects that are both permanent and temporary, direct and indirect, on the physical, chemical, and biological properties of the soil (Redin *et al.*, 2011; Zavala *et al.*, 2014). The greatest soil degradation occurs after the fire event and tends to decrease over time (Giorgis *et al.*, 2021; Orumaa *et al.*, 2022). The degree of post-fire soil disturbance is linked to factors such as fire recurrence, intensity, and severity (Bodi, Cerdà, Mataix, and Doerr, 2012), the topography of the site, processes of erosion, the capacity of the vegetation to regenerate (Caon, Vallejo, Coen, and Geissen, 2014), moisture content (Ferreira, Coelho, Ritsema, Boulet, and Keizer, 2008), and type of soil (Mataix-Solera *et al.*, 2011). The interaction of these factors results in a heterogeneous burn in the affected area, creating mosaics with different burn levels (Rab, 1996), from which different categories of burn severity can be derived that not only act as visual indicators but also enable the level of soil degradation to be inferred (Vega *et al.*, 2013).

In Paraguay, there is a notable dearth of scientific literature examining the effects of fire on elements of the landscape (Baumann, Piquer-Rodríguez, Fehlenberg, Gavier-Pizarro, and Kuemmerle, 2016). This paucity is even more noticeable for the western region of the country, known as the Paraguayan Chaco, as noted by Vidal-Riveros, Souza-Alonso, Bravo, Laino, and Bieng (2023), who report that just 1.25% of all the literature on fires in the Gran Chaco region relates to Paraguay. The limited studies on fires in the Chaco are mainly based on reports of heat sources (Molinas-Gobzález and Florentín, 2021), showing an increase in the frequency of fires in the region over recent years (Coronel *et al.*, 2021). Bearing in mind that savanna burning is a common management practice in this region that has been historically and culturally linked to cattle farming (Laino, Musalem, Caballero-Gini, Bueno-Villafañe, and Chaparro, 2018), this research proposed evaluating the impact of fire on the chemical soil properties of the savanna in the Paraguayan Humid Chaco ecoregion over the medium term, two years after the event.

MATERIALS AND METHODS

Study Area

The research was conducted in the Paraguayan Humid Chaco ecoregion (Yanosky *et al.*, 2016) in the Benjamín Aceval district of the Presidente Hayes Department. The study area was composed of three cattle farming establishments located at 24° 58′ S, 57° 22′ W, covering a total area of 8085 ha (Figure 1). The climate of the area is characterized by an average rainfall ranging from 1000 to 1200 mm, with an average temperature of 24 to 25 °C (Mereles *et al.*, 2013). The landscape is made up of palm savannas, wetlands, and remnants of forest in combination with wide stretches of savanna, where low-intensity cattle rearing is practiced (Laino *et al.*, 2022), with a density of one livestock unit per 2 ha (Merenciano-González *et al*., 2018). The predominant soils in the study area are classified as *Eutric Fluvisol*, *Eutric Gleysol*, *Stagnic Solonetz*, and *Haplic Solonetz* (Kruck, 1994). It is of great ecological importance due to the ecosystem services that it provides (Merenciano-González *et al*., 2018), with a rich biodiversity that includes amphibians and reptiles (Mereles *et al*., 2020), as well as a notable diversity of wild fauna (Laino *et al.*, 2022). It is home to endangered species, most notably the *Panthera onca* (Laino, Musalem, Weiler, and González-Maya, 2021).

Selection of Sampling Sites

In order to determine the soil sampling sites, the historic patterns of fire events within the study area and the surrounding area over a period of 12 years (2010 to 2022) were analyzed. The year with the most recent fire was identified by examining 13 maps of burned areas generated by the MODIS Burned Area product (MCD64A1 v. 6). The most significant recent event was discovered to have occurred in 2020, affecting a burned area of 2730.8 ha (Figure 2).

It is important to underline that the livestock establishments located in the study area carry out prescribed burns as part of their production management. In other words, controlled burns are used to avoid uncontrolled wildfires during the dry season. In the study area, the main ally in preventing the excessive accumulation of herbaceous material is cattle, together with other herbivores in the savannas (mammals, birds, ants, etc.) that feed on natural pasture. Even so, when too much material has accumulated, controlled burns are used. Figure two shows that fires generally spread from the north, and on some occasions from the south, as occurred in 2020, one of the years most affected by fires regionally and globally.

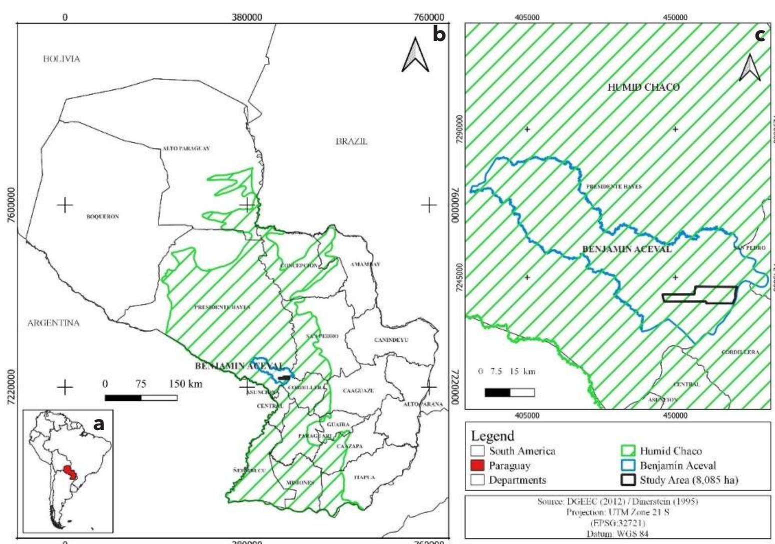

Figure 1. Study area, Benjamín Aceval district, Humid Chaco ecoregion, Paraguay. (a) Paraguay in South America, (b) Paraguayan Humid Chaco ecoregion, and (c) study area.

Figure 2. Burned areas (2010-2022) within the study area, Benjamín Aceval district, Humid Chaco ecoregion, Paraguay.

In order to identify the areas affected by the fire, the Fire Severity Index was calculated from the dNBR (delta Normalized Burn Ratio) (Key and Benson, 2006), and the respective map was created. The dNBR, derived from the Normalized Burn Ratio index (NBR), evaluates burn severity and scars by combining near infrared spectral bands (NIR) and short-wave infrared (SWIR) (Saputra, Setiabudidaya, Setyawan, Khakim, and Iskandar, 2017). Pre- and post-fire burn satellite images were used to calculate the dNBR. To determine the exact date of the fire, 2020 heat sources registered in the FIRMS database were used. The month of September was shown to register the highest number of heat sources. The dNBR for September 2020 was estimated based on this information, using the following equation:

$$dNBR = \text{Pre-fire NBR} - \text{Post-fire NBR} \quad (1)$$

Where "Pre-fire NBR" corresponds to the NBR index prior to the fire (August 2020) and "Post-fire NBR" corresponds to the NBR index after the fire (September 2020).

The dNBR map was categorized using the fire severity levels proposed by the United States Geological Service (USGS) (Table 1).

A land cover map was created that included the categories of cultivated land, savanna, flood-prone savanna, flooded savanna, forest cover, urban areas, and bodies of water. For the map of the study area, the methodology proposed by the Forestry and Forest Products Research Institute (FFPRI) and the Facultad de Ciencias Agrarias of the Universidad Nacional de Asunción in 2013 was used.

Table 1. Fire severity levels (dNBR), proposed by the USGS.

Levels of Severity	dNBR Range	dNBR Range
	scaled by 103	not scaled)
Enhanced regrowth, high (post-fire)	-500 to -251	-0.500 a -0.251
Enhanced regrowth, low (post-fire)	-250 to -101	-0.250 a -0.101
Unburned	-100 a -99	-0.100 a -0.99
Low severity	100 a 99	100 a 0.269
Moderate-low severity	270 a 439	0.270 a 0.439
Moderate-high severity	440 a 659	0.440 a 0.659
High severity	660 a 1300	0.660 a 0.1300

Both maps were superimposed in order to select the soil sampling sites. Criteria considered for the site selection included edge effects of the patches and the distance between sampling sites within each patch. All samples were taken at a minimum distance of 300 m from the edge of the patches. When two samples were taken within a single patch, information independence was ensured by separating them by a distance of at least 1 kilometer, km.

Soil Sampling

A total of nine patches of different sizes were selected, of which five were flooded savannas and four were savannas. Within each patch, areas that had been affected by fire were distinguished from those that were unaffected, and in each soil, sampling was carried out at two depths: 0-3 cm and 3-6 cm, resulting in 36 sample units. The choice of these depths was based on studies indicating that the effects of fire are primarily manifested in the surface layer of the soil, especially about organic matter and nutrients, being most evident up to 2–3 cm depth; deeper sampling could mask these effects (Alexis, Rasse, Knicker, Anquetil, and Rumpel, 2012; Badía *et al.*, 2014; Mallik and Gimingham, 1985). Stratification sought to identify possible differences between the immediate surface and a slightly deeper layer.

Each sample unit was obtained from a composite sample, consisting of ten subsamples collected in a zigzag pattern over an area of 25 m², with a fixed distance of 1 meter between subsamples (Faria *et al.*, 2015). The subsamples were homogenized in a container in order to obtain a representative compound sample for each sample site. At each sampling point, the geographic coordinates in UTM format were recorded using a Global Positioning System (GPS) device (Figure 3).

In order to measure levels of pH, OM, P, Ca, Mg, and K, the collected soil samples were labeled, geo-referenced, and sent to the Soil Laboratory of the Faculty of Agricultural Sciences (FCA, Facultad de Ciencias Agrarias) of the National University of Asunción (UNA, Universidad Nacional de Asunción), located in the city of San Lorenzo, Paraguay, for chemical analysis. The resulting analytical values were classified by level, using the classification criteria established by the Soil Laboratory of the FCA-UNA FCA-UNA (Table 2).

Data Analysis

Checks were carried out to avoid possible errors, such as atypical values or inconsistencies, with a view to ensuring the quality and reliability of the data and subsequent results. In order to determine the effect of the type of cover, burn condition, and depth on the chemical variables of the soil, adjusted general and mixed linear models were applied, using the following model:

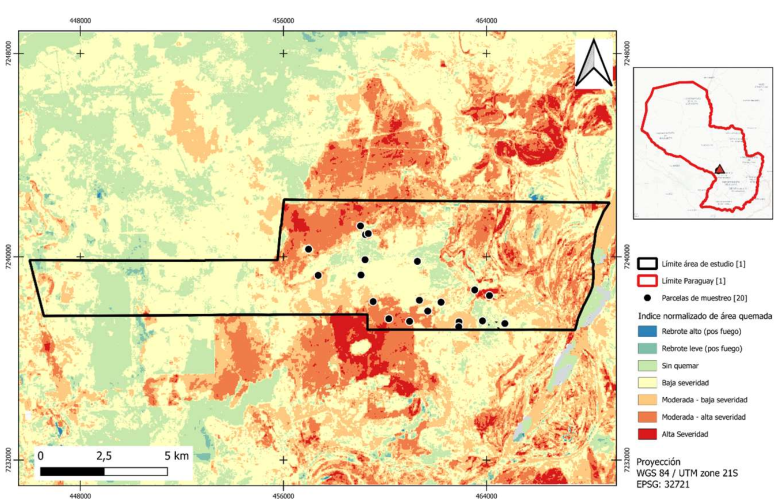

Figure 3. dNBR (2020) for the study area with selected sampling points.
Benjamín Aceval district, Humid Chaco ecoregion, Paraguay.

Tabla 2. Classification criteria for chemical variables by level, Soil Laboratory, FCA-UNA, San Lorenzo, Paraguay.

		Levels			
		Acid	Slightly Acid	Neutral	Alkaline
	pH_{water}	<5.5	5.6-6.4	6.5-7.4	>7.4
		Levels			
		Low		Medium	High
Chemical variables	OM (%)	<1.2		1.2-2.8	>2.8
	P (mg kg^{-1})	<12		12-30	>30
	Ca (cmolc kg^{-1})	<2.51		2.51-6.0	>6.0
	Mg (cmolc kg^{-1})	<0.4		0.4-0.8	>0.8
	K (cmolc kg^{-1})	<0.12		0.12-0.17	>0.17

$$y_{ijkl} = \mu + \alpha_i + \beta_j + \delta_k + \alpha\beta_{ij} + \alpha\delta_{ik} + \beta\delta_{jk} + \alpha\beta\delta_{ijk} + p_{il} + sp_{ijl} + \epsilon_{ijkl} \quad (2)$$

i=1,2; j=1,2; k=1,2; l=1,...,9

where, y_{ijkl}: is the response observed in the i-th type of cover, j-th burn condition, and k-th depth.

μ: general mean, α_i: effect of the i-th type of cover, β_j: effect of the j-th burn condition, δ_k: effect of the k-th depth, $\alpha\beta_{ij}$: effect of the interaction between the i-th type of cover and j-th burn condition, $\alpha\delta_{ik}$: effect of the interaction between the i-th type of cover and k-th depth, $\beta\delta_{jk}$: effect of the interaction between the j-th burn condition and k-th depth, $\alpha\beta\delta_{ijk}$: effect of the interaction between the i-th type of cover, j-th burn condition and k-th depth, p_{il}: random error associated with the main plot, which is assumed to follow a normal distribution, with a mean of zero and variance of σ_p^2, sp_{ijl}: random error associated with the burn condition within the main plot (subplot), which is assumed to follow a normal distribution, with a mean of zero and constant variance of σ_{sp}^2, ϵ_{ijkl}: residual random error following a normal distribution, with a mean of zero and a variance of σ^2. It is also assumed that $cov\ (e_{ijkl}, e_{i'j'k'l'})=0\ \forall\ ijkl \neq i'j'k'l'$. Furthermore, p_{il}, sp_{ijl} and ϵ_{ijkl} correspond to the random effects of the main plot, burn condition within the main plot (subplot), and residual experimental error, which are assumed to be independent.

Diagnostic plots were used to evaluate the distributional assumptions about the error. When it was suspected that the assumptions were not confirmed, the data were remodeled by restating different structures of error correlation and heterogeneous variance. Selection of the best model was based on Akaike (AIC) and Schwartz (BIC) penalized information criteria. For those factors where there were statistically significant differences (p < 0,05), the means comparison test developed by Di Rienzo *et al*. (2011) was carried out. The statistical analyses were performed using InfoStat software version 2017 (Di Rienzo *et al.*, 2011).

RESULTS AND DISCUSSION

Regarding pH, no significance was found with any factor or their interactions. In the case of OM, a significant interaction was found between the burn condition and sample depth. In relation to P, there was evidence of a significant interaction between the type of cover and sample depth. Sample depth was observed to have a significant effect on Ca, Mg, and K (Table 3).

pH

In the present investigation, no significant differences were found in soil pH values two years after the burning event, for any of the model terms evaluated. This result may be related to the time elapsed between the fire and the pH evaluation, which could have allowed the recovery of the original soil conditions. Similar results were reported by Afif-Khouri, Oliverira-Prendes (2006), who also found no significant differences between burned and unburned areas one year after the fire event.

However, these results contrast with those found by Simon *et al.* (2016), who observed differences in soil pH as a consequence of burning, depending on depth. In their study, pH values were higher in the 0-5 cm layer compared to the 5-10 cm layer, which was attributed to the accumulation of ashes on the surface, rich in basic cations (Pereira *et al.*, 2014). Similarly, Rheinheimer, Santos, Fernandes, Mafra, and Almeida (2003) reported a slight increase in soil pH immediately after burning, mainly in the surface layer (0-2 cm), while in deeper layers (3-5 and 5-10 cm) no significant changes were observed. However, 220 days after the fire, a decrease in pH was observed in the burned area, a behavior that did not occur in the unaffected area.

Table 3. Soil chemistry variables and their interactions by type of cover, burn condition, and sample depth with F-statistic and p-value (p).

Variables	Model Terms						
	Cover	Condition	Depth	Cover* Condition	Cover* Depth	Condition* Depth	Cover* Condition* Depth
	F *p*-value	F *p*-value	F *p*-value	F *p*-value	F *p*-value	F *p*-value	F *p*-value
pH	2.71 0.1438	0.07 0.7965	0.15 0.7083	0.33 0.5839	0.00 >0.9999	3.65 0.0769	2.33 0.1489
OM	0.61 0.4613	0.47 0.5147	35.38 <0.0001	0.55 0.4826	1.10 0.3122	4.84 0.0451*	0.02 0.8834
P	1.38 0.2784	2.14 0.1870	39.06 <0.0001	1.78 0.2238	4.90 0.0439*	3.1 0.0949	1.42 0.2532
Ca	0.23 0.6438	0.88 0.3796	9.18 0.0090*	0.04 0.8525	4.90E-03 0.9450	3.04 0.1031	1.13 0.3051
Mg	0.44 0.5270	0.01 0.9206	28.98 0.0001*	2.10E-03 0.9649	1.10 0.3112	2.89 0.1111	1.15 0.3011
K	0.62 0.4577	0.13 0.7326	16.57 0.0011*	2.92 0.1313	0.32 0.5784	0.66 0.4292	1.84 0.1963

Values with asterisks (*) indicate statistical differences ($p < 0.05$).

On the other hand, some studies have reported a decrease in soil pH after fire. Gonzáles *et al*. (2024), for example, found a reduction in pH one month after the fire in the affected area, compared to the unburned area. Similarly, Dhungana, Thapa-Chhetri, Baniya, and Sharma (2024) mention that the average pH in areas affected by fire is lower than in unaffected areas. This decrease in pH may be related, as suggested by Martínez, de las Heras, and Herranz (1991), to the washing and entrainment of cations during periods of intense rainfall, which could cause an impoverishment of the base reserve in the soil and, therefore, acidification.

Overall, the results found in the literature show that the effects of fire on soil pH are contradictory and may vary depending on the time elapsed since the event, the soil depth evaluated, the climatic conditions after burning, and the dynamics of cations in the soil profile. In this study, the absence of significant differences suggests a recovery of soil pH to levels like those of unburned areas, two years after the event.

Organic Material (OM)

In both burn conditions, OM content was observed to reduce as depth increased. However, the level of OM in unburned soil was found to reach the same level as OM in burned soil at a depth of 3-6 cm (Figure 4).

The lack of variation of OM levels in burned and unburned soils could be attributed to a variety of factors, such as fire type and intensity, soil moisture, soil type, and nature of the burned material (González-Pérez *et al*., 2004). According to Hernández-Valencia and López-Hernandez (2002), in savannas subjected to burning, the rapid combustion of organic material in combination with the dispersion of ash and volatilization of nutrients in gaseous form, reduces the effective contribution of OM and elements to the soil. In fact, from their research, they reported reductions in OM content as a consequence of burning. Unburned savanna plots presented higher concentrations of OM in comparison to burned plots (1.63% compared to 1.32%). (Neary and Leonard, 2020) mention that grassland fires, such as those that happen in our study area, tend to occur on a small scale due to the low fuel load and short burn duration, generally less than 15 seconds in any one area. As a result, grassland recovery tends to be rapid, so that the occurrence of fire is masked within a year by the regrowth of the vegetation. This view aligns with the proposition of Humphreys and Craig (1981), who suggest that the maximum temperatures reached during grassland fires are in the region of 70 °C. According to the temperature thresholds proposed by Neary *et al*. (2005), who classify OM as moderately sensitive, changes in its composition are observable when fire temperatures range between 100 and 400 degrees Celsius, °C.

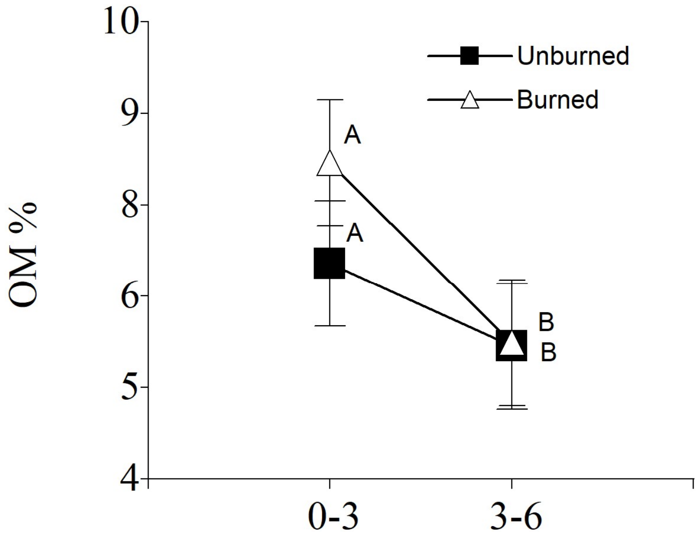

Figure 4. OM content (%) by sample depth, according to burn condition. Adjusted means and standard error were obtained through the DGC test ($p < 0.05$). Mean values that share the same letter indicate no significant difference.

On the other hand, differences in the concentration of OM at various depths were to be expected, since the topsoil layer is exposed to a greater input of OM as plant litter and organic waste are deposited. Furthermore, decomposition is faster as a result of optimal oxygen and temperature conditions, generating greater biological activity. These results coincide with the findings of Simon *et al*. (2016), whose evaluation eight days after a cornfield fire event found no differences in the levels of OM in burned and unburned soil, but did find significant variation by depth. Specifically, at a depth of 0-5 cm, they recorded a greater presence of OM in the soil, with a content of 34.44%, when compared to a depth of 5-10 cm, at which the OM content was 29.83%. By contrast, in the case of a prescribed grassland fire, an immediate increase in OM levels was observed in the burned plots. The highest concentration of OM, with an average of 4.59%, was found in the topsoil layer at a depth of 0-3 cm, compared with the layer at 3-5 cm deep, with an average of 2.82% OM (Hermitaño-Montalvo and Crisóstomo-Hilario, 2021[1]).

Phosphorus (P)

The pattern is similar to that found with OM. Content was found to be less at depths of 3-6 cm, irrespective of the type of plant cover. At this depth, P content is similar between the different types of cover (Figure 5).

No significant difference in the concentration of P in burned and unburned soil was found, independently of the type of cover. The lack of variation in concentrations of P under burn and non-burn conditions may be explained by the fact that the increase in available P in burned soil is usually associated with the presence of ash that is rich in P (Ogundele, Eludoyin, and Oladapo, 2011). However, since grassland fires tend to propagate rapidly with the wind, involve little biomass as combustible material, ash deposits in the soil resulting from the combustion of organic matter are minimal (Neary and Leonard, 2020).

Furthermore, although a temporary increase in P availability is observed, this enrichment tends to reduce rapidly due to processes such as chemisorption in acidic soils, in which P bonds with aluminum, iron, and manganese oxides (Certini, 2005), or P precipitation processes in which P bonds with soluble calcium in the soil (calcium concentration also tends to increase due to heating of the soil), forming calcium phosphates that are not available to plants (Badía *et al.*, 2014). Several studies have reported temporary increases in P concentrations after fire (Becerra, Rodríguez, Martínez, Vichot, and Sospedra, 2004; Trabaud, 1994). Alcañiz, Outeiro, Francos, Farguell, and Úbeda (2016) reported a significant increase in P concentrations immediately after a prescribed fire. Values for P increased from 78.2 to 86.3 mg kg^{-1}. However, a year after the event, a marked decrease in P concentrations, falling to 52.1 mg kg^{-1}, even lower than the level recorded prior to the fire. In the study conducted by Afif-Khouri, Oliverira-Prendes (2006), an extraordinary increase in P concentrations was observed immediately after a scrub

[1] Hermitaño-Montalvo, H. R., & Crisóstomo-Hilario, X. B. (2021). *Efecto de la quema de pastizales en las propiedades de los suelos en Huamancaca Chico, Huancayo,* 2020. Tesis de para obtener el grado en la Universidad Continental. Repositorio Institucional Universidad Continental.

burn (F = 116.457; $p < 0.001$). However, this increase in fertility turned out to be fleeting, as only three months after the event, the fertility that had emerged had completely disappeared. In research conducted by Hernández-Valencia and López-Hernandez (2002), savanna plots that had been subjected to fire were compared with unaffected plots, with an evaluation of P concentrations at a depth of 0-5 cm. The results revealed that unburned savanna plots showed the highest levels of P, with a concentration of 3.9 mg kg^{-1}, compared to burned plots with a concentration of 2.3 mg kg^{-1}. These results suggest that savanna burning leads to a fall in soil nutrients, specifically concentrations of P.

On the other hand, a higher concentration of P may predictably be found in the topsoil when compared with deeper layers. This is because P can enter the soil from various external sources, such as the decomposition of organic material, the application of fertilizers, and the incorporation of plant waste. These sources tend to be more concentrated in the topsoil, resulting in a higher level of P within this layer. According to Badía *et al*. (2014), available P enrichment is mainly limited to the upper 3 cm of the soil. In an evaluation carried out a week after the fire, three depths were compared: 0-1, 1-2, and 2-3 cm. Increases in P concentrations of 82.5, 32.6, and 2.1 mg kg^{-1}, respectively, were observed. In the study undertaken by Hermitaño-Montalvo and Crisóstomo-Hilario (2021[1]), which evaluated the effects of fire on grassland immediately after the fire, an increase in the amount of available P was observed at depths of 0-3 and 3-5 cm. At a depth of 0-3 cm, P concentrations increased from 45.6 to 114.5 mg kg^{-1}, while at a depth of 3-5 cm they increased from 31.4 to 37.9 mg kg^{-1}. In both studies, a fall in the increase of P with depth was evident.

Calcium (Ca), magnesium (Mg), and potassium (K). A similar pattern exists (significant effect of depth) in the variables analyzed. The highest values correspond to depths of 0-3 cm compared to depths of 3-6 cm, with concentrations of 3.2 versus 2.5 $cmol_c$ kg^{-1} for Ca; 1.4 versus 1.2 $cmol_c$ kg^{-1} for Mg and 0.5 compared to 0.3 $cmol_c$ kg^{-1} for K. Significant evidence for levels Ca, Mg y K under burn conditions was not detected (Figure 6). The inorganic cations of Ca, Mg, and K display a similar pattern to P as a consequence of fire, according to Alcañiz *et al*. (2016). The lack of change under burn and non-burn conditions that was observed in the research may be explained by the lack of changes in OM, since the availability of these nutrients in burned soils is linked to OM combustion and its incorporation into the soil in the form of ashes (Afif-Khouri, Oliverira-Prendes, 2006; Úbeda, Lorca, Outeiro, Bernia, and Castellnou, 2005). According to Neary and Leonard (2020), Ca, Mg, and K cations are considered to be relatively insensitive, requiring temperatures above 450 °C to produce significant changes in levels. As mentioned above, the temperatures usually achieved during grassland fires do not reach the necessary threshold to affect the cations. Similar results were obtained by various authors. For example, in the studies conducted by Becerra *et al*. (2004) and Alcañiz *et al*. (2016), no significant changes in the concentrations of Ca, Mg, and K were found one year after the fire event. In the evaluation carried out by Outeiro, Asperó, and

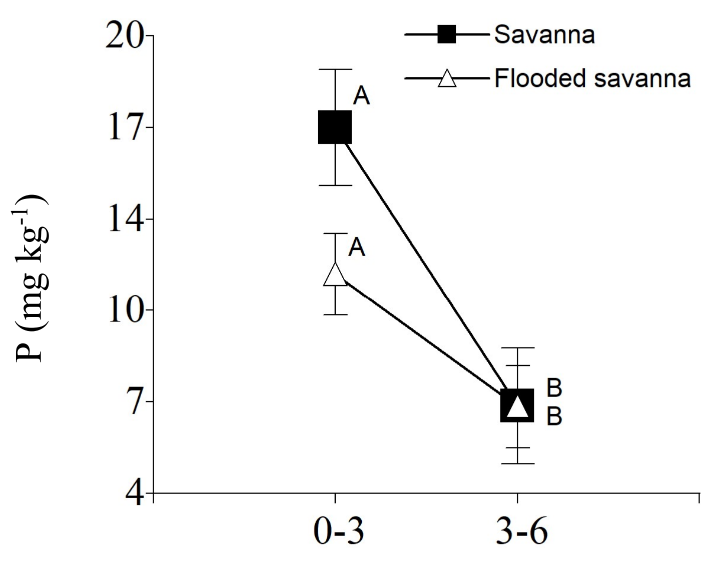

Figure 5. P content (mg kg^{-1}) by sample depth, according to the type of cover. Adjusted means and standard error were obtained through the DGC test ($p < 0.05$). Mean values that share the same letter indicate no significant difference.

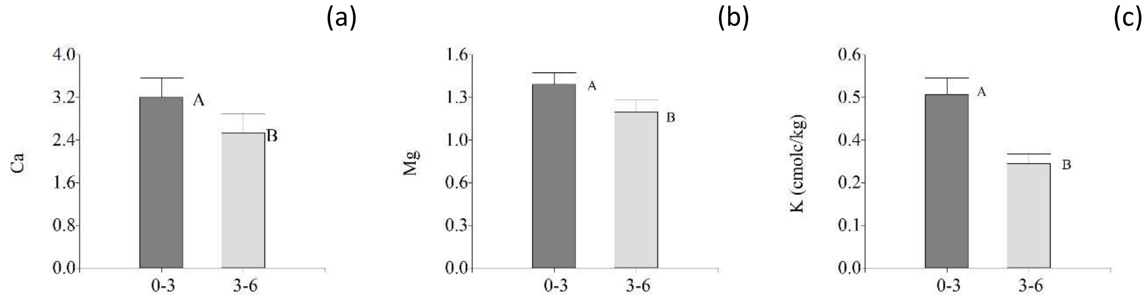

Figure 6. Content of a) Ca, (b) Mg, and (c) K ($cmol_c$ kg^{-1}) by sample depth. Adjusted means and standard error were obtained through the DGC test ($p < 0.05$). Mean values that share the same capital letter indicate no significant difference.

Úbeda (2008), three years after the fire event, concentrations of both Ca and Mg remained at similar levels to before the fire, while K concentrations were even lower than their initial level. On the other hand, in a study conducted by Badía *et al.* (2014), in a Rendzic Phaeozem soil type located in a pine forest, levels of Ca, Mg and K had increased significantly in the burned soils a week after the fire when compared to soils that were not affected by the fire, particularly in the topsoil at a depth of 0-1 cm. Higher values were recorded in burned soils compared to unburned soils for Ca (27.5 compared to 9.23 $cmol_c$ kg^{-1} for the control), Mg (6.06 compared to 0.98 $cmol_c$ kg^{-1} in the control), and K (3.54 compared to 0.62 $cmol_c$ kg^{-1} in the control). In a second evaluation carried out a year after the fire, there were marked changes in nutrient concentrations, most notably a drop in content levels in the burned soils compared to the initial evaluation. In the topsoil at a depth of 0-1 cm, values of 13.46 $cmol_c$ kg^{-1} were recorded for Ca (versus 4.88 $cmol_c$ kg^{-1} for the control), 1.98 $cmol_c$ kg^{-1} for Mg (versus 0.86 $cmol_c$ kg^{-1} in the control), and 0.56 $cmol_c$ kg^{-1} for K (versus 0.41 $cmol_c$ kg^{-1} in the control). Despite this decrease, there was still a significant increase in the concentrations of Ca, Mg, and K in the burned soils compared to the unaffected soils, a year after the fire event.

The higher concentrations of Ca, Mg, and K found in the 0-3 cm depth layer may be attributable to a greater input of OM and root activity in the topsoil, resulting in greater retention and recycling of these nutrients. Continuous decomposition of OM also gradually releases these nutrients into the topsoil. According to the evaluation by Simon *et al.* (2016), eight days after a cornfield fire, no interaction between the burn and depth was found for Ca, Mg, and K, while significant differences were found in relation to depth. The highest values for Ca, Mg, and K availability were recorded in the topsoil layer at 0-5 cm, with concentrations of 3.02, 1.01 and 0.21 $cmol_c$ kg^{-1} respectively, as compared to the subsurface layer at a depth of 5-10 cm, which showed values of 1.91, 0.67 and 0.16 $cmol_c$ kg^{-1}, respectively.

CONCLUSIONS

Two years after the fire, no significant effects on soil pH were observed in the humid Chaco savannas of Paraguay. Organic matter exhibited an interaction between burn condition and depth, indicating a possible vertical redistribution of carbon. Phosphorus was influenced by the interaction between the type of cover and depth, while calcium, magnesium, and potassium varied only with depth. Overall, the results suggest that the impact of burning on the chemical properties of the soil was limited and dependent on the evaluated variable, with no evidence of lasting effects. However, considering that the study is restricted to certain parameters and a two-year period following the fire, it is recommended to conduct complementary studies across different temporal and environmental scales to further explore the effects of fire on soil chemical variables.

ETHICS STATEMENT

Not applicable.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF SUPPORTING DATA

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

COMPETING INTERESTS

The authors declare that they have no competing interests.

FINANCING

The Centro Agronómico Tropical de Investigación y Enseñanza (CATIE) and the Forestry Unit, through the Canada Scholarship program, for the financial support provided through the scholarship.

AUTHORS' CONTRIBUTIONS

Conceptualization, A.B.C.D., W.J.W.R., and J.W.R.A.; methodology, A.B.C.D., J.W.R.A., and L.K.R.N.; software, L.K.R.N.; validation, A.B.C.D., W.J.W.R., J.W.R.A., and R.L.G.; formal analysis, A.B.C.D.; investigation, W.J.W.R., J.W.R.A., and R.L.G.; resources, J.W.R.A., R.L.G., and L.K.R.N.; data curation, A.B.C.D.; writing-original draft preparation, A.B.C.D., W.J.W.R., J.W.R.A., and R.L.G.; writing-review and editing, A.B.C.D., W.J.W.R., J.W.R.A., and R.L.G.; visualization, A.B.C.D., W.J.W.R., J.W.R.A., and R.L.G.; supervision, J.W.R.A., and R.L.G.; project administration, A.B.C.D., and J.W.R.A.; funding acquisition, W.J.W.R.

ACKNOWLEDGMENTS

The main author expresses her deep gratitude to the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE) and to the Forestry Unit through the Canada Scholarships for the scholarship granted, which made possible the development of his master's degree. To the Centro de Investigación del Chaco Americano, for providing the facilities for the execution of the field phase. To the Facultad de Ciencias Agrarias de la Universidad Nacional de Asunción, for allowing the laboratory analyses to be carried out in its facilities. To the Programa Universitario de Becas para la Investigación Andrés Borgognon Montero (PUBIABM) for financial support for the acquisition of the chemical reagents used in the analysis, through the various scholarships granted to undergraduate students. To Dr. Karim Musalem for his support and guidance during the research and fieldwork; to MSc. Christian Brenes Pérez for his collaboration in the elaboration of the maps; to MSc. Eduardo Brenes for his advice on the statistical analysis of the data, and to Forestry Engineer Pablo Godoy for his support during the field phase.

REFERENCES

Afif-Khouri, E., & Oliveira-Prendes, J. A. (2006). Efectos del fuego prescrito sobre matorral en las propiedades del suelo. *Investigación Agraria: Sistemas y Recursos Forestales, 15*(3), 262-270.

Agbeshie, A. A., Abugre, S., Atta-Darkwa, T., & Awuah, R. (2022). A review of the effects of forest fire on soil properties. *Journal of Forestry Research, 33,*1419-1441. https://doi.org/10.1007/s11676-022-01475-4

Alcañiz, M., Outeiro, L., Francos, M., Farguell, J., & Úbeda, X. (2016). Long-term dynamics of soil chemical properties after a prescribed fire in a Mediterranean forest (Montgrí Massif, Catalonia, Spain). *Science of the Total Environment, 572*, 1329-1335. https://doi.org/10.1016/j.scitotenv.2016.01.115

Alexis, M. A., Rasse, D. P., Knicker, H., Anquetil, C., & Rumpel, C. (2012). Evolution of soil organic matter after prescribed fire: A 20-year chronosequence. *Geoderma, 189-190*, 98-107. https://doi.org/10.1016/j.geoderma.2012.05.003

Andela, N., Morton, D. C, Giglio, L., Chen, Y., Van der Werf, G. R., Kasibhatla, P. S., ... & Randerson, J.T. (2017). A human-driven decline in global burned area. *Science, 356*(6345), 1356-1362. https://doi.org/10.1126/science.aal4108

Armenteras, D., Meza, M. C., González, T. M., Oliveras, I., Balch, J. K., & Retana, J. (2021). Fire threatens the diversity and structure of tropical gallery forests. *Ecosphere, 12*(1), 1-16. https://doi.org/10.1002/ecs2.3347

Badía, D., Martí, C., Aguirre, A. J., Aznar, J. M., González-Pérez, J. A., De la Rosa, J. M., ... & Echeverria, T. (2014). Wildfire effects on nutrients and organic carbon of a Rendzic Phaeozem in NE Spain: Changes at cm-scale topsoil. *Catena, 113*, 267-275. https://doi.org/10.1016/j.catena.2013.08.002

Barlow, J., Berenguer, E., Carmenta, R., & França, F. (2020). Clarifying Amazonia's burning crisis. *Global Change Biology, 26*(2), 319-321. https://doi.org/10.1111/gcb.14872

Baumann, M., Piquer-Rodríguez, M., Fehlenberg, V., Gavier-Pizarro, G., & Kuemmerle, T. (2016). Land-use competition in the South American Chaco. In. Land-use competition in the South American Chaco. En J. Niewöhner, A. Bruns, P. Hostert, T. Krueger, J. O. Nielsen, H. Haberl, C. Lauk, J. Lutz, & D. Müller (Eds.). *Land use competition: Ecological, economic and social perspectives* (pp. 215-229). Cham, Suiza: Springer International Publishing. https://doi.org/10.1007/978-3-319-33628-2_13

Becerra, L. M., Rodríguez, M. R., Martínez, I. C., Vichot, M. B., & Sospedra, R. S. (2004). Efectos de quemas prescritas sobre las propiedades del suelo en bosques de Pinus tropicalis Morelet, en Cuba. *Revista Chapingo: Serie Ciencias Forestales y Del Ambiente, 10*(1), 31-35.

Bento-Gonçalves, A., Vieira, A., Úbeda, X., & Martin, D. (2012). Fire and soils: Key concepts and recent advances. *Geoderma, 191*, 3-13. https://doi.org/10.1016/j.geoderma.2012.01.004

Bodi, M. B., Cerdà, A., Mataix-Solera, J., & Doerr, S. H. (2012). Efectos de los incendios forestales en la vegetación y el suelo en la cuenca mediterránea: Revisión bibliográfica. *Boletin de La Asociacion de Geografos Espanoles, 58*, 33-55. https://doi.org/10.21138/bage.2058

Bond, W. J., & Keeley, J. E. (2005). Fire as a global 'herbivore': the ecology and evolution of flammable ecosystems, *20*(7), 387-394. https://doi.org/10.1016/j.tree.2005.04.025

Bowman, D. M., Williamson, G. J., Abatzoglou, J. T., Kolden, C. A., Cochrane, M. A., & Smith, A. M. (2017). Human exposure and sensitivity to globally extreme wildfire events. *Nature Ecology and Evolution, 1*, 0058. https://doi.org/10.1038/s41559-016-0058

Budde, K. B., González-Martínez, S. C., Navascués, M., Burgarella, C., Mosca, E., Lorenzo, Z., ... & Heuertz, M. (2017). Increased fire frequency promotes stronger spatial genetic structure and natural selection at regional and local scales in Pinus halepensis Mill. *Annals of Botany*, *119*(6), 1-12. https://doi.org/10.1093/aob/mcw286

Caon, L., Vallejo, V. R., Coen, R. J., & Geissen, V. (2014). Effects of wildfire on soil nutrients in Mediterranean ecosystems. *Earth-Science Reviews*, 139, 47-58. https://doi.org/10.1016/j.earscirev.2014.09.001

Capulín-Grande, J., Mohedano-Caballero, L., & Razo-Zarate, R. (2010). Cambios en el suelo y vegetación de un bosque de pino afectado por incendio. *Terra Latinoamericana, 28*(1), 79-87.

Certini, G. (2005). Effects of fire on properties of forest soils: A review. *Oecologia, 143*(1), 1-10. https://doi.org/10.1007/s00442-004-1788-8

Chen, Y., Morton, D. C., Jin, Y., Collatz, G. J., Kasibhatla, P. S., van der Werf, G. R., ... & Randerson, J. T. (2013). Long-term trends and interannual variability of forest, savanna and agricultural fires in South America. *Carbon Management, 4*(6), 617-638. https://doi.org/10.4155/cmt.13.61

Cochrane, M. A., & Barber, C. P. (2009). Climate change, human land use and future fires in the Amazon. *Global Change Biology, 15*(3), 601-612. https://doi.org/10.1111/j.1365-2486.2008.01786.x

Coronel, G., Partén, M., Breuer, N., Celeste, A., Rejalaga, L., Monte-Domecq, F., & Nagy, G. J. (2021). Wildfires in Paraguay: Environmental and Humans Impacts. In W. Leal-Filho, A. F. Freitas-Setti, & U. Miranda-Azeiteiro (Eds.). *Sustainability in Natural Resources Management and Land Planning* (pp. 429–444). Cham, Suiza: Springer International Publishing.

Devisscher, T., Anderson, L. O., Aragão, L. E. O. C., Galván, L., & Malhi, Y. (2016). Increased wildfire risk driven by climate and development interactions in the Bolivian Chiquitania, Southern Amazonia. *PLoS One, 11*(9), 1-19. https://doi.org/10.1371/journal.pone.0161323

Dhungana, B. P., Thapa-Chhetri, V., Baniya, C. B., & Sharma, S. P. (2024). Low-Intensity Wildfire Alters Selected Soil Properties in the Tropical Shorea robusta Forest. *International Journal of Forestry Research, 2024*, 1-11. https://doi.org/10.1155/2024/4686760

Di Rienzo, J. A., Casanoves, F., Balzarini, M. G., González, L. A., Tablada, E. M., & Robledo, C. W. (2011). *InfoStat versión 2011*. *software estadistico*. Córdoba, Argentina: Grupo InfoStat.

Doerr, S. H., & Santín, C. (2016). Global trends in wildfire and its impacts: Perceptions versus realities in a changing world. *Philosophical Transactions of the Royal Society B: Biological Sciences, 371*(1696), 1-10. https://doi.org/10.1098/rstb.2015.0345

Drüke, M., Forkel, M., Von Bloh, W., Sakschewski, B., Cardoso, M., Bustamante, M., ... & Thonicke, K. (2019). Improving the LPJmL4-SPITFIRE vegetation-fire model for South America using satellite data. *Geoscientific Model Development, 12*(12), 5029-5054. https://doi.org/10.5194/gmd-12-5029-2019

Faria, S. R., De La Rosa, J. M., Knicker, H., González-Pérez, J. A., Villaverde, J., & Keizer, J. J. (2015). Wildfire-induced alterations of topsoil organic matter and their recovery in Mediterranean eucalypt stands detected with biogeochemical markers. *European Journal of Soil Science, 66*(4), 699-713. https://doi.org/10.1111/ejss.12254

Ferreira, A. J. D., Coelho, C. O. A., Ritsema, C. J., Boulet, A. K., & Keizer, J. J. (2008). Soil and water degradation processes in burned areas: Lessons learned from a nested approach. *Catena, 74*(3), 273-285. https://doi.org/10.1016/j.catena.2008.05.007

Giorgis, M. A., Zeballos, S. R., Carbone, L., Zimmermann, H., von Wehrden, H., Aguilar, R., ... & Jaureguiberry, P. (2021). A review of fire effects across South American ecosystems: the role of climate and time since fire. *Fire Ecology, 17*(21), 1-2. https://doi.org/10.1186/s42408-021-00107-2

Gonzáles, H., Ocaña, C. L., Cubas, J. A., Vega-Nieva, D. J., Ruíz, M., Santos, A., & Barboza, E. (2024). Impact of forest fire severity on soil physical and chemical properties in pine and scrub forests in high Andean zones of Peru. *Trees, Forests and People, 18*, 100659. https://doi.org/10.1016/j.tfp.2024.100659

González-Pérez, J. A., González-Vila, F. J., Almendros, G., & Knicker, H. (2004). The effect of fire on soil organic matter - A review. *Environment International, 30*(6), 855-870. https://doi.org/10.1016/j.envint.2004.02.003

Harrison, S. P., Prentice, I. C., Bloomfield, K. J., Dong, N., Forkel, M., Forrest, M., ... & Simpson, K. J. (2021). Understanding and modelling wildfire regimes: An ecological perspective. *Environmental Research Letters, 16*(12), 1-14. https://doi.org/10.1088/1748-9326/ac39be

Hernández-Valencia, I., & López-Hernández, D. (2002). Pérdida de nutrimentos por la quema de la vegetación en una sabana de Trachypogon. *Revista de Biologia Tropical, 50*(3-4), 1013-1019.

Humphreys, F. R., & Craig, F. G. (1981). Effects of fire on soil chemical, structural and hydrological properties. In A. M. Gill, R. H. Groves, & I. R. Noble (Eds.), *Fire and the Australian Biota* (pp. 177-200). Canberra, Australia: Australian Academy of Science.

Kernan, B. S., Cordero, W., Macedo-Sienra, A. M., & Villaba-Marín, J. (2010). *Report on biodiversity and tropical forests in Paraguay*. Asuncion, Paraguay: USAID. Consultado el 20 de febrero, 2024, desde https://www.usaid.gov/sites/default/files/documents/1862/paraguay_biodiversity_tropical_forest_report.pdf

Key, C. H., & Benson, N. C. (2006). Landscape assessment (LA): Sampling and analysis methods. En D. C. Lutes, R. E. Keane, J. F. Caratti, C. H. Key, N. C. Benson, & L. J. Gangi (Eds.). *FireMon: Fire effects monitoring and inventory system (General Technical Report RMRS-GTR-164* (pp. 1-55). Fort Collins, CO: USA: Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Kruck, W. (1994). *Proyecto Sistema Ambiental del Chaco: Inventario, evaluación y recomendaciones para la protección de los espacios naturales en la Región Occidental del Paraguay*. Asunción, Paraguay: GTZ / SEAM.

Laino, R., Musalem, K., Caballero-Gini, A., Bueno-Villafañe, D., & Chaparro, S. (2018). Uso de hábitat y comportamiento de Crax fasciolata en el Chaco Húmedo Paraguayo. *Hornero, 33*(2), 121-127.

Laino, R., Musalem, K., Laino, L. D., Caballero-Gini, A., Bueno-Villafañe, D., Aranda, L., ... & Irala, R. (2022). Islands of forests among savannas: Key elements for conservation and production in the Paraguayan humid Chaco. In K. Henle, C. A. Branquinho, & J. L. Brown (Eds.), Biodiversity islands: Strategies for conservation in human-dominated environments (pp. 185–205). Cham, Suiza: Springer International Publishing. https://doi.org/10.1007/978-3-030-92234-4_8

Laino, R., Musalem, K., Weiler, A., & González-Maya, J. F. (2021). Roaming among humans: noteworthy records of jaguar (Panthera onca) close to human settlements in the Paraguayan Humid Chaco. *Arxius de Miscellania Zoologica, 19*, 197-204. https://doi.org/10.32800/amz.2021.19.0197

Lizundia-Loiola, J., Pettinari, M. L., & Chuvieco, E. (2020). Temporal anomalies in burned area trends: Satellite estimations of the amazonian 2019 fire crisis. *Remote Sensing, 12*(1), 1-8. https://doi.org/10.3390/RS12010151

Mallik, A. U., & Gimingham, C. (1985). Ecological effects of heather burning. *Journal of Ecology, 73*, 633-644.

Martínez, S. J., De las Heras, I. J., & Herranz, S. J. M. (1991). Impacto ecológico de los incendios forestales. *Al-Basit: Revista de Estudios Albacetenses*, (29),105-117.

Mataix-Solera, J., Cerdà, A., Arcenegui, V., Jordán, A., & Zavala, L. M. (2011). Fire effects on soil aggregation: A review. *Earth-Science Reviews, 109*(1-2), 44-60. https://doi.org/10.1016/j.earscirev.2011.08.002

Mereles, F., Cartes, J. L., Clay, R. P., Cacciali, P., Paradeda, C., Rodas, O., & Yanosky, A. (2013). Análisis cualitativo para la definición de las ecorregiones de Paraguay Occidental. *Paraquaria Natural, 1*(2), 12-20.

Mereles, M. F., Céspedes, G., Cartes, J. L., Goerzen, R., Egea-Elsam, J. D., Rodríguez, L., ... & Cacciali, P. (2020). Biological Corridors as a Connectivity Tool in the Region of the Great American Chaco: Identification of Biodiversity Hotspots in the Ecoregions of the Paraguayan Chaco. *Research in Ecology, 2*(1), 20-26. https://doi.org/10.30564/re.v2i1.1324

Merenciano-González, A. M., Musálem, K., Laino, R., Benayas, J. R., Cruz-Alonso, V., El-Raiss-Cordero, Z., ... & Enciso, C. (2018). Ecosystem services in the Paraguayan Humid Chaco: challenges for ecosystem-based management. *Ecosistemas, 27*(2), 115-125. https://doi.org/10.7818/ECOS.1531

Minervini, M., Morrás, H., & Taboada, M. (2018). Efectos del fuego en la matriz del suelo. Consecuencias sobre las propiedades físicas y mineralógicas. *Ecología Austral, 28*, 12-27. https://doi.org/https://doi.org/10.25260/EA.18.28.1.0.127

Molinas-González, C. R., & Florentín, P. (2021). Incendios forestales en Paraguay: implicaciones para su prevención y manejo. *Investigaciones y Estudios UNA, 12*, 47-57. https://doi.org/10.47133/ieuna2115

Neary, D. G., & Leonard, J. M. (2020). Effects of fire on grassland soils and water: A review. En V. Missiakô Kindomihou (Ed.), *Grasses and Grassland Aspects*. London: IntechOpen. https://doi.org/10.5772/intechopen.90747

Neary, D. G., Ryan, K. C., Debano, L. F., Landsberg, J. D., & Brown, J. K. (2005). Introduction. In Wildland Fire in Ecosystems: effects of fire on soils and water (pp. 1-20). Ogden, Utah: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. http://digitalcommons.unl.edu/jfspsynthesishttp://digitalcommons.unl.edu/jfspsynthesis/18

Ogundele, A. T., Eludoyin, O. S., & Oladapo, O. S. (2011). Assessment of impacts of charcoal production on soil properties in the derived savanna , Oyo state , Nigeria. *Journal of Soil Science and Environmental Management, 2*(5), 142-146.

Ondik, M. M., Bennell, M., Davies, R. J. P., Ooi, M. K. J., & Muñoz-Rojas, M. (2022). Fire and land use impact soil properties in a Mediterranean dry sclerophyll woodland. *Journal of Environmental Management, 324*, 116245. https://doi.org/10.1016/j.jenvman.2022.116245

Orumaa, A., Agan, A., Anslan, S., Drenkhan, T., Drenkhan, R., Kauer, K., ... & Metslaid, M. (2022). Long-term effects of forest fires on fungal community and soil properties along a hemiboreal Scots pine forest fire chronosequence. *Science of the Total Environment, 851*, 158173. https://doi.org/10.1016/j.scitotenv.2022.158173

Outeiro, L., Asperó, F., & Úbeda, X. (2008). Geostatistical methods to study spatial variability of soil cations after a prescribed fire and rainfall. *Catena, 74*(3), 310-320. https://doi.org/10.1016/j.catena.2008.03.019

Pausas, J. G., & Keeley, J. E. (2009). A Burning Story : The Role of Fire in the History of Life. *Bioscience, 59*(7), 593-601. https://doi.org/10.1525/bio.2009.59.7.10

Pereira, P., Úbeda, X., Martin, D., Mataix-Solera, J., Cerdà, A., & Burguet, M. (2014). Wildfire effects on extractable elements in ash from a Pinus pinaster forest in Portugal. *Hydrological Processes, 28*(11), 3681-3690. https://doi.org/10.1002/hyp.9907

Rab, M. A. (1996). Soil physical and hydroligical properties following loggin and slash burning in the Eucalyptus regnans forest of southeastern Australia. *Forest Ecology and Management 84*, 159-176. https://doi.org/https://doi.org/10.1016/0378-1127(96)03740-1

Redin, M., Santos, G. D. F. D., Miguel, P., Denega, G. L., Lupatini, M., Doneda, A., & Souza, E. L. D. (2011). Impactos Da Queima Sobre Atributos Químicos, Físicos E Biológicos Do Solo. Ciência Florestal, 21(2), 381-392. https://periodicos.ufsm.bhttps//doi.org/10.5902/198050983243

Rheinheimer, D. D. S., Santos, J. C. P., Fernandes, V. B. B., Mafra, Á. L., & Almeida, J. A. (2003). Modificações nos atributos químicos de solo sob campo nativo submetido à queima Changes of chemical attributes of a soil after burning its native permanent pasture. *Ciência Rural, 33*(1), 49-55. http://www.scielo.br/pdf/%0D/cr/v33n1/14142.pdf

Saputra, A. D., Setiabudidaya, D., Setyawan, D., Khakim, M. Y. N., & Iskandar, I. (2017). Burnscar analysis using normalized burning ratio (NBR) index during 2015 Forest fire at merang-kepahyang peat forest, South Sumatra, Indonesia. *AIP Conference Proceedings, 1857*, 100001.

Shlisky, A., Waugh, J., Gonzalez, P., Gonzalez, M., Manta, M., Santoso, H., … Fulks, W. (2007). *Fire, ecosystems and people: Threats and strategies for global biodiversity conservation* (The Nature Conservancy Global Fire Initiative Technical Report No. 2, pp. 1-17). The Nature Conservancy.

Simon, C. A., Ronqui, M. B., Roque, C. G., Desenso, P. A. Z., Souza, M. A. V., Kühn, I. E., ... & Penha-Simon, C. (2016). Efeitos da Queima de Resíduos do Solo Sob Atributos Químicos de um Latossolo Vermelho Distrófico do Cerrado. *Nativa, 4*(4), 1-17.

Souza-Alonso, P., Saiz, G., García, R. A., Pauchard, A., Ferreira, A., & Merino, A. (2022). Post-fire ecological restoration in Latin American forest ecosystems: Insights and lessons from the last two decades. *Forest Ecology and Management, 509*, 120083. https://doi.org/10.1016/j.foreco.2022.120083

Trabaud, L. (1994). The effect of fire on nutrient losses and cycling in a Quercus coccifera garrigue (southern France). *Oecologia, 99*(3-4), 379-386. https://doi.org/10.1007/BF00627752

Úbeda, X., Lorca, M., Outeiro, L. R., Bernia, S., & Castellnou, M. (2005). Effects of prescribed fire on soil quality in Mediterranean grassland (Prades Mountains, north-east Spain). *International Journal of Wildland Fire, 14*(4), 379-384. https://doi.org/10.1071/WF05040

Vega, J. A., Fontúrbel, T., Merino, A., Fernández, C., Ferreiro, A., & Jiménez, E. (2013). Testing the ability of visual indicators of soil burn severity to reflect changes in soil chemical and microbial properties in pine forests and shrubland. *Plant and Soil, 369*, 73-91. https://doi.org/10.1007/s11104-012-1532-9

Vidal-Riveros, C., Souza-Alonso, P., Bravo, S., Laino, R., & Bieng, M. A. N. (2023). A review of wildfires effects across the Gran Chaco region. *Forest Ecology and Management, 549*, 121432. https://doi.org/10.1016/j.foreco.2023.121432

Yanosky, A., Weiler, A., Mereles, F., Helman, G., Campos, J. M., Batrina, L., & Arévalos, M. (2016). *Ecorregiones del Paraguay: Definición de prioridades en conservación (Versión I)*. Asunción Paraguay: Instituto LIFE.

Zavala, L. M., De Celis, R., & Jordán, A. (2014). How wildfires affect soil properties. A brief review. *Cuadernos de Investigación Geográfica, 40*(2), 311-332. https://doi.org/10.18172/cig.2522