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Impact of forest fire severity on soil physical and chemical properties in pine and scrub forests in high Andean zones of Peru

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ABSTRACT

Forest fires are the main threat to ecosystems and human life. The frequency, seasonality, extent and severity of fires affect ecosystems and the physical and chemical properties of the soil by direct (heating) and indirect (ash) effects. This could affect biodiversity and forest residency in the face of climate change. In this study, we evaluated the impact of fire severity on soil physical and chemical properties caused by forest fires in a high Andean area of Peru. For this purpose, the severity levels, the degree of hydrophobicity, and the physical and chemical properties of the soil were analyzed by sampling in affected areas (*Pinus radiata* D. Don plantation and shrubland) and unaffected areas. The results showed a very low severity in soil components, with a strong hydrophobicity, more persistent in the forest plantation area than in the shrubland. The physical properties of the soil did not show variations; however, in the Pinus plantations they showed variations in their chemical properties such as pH, electrical conductivity, organic matter, nitrogen and cation exchange capacity compared to areas not affected by the forest fires. Likewise, in the study area an adequate regeneration process was evidenced; in fact, it is important to apply mechanisms to accelerate the restoration of the vegetation cover and the physical and chemical quality of the vegetation.

1. Introduction

Human- and climate-induced wildfires are becoming more frequent globally and in recent decades have increased considerably (Marfella et al., 2023; Mehmood et al., 2024a). They can affect ecosystem service functions causing substantial and significant losses (Adhikari and Hartemink, 2016; Bousfield et al., 2023; Pereira et al., 2018; Van et al., 2021). In addition, of the various forests changing the structure (Peña-Molina et al., 2024; Ross et al., 2024; Stambaugh et al., 2024) and the physical, chemical and biological attributes of soils in different parts of the world (Agbeshie et al., 2022; Barboza et al., 2020). Between 2001 and 2019 fires increased significantly in South America (Barboza et al., 2020; Lizundia-Loiola et al., 2020). In Peru during 2016, 281 forest fires occurred and in the month of November alone 93 fires were reported, affecting various high Andean areas (Manríquez, 2019). For 2018 and 2019, fires increased to 10,000 in the Peruvian Andes, affecting approximately 367,000 ha of vegetation cover (SERFOR, 2019).

In the soil, forest fires cause significant impacts such as increased acidity level, structural integrity, water retention capacity, low nutrient circulation and soil biological activity (Joos and De Tender, 2022; Montico et al., 2023; Puga et al., 2024; Rosero, 2013a). For Minervini et al. (2018) soil structure is the physical property most affected by fire, presenting a significant increase in hydrophobicity. These effects, in turn, alter soil water-related properties, reducing infiltration capacity

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and increasing erosion risks (Bodí et al. 2012; Arreaga, 2023). In this sense, Benito et al. (2014) indicate that the impact of fire on susceptibility to erosion varies according to severity levels, the greater the severity the greater the soil erodibility (Añó et al. 2022). In all cases, the period of reestablishment of initial soil conditions can be very long, or indeed changes become permanent (Agbeshie et al., 2022; Baade et al., 2024; Brevik et al., 2022; Duivenvoorden et al., 2024; Fernández, 2023; Francos et al., 2018; Lal, 2015; Marfella et al., 2023; Yang et al., 2022). However, the extent of soil disturbance by fire depends largely on fire intensity, duration and recurrence, fuel load and soil characteristics (Agbeshie et al., 2022).

The response of vegetation to fire depends mainly on the natural regeneration mechanisms of the species themselves, which will be conditioned by the age of the plants, weather conditions, severity and recurrence of fires (Keeley et al., 2008; Vega et al., 2013). In coniferous species, generally after fire they present a higher mortality, with a slower regeneration, than deciduous and sclerophyllous species such as eucalyptus, which have a higher regrowth speed and ground cover

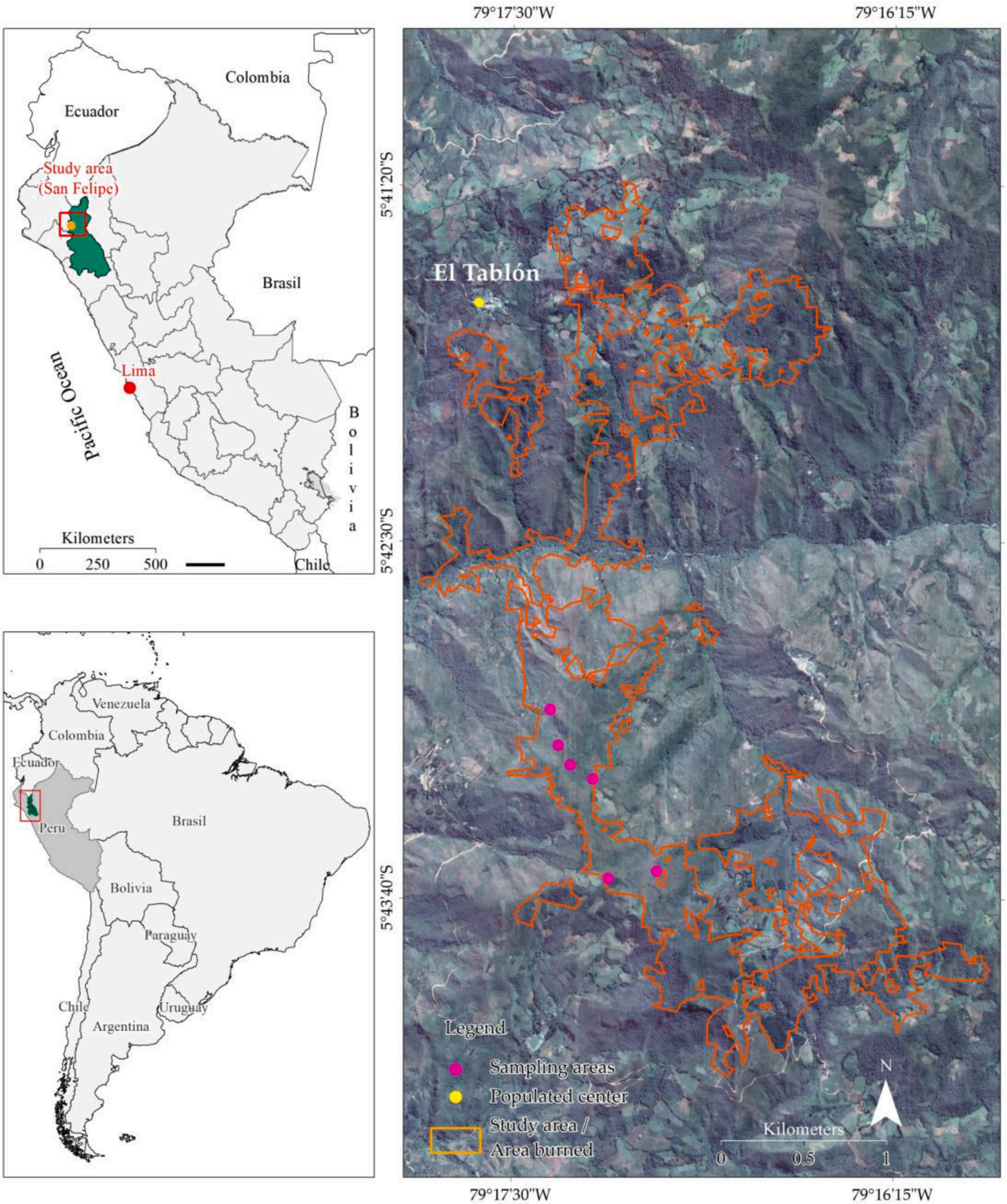

Fig. 1. Location of the burned area in the El Tablón village, San Felipe district, Cajamarca department, Peru.

(Enayetullah et al., 2022; Mayer et al., 2020; Vallejo et al., 2012; Vasques et al., 2023). In shrublands, vegetation recovery could be very rapid, but will be conditional on the favorable post-fire precipitation regime (Liu et al., 2022; Rodrigues et al., 2024; Vega et al., 2013).

Many studies have evaluated the long-term impact of forest fires on the physical, chemical and biological properties of forest soils, evidencing the processes of nitrogen mineralization and nitrification in burned areas (Marfella et al., 2024; Úbeda et al., 2005), significant long-term increases in total phosphorus in the soil after a fire (Johnson et al., 2005) and short-term loss of potassium (Alcañiz et al., 2016; Úbeda et al., 2005). At the physical level, soil fertility is reduced by increasing the pH and electrical conductivity (Alcañiz et al., 2016). Others have focused on understanding fungal communities (Yang et al., 2024) and evaluating soil ecosystem services after forest fires (Francos et al., 2024; Manning et al., 2018). On the other hand, the application of remote sensing techniques has demonstrated its potential to assess the impacts of forest fires in different ecosystems and scales (Manning et al., 2018; Mehmood et al., 2024a, 2024b; Shahzad et al., 2024).

Cajamarca is a department where fires have become a local problem, generating economic, social and environmental impacts. In 2016, 23 forest fires were recorded, affecting 27,561 ha of vegetation cover, representing 44.6 % of the total cover loss in the country (SERFOR, 2018). By 2020, the figure increased, registering 94 forest fire emergencies between the months of July and November (CENEPRED, 2020). Reports on fire severity and identification of soils affected by fires are limited to help make better decisions on the management and management of affected areas. Therefore, the objective of the research focused on evaluating the severity and impact of forest fires on the physical and chemical properties of soil in pine forests and shrublands, in order to generate baseline information for governments and decision makers in the design and implementation of actions for the recovery of areas affected by forest fires.

2. Materials and methods

2.1. Study area

The study area (5°42′53.80″ S and 79°17′15.56″ W) was located in the El Tablón hamlet of the San Felipe district in the Jaén province, Cajamarca (Peru) (Fig. 1). The San Felipe district is located at an altitude of 1850 m a.s.l., has an approximate area of 255.49 km^2 and a population of 4693 inhabitants (INEI, 2017). The topography is characterized by being rugged, with slopes that range from moderate, semi-flat and strongly inclined with variations and undulations (GRC, 2011). The physiography varies from steep to very steep with orientations from north to south. The climate has two well-marked seasons during the year, the wet season from November to May and the dry season from June to November. The average annual rainfall for 2020 was 333.5 mm and the maximum temperature was 31.8 °C and the minimum was 21.5 °C (SENAMHI El Limón meteorological station, https://www.senamhi.gob.pe/servicios/?p=estaciones).

The area has typical characteristics of the jungle brow region, with a variety of vegetation that includes shrubs, trees, and herbaceous species. The soils are Leptosol-Regosol with a moderately coarse texture and low fertility (GRC, 2011). However, on November 1 and 2, 2020, a forest fire occurred in the study area, affecting the vegetation cover with an area of

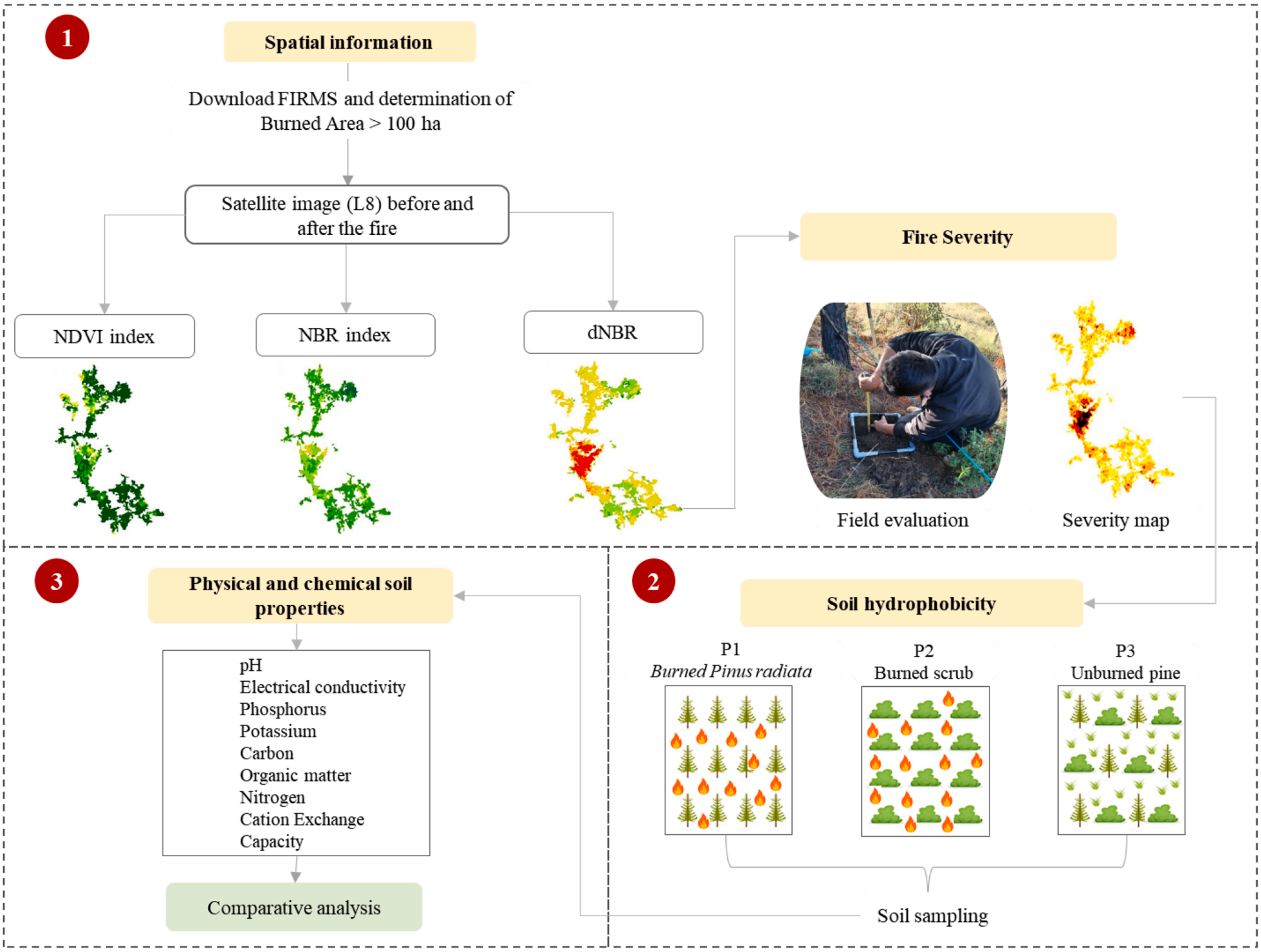

Fig. 2. Process for assessing the severity of forest fires on soil physical and chemical properties in pine and scrub forests.

approximately 171 ha.

Fig. 2 shows the procedure to evaluate the severity of forest fires on the physical and chemical properties of the soil in pine and scrub forests. The first step was to acquire information to select fires larger than 100 ha and to determine fire severity in the field and by remote sensing. Then to analyze hydrophibosity in the field and finally to analyze the impact of the fires on the physical and chemical properties of the soil in three different types of plots.

2.2. Spatial information

The spatial information consisted of fire hotspots downloaded from the Fire Information for Resource Management System (FIRMS) platform (https://firms.modaps.eosdis.nasa.gov) and the Geoserver of the Ministry of Environment (https://geoservidorperu.minam.gob.pe/geocfoi/minam/downloaddata/index). This data was processed using ArcGIS v. 10.6 to generate Clusters of Fire Hotspots (CFC), which helped identify potential fires. Two criteria were applied: (i) burned area greater than 100 ha and (ii) heat intensity with Fire Radiative Power (FRP) $\geq$ 100 MW/km^2 within Jaén province. Field verification included identifying burned and unburned areas, mapping the burned area's perimeter, and noting tree presence.

2.3. Determination of fire severity

Fire severity refers to the loss or change of organic matter above and below ground, influenced by vegetation characteristics, terrain slope, and climate (Keeley, 2009; Parks et al., 2018). The first step was to download images from the Landsat 8 satellite from the Earth Explorer (https://earthexplorer.usgs.gov/) platform and then process it using Geographic Information Systems (GIS) tools and remote sensing to analyze pre, during, and post-fire conditions, specifically: (i) analyzing photosynthetic activity using the Normalized Difference Vegetation Index (NDVI, Eq. (1)) (Duncan et al., 1993; Rouse et al., 1974) and (ii) determining fire severity levels through the Normalized Burn Ratio (NBR, Eq. (2)) (Key and Benson, 1999), which identifies areas with significant vegetation loss (Dos Santos et al., 2020; Navazo et al., 2016). Additionally, we calculated the bitemporal difference of preprocessed NBR images to obtain the dNBR (Eq. (3)) (Key and Benson, 2006; Roy et al., 2006). The whole procedure was performed with ArcGIS v. 10.6 software.

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)} \tag{1}$$

$$NBR = \frac{(NIR - SWIR)}{(NIR + SWIR)} \tag{2}$$

$$dNBR = NBR_{pre} - \quad NBR_{post} \tag{3}$$

Where:

Red: band 4, NIR: band 5 y SWIR: band 7 from OLI sensor, Landsat 8.

The second step was to evaluate fire severity in the field by identifying and selecting 10 plots. Two plots with a 9 m radius and eight plots with a 15 m radius were identified (Morfin-Ríos et al., 2012). Then, in each plot three transects were established, where in each of the transects three 30 x 30 cm square sampling subsites were identified as indicated in Fig. 3 and as proposed by Silva-Cardoza et al. (2021).

The layout of each sampling subsite was done at 3 and 5 m in each of the transects, depending on the radius of the plot. Systematic cover measurements were made and included: Herbaceous cover (C.HER), Ferment cover: referring to the visual cover of the fermentation layer (C.FER), Litter cover (C.HOJ), Bare soil cover (C.SUE), Cover of exposed rock (C.ROE) and Cover of mineral ash (C.CEN). The sum total of these categories equaled 100 % (Silva-Cardoza et al., 2021). The application of Eq. (4), allowed determining the severity levels for each evaluated plot of the edaphological component was developed considering five levels: very low, low, moderate, high and very high (Vega et al., 2013), resulting from the average of the weighted coverage of each of these levels (1–5), scaled from 1 to 100 to homogenize with the vegetation severity units (%) according to Eq. (4) proposed by Silva-Cardoza et al. (2021).

$$PSU_j = \frac{\sum_i CNS1_i * 1 + \ CNS2_i * 2 + \ CNS3_i * 3 + \ CNS4_i * 4 + \ CNS5_i * 5}{100} * 20 \tag{4}$$

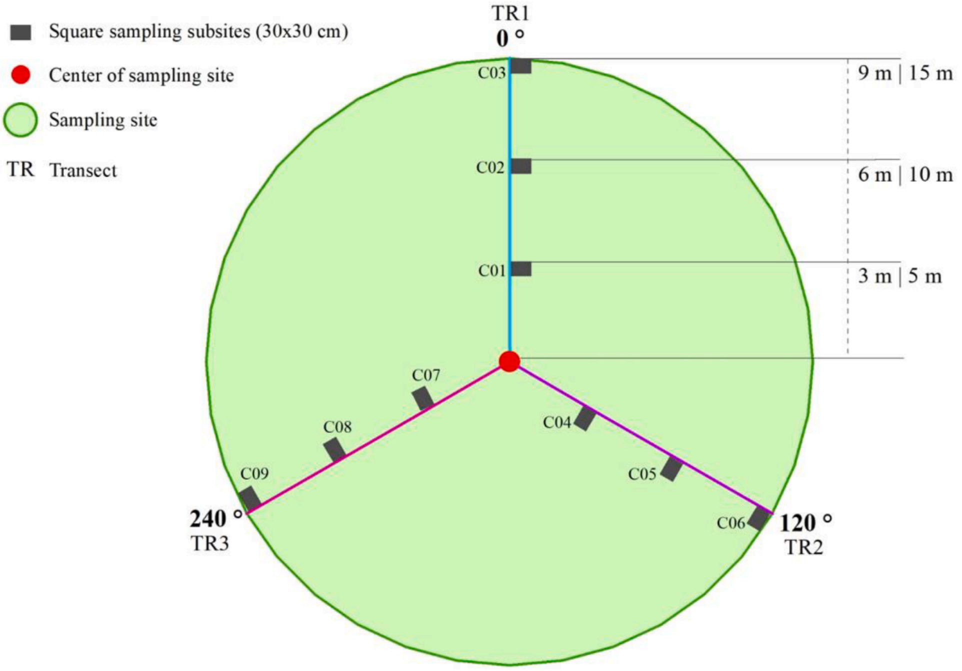

Fig. 3. Arrangement of the square sampling sub-sites at each site in the edaphological component in 9 and 15 m plots (Silva-Cardoza et al., 2021).

Where:

PSUj: Percentage of severity in the soil of the j-th sampling square subsite (%),

CNS1: Coverage of severity level 1 (very low) of the $j-th$ subsite

CNS2: Coverage of severity level 2 (low)

CNS3: Severity level 3 coverage (medium)

CNS4: Coverage of severity level 4 (high)

CNS5: Severity level 5 coverage (extreme)

2.4. Determination of soil hydrophobicity

The water repellency of soils reduces the affinity of soils for water and may have implications for slope hydrology and soil erosion (Doerr et al., 1998; Tinebra et al., 2019). The first step was to identify three plots, the first (P1) and second plot (P2) were established within plantations of *Pinus radiata* D.Don and shrubland, respectively, affected by the wildfire: The plot (P3) was located on soil not affected by the wildfire and was evaluated as a control for comparison. The second step was to determine the hydrophobicity of the soil by applying the Water Drop Penetration Time (WDPT) technique (Agbeshie et al., 2022), which consisted of using a graduated micropipette, where 10 drops of distilled water were applied on the surface of the mineral soil at 1 cm depth of the soil, it was necessary to record the time required for complete infiltration of each drop into the soil in the three plots evaluated (Gil et al. 2010). The results were classified into five repellency classes, ranging from hydrophilic to extremely repellent as indicated in Table 1 (Bisdom et al. 1993).

2.5. Impact of fire on physical and chemical soil properties

Wildfires affect the physicochemical quality of soils and decrease the nutrient pool (Agbeshie et al., 2022; Pellegrini et al., 2018). After fire some properties may be higher than the unburned area. Whereas, low fire intensity may cause soil organic matter and leaf litter to burn, increasing nutrient availability (Elakiya et al., 2023).

Sampling points were selected based on visual observation of the areas, and areas with medium to high burn severity and areas not affected by fires were selected (Dhungana et al., 2024). Sampling was carried out at a depth of 0 cm to 25 cm for each of the three plots evaluated (Table 2). This depth selection considered the representativeness of the soil that was most affected by the fire (Samburova et al., 2023; Tinoco et al., 2006). For sample collection, six 10 m x 10 m plots were set up, considering two plots within a P. radiata plantation affected by the fire (P1), two plots within affected scrubland (P2), and two plots in unaffected *P. radiata* soil (P3) (Table 2). In each plot, a collection consisting of three subsamples was carried out, distributed randomly, making a total of twelve subsamples of affected soil and six samples obtained from unaffected soil. Subsequently, the samples were dried under shade, sieved and homogenized separately, in order to obtain a total of 1 kg of sample per type of affected vegetation (INTAGRI, 2021). The three samples were analyzed in the Soil and Water Research Laboratory of the Toribio Rodríguez National University of Mendoza (Curatola et al., 2023).

The data were analyzed using descriptive statistics through graphical representation. This is due to the fact that there was one data for each plot analyzed.

Table 1
Water repellency classes and ranges according to the WDPT method.

Class	Time (s)	Grade
0	0–5s	Hydrophilic
1	5s-60s	Slightly repellent
2	60s-600s	Strongly repellent
3	600s-3600s	Severely repellent
4	>6h	Extremely repellent

Source: Bisdom et al. (1993).

Table 2
Distribution of plots by vegetation type.

Plot	Type of vegetation
P1	Burned pine (*Pinus radiata*) plantation
P2	Burned scrub
P3	Unburned pine (*Pinus radiata* D.Don) plantation

3. Results

3.1. Wildfire severity through satellite imagery

In the study area, prior to the wildfire, the vegetation exhibited predominantly very high photosynthetic activity (64.12 %), followed by high (24.28 %) and medium-high (7.25 %) levels (Fig. 4a). During the wildfire, photosynthetic activity decreased significantly from very high (37.84 %) and medium-high (4.45 %) to predominantly very low (11.41 %), low (3.21 %), and medium (5.24 %) levels, mainly concentrated in the northern and central parts of the study area (Fig. 4b). Subsequently, after the wildfire, vegetation photosynthetic activity rebounded with increases in medium-high (3.05 %), high (17.53 %), and very high (78.92 %) levels (Fig. 4c).

Before the wildfire, based on NBR calculations, 96.30 % (334.04 ha) of the surface area exhibited positive values indicating varying degrees of vegetation density (Fig. 4d). Post-wildfire, the area with positive NBR values reduced to 27.62 % of the total surface area, equivalent to 95.8 ha, with 72.38 % of the area showing negative NBR values (251.04 ha) (Fig. 4e). Severity levels are depicted in Fig. 4f, with low severity covering 59.77 %, medium severity 30.53 %, high severity 6.88 %, and extreme severity 2.81 % of the affected area.

3.2. Forest fire severity by field work

Fig. 5 shows the results of the wildfire severity assessment in the 10 selected plots. Measurements were made in each of the plots (Fig. 5a–c). Of the total plots evaluated, the results reported that 66.30 % presented levels considered as "very low severity", followed by 29.30 % showing levels of "low severity" severity and only 4.40 % were found in levels of "high severity" (Fig. 5d).

3.3. Determination of soil repellency

Penetration times varied depending on the evaluation plots (P1, P2 and P3). In plot P1 (burned area), at surface soil the infiltration time was below 10 s and at 1 cm depth it was close to 1000s. In P2, at surface soil the time was 6 s while at 1 cm depth it exceeded 1000s. In P3 (unburned area) the penetration time was minimum 2 s at surface soil and less than 10 s at 1 cm depth as shown in Fig. 6.

Soil repellency levels were evaluated at soil surface level and at 1 cm depth. Plots P1 and P2 at soil surface level reported class 0 (0–5 s) with hydrophilic grade (H) and repellency of 80 and 90 %, while for P3 its repellency was 100 %. On the other hand, repellency at 1 cm depth, P1 and P2 reported class 2 (60s–600 s) with strongly repellent grade (FR) and repellency percentages of 60 and 80 %, respectively. However, P2 reported a class 0, grade H and repellency percentage of 80 % as indicated in Table 3.

3.4. Physicochemical properties of the soil

Table 4 presents the results of the physical and chemical properties of the soil sampled in the three selected plots. P1, which was represented by a burned plot of *Pinus radiata* forest, reported higher levels of phosphorus (33.18 ppm), carbon (3.73 %), organic matter (6.44 %) and nitrogen (0.32 %) compared to P2. P2 outperformed P1 in the parameters

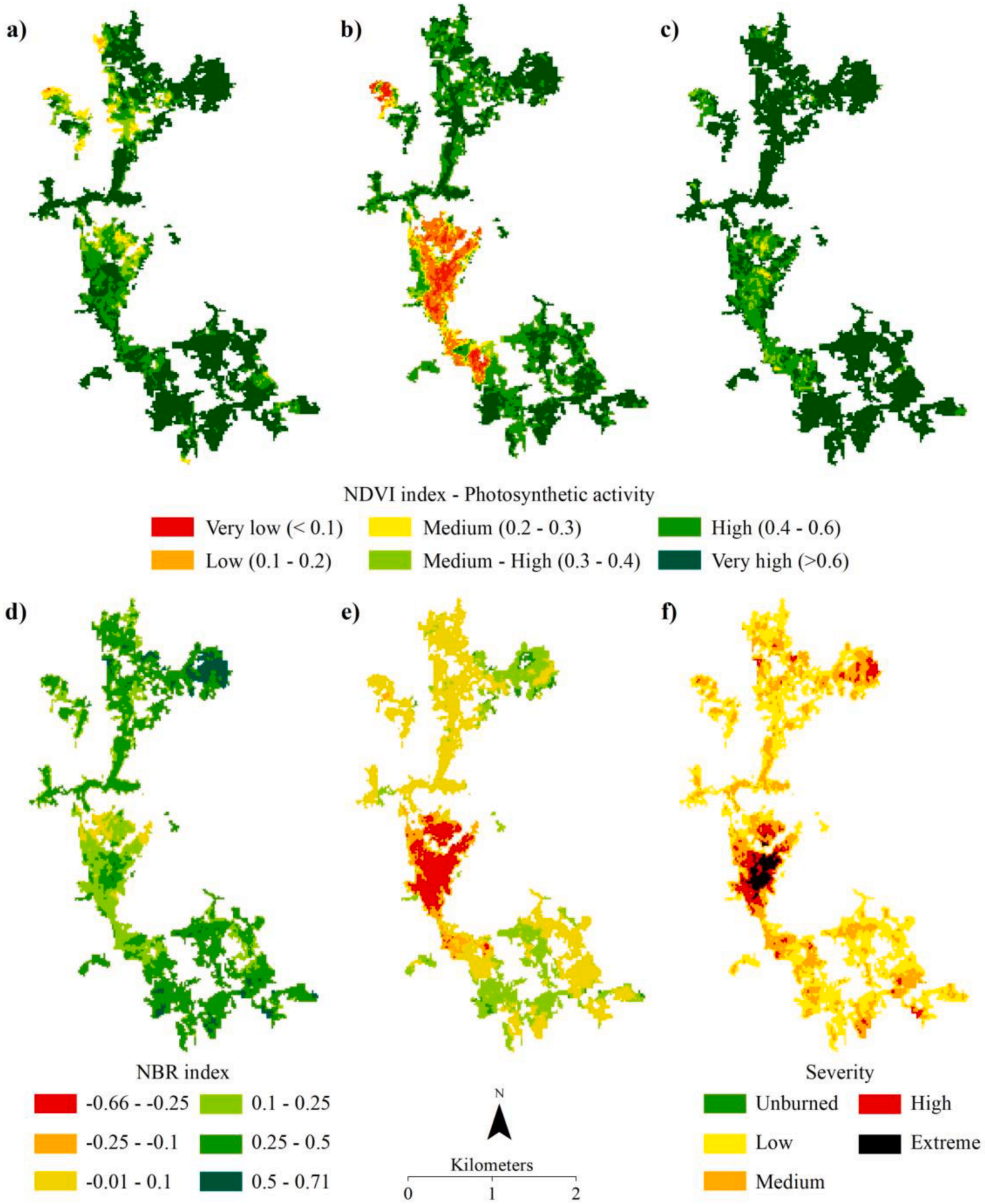

Fig. 4. Determination of vegetation photosynthetic activity: (a) Pre-fire NDVI (August 5, 2020), (b) During-fire NDVI (October 1, 2020), (c) Post-fire NDVI (December 1, 2020), and (d) Wildfire severity levels:(d) NBR before the fire,(e) NBR after the fire, and (f) Wildfire severity levels.

pH (6.62), potassium (502.1 ppm) and cation exchange capacity (14.40 Meq/100 g). However, at the level of P3 (unburned plot of *Pinus radiat*a forests) it reported higher values of potassium (255.03 ppm), carbon (4.27%), organic matter (7.36%) and nitrogen (0.37%) than P1 and P2 as shown in Table 4.

Fig. 7 shows the impact of fire on soil physical and chemical properties in the three plots evaluated. In P1, fire resulted in an increase in phosphorus and potassium, but also reduced organic matter and increased soil acidity, which could negatively affect nutrient availability in the long term. P2 showed an increase in electrical conductivity and higher cation exchange capacity, although combustion significantly decreased phosphorus and nitrogen levels, suggesting a reduction in soil fertility. On the other hand, P3, not having been affected by fire, showed higher levels of carbon and organic matter, indicating a more stable and fertile soil structure.

4. Discussion

The NDVI, NBR and dNBR spectral indices have been widely used for the detection of burned areas, fire severity and post-fire vegetation changes in different areas of the world. In this context, NDVI, NBR and dNBR allowed to complement the field assessments, showing the compatibility of the study results (Barboza et al., 2020; Demir, 2023; Demir and Dursun, 2023, 2024; Demir and Başayiğit, 2024). The maps

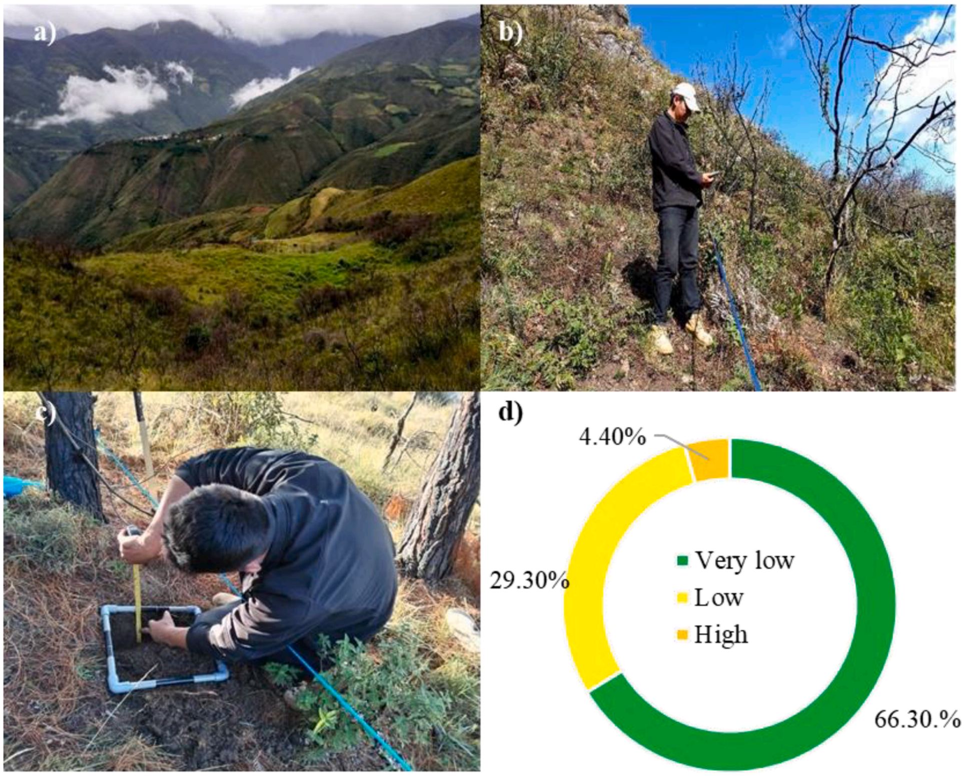

Fig. 5. Wildfire severity levels, (a) panoramic view of the burned plot, (b) measurement of transects, (c) severity assessment in 30 x 30 cm subsites and (d) results of severity levels in the 10 plots.

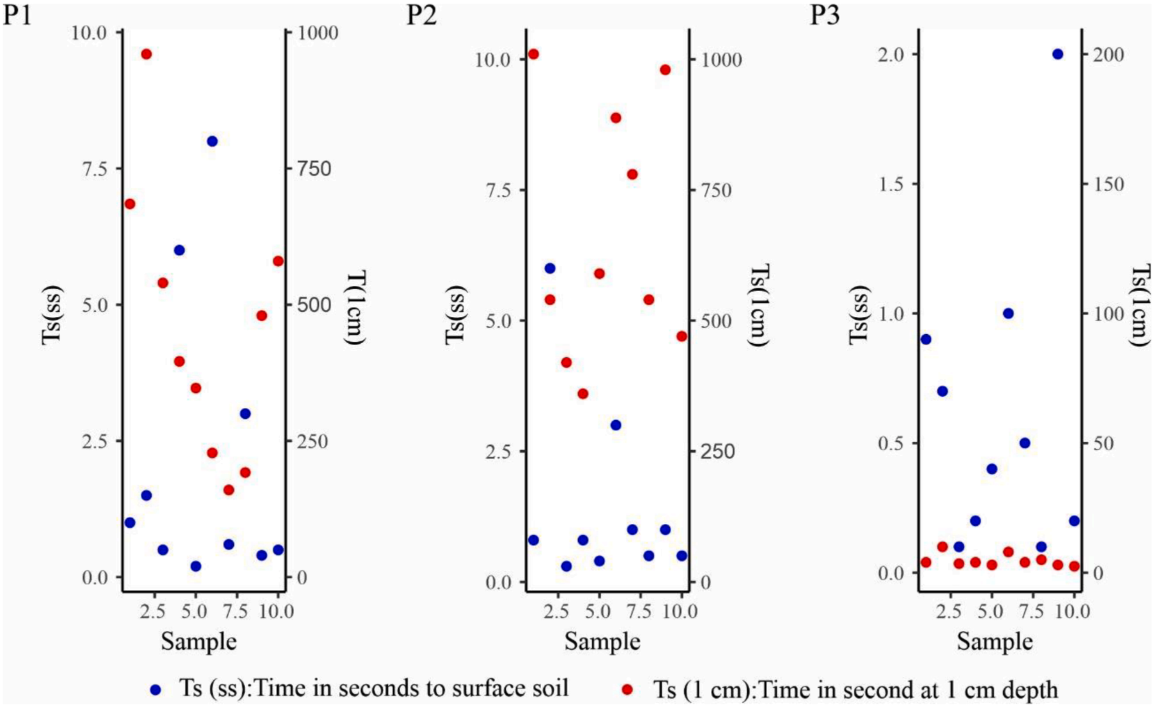

Fig. 6. Distribution of WDPT method by each of the selected plots.

generated from each index provide visual/spectral information on the distribution of NDVI and dNBR levels before and after the fire, allowing to assess vegetation health and fire severity levels (Demir and Başayiğit, 2024; Guo et al., 2024; Hamilton et al., 2023).

Forest fires are historically a major threat to forest species; However, little is known about the effects of forest fires on their soil properties (Xue et al., 2014), but in general, recently burned soils are more prone to erosion than unburned soils, as they tend to be more hydrophobic, less structured and less protected by an organic layer (Fernández-García et al., 2021). According to Debano (1991), fire affects the nutrient cycle

Table 3
WDPT water repellency rating of the evaluated plots.

Plots	A Soil surface			At 1 cm of depth		
	Class	Grade	%	Class	Grade	%
P1	0	H	80	2	FR	80
P2	0	H	90	2	FR	60
P3	0	H	100	0	H	80

Table 4
Soil test results: burned plots P1 and P2, and unburned plot P3.

Physicochemical properties evaluated	**P1**	**P2**	**P3**
pH	5.50	6.62	5.84
Electrical conductivity (dS/m)	0.08	0.15	0.10
Phosphorus (ppm)	33.18	11.43	22.41
Potassium (ppm)	491.36	502.1	255.03
Carbon (%)	3.73	3.20	4.27
Organic matter (%)	6.44	5.52	7.36
Nitrogen (%)	0.32	0.28	0.37
Cation Exchange Capacity (Meq/100 g)	11.20	14.40	14.40

and the physical, chemical and biological properties of soils occupied by mountain forests. In this regard Agbeshie et al. (2022) indicated that fire leads to total or partial burning of organic matter and ash deposition on the soil surface. Therefore, the mixture of ash and partially burned organic materials significantly alters soil chemistry. On the other hand, the various levels of severity are found depending on the affected species, as well as the areas affected by each level of damage (Díaz-Delgado and Xavier, 1999). The severity of the fire was not homogeneous in the study area, which may be due to areas more exposed to desiccant radiation from the fuel, as well as the type of vegetation cover (Kitzberger and Grosfeld, 2017; Fernández-García et al. 2019). 66.3 % of the soil component with *Pinus radiata* D. Don, presented "very low" severity, coinciding with the studies reported by Vega et al. (2013) and Parsons et al. (2022) who indicated that low severity levels are related to the fire partially consuming the superficial organic layers (litter stratum) and the mulch only partially consumed (Fernández et al., 2022).

Severity may be associated due to the reduction in fuel loads (Kitzberger and Grosfeld, 2017). On the other hand, 29.30 % corresponds to medium severity, at this level the soil presented black tones due to the consumption of the vegetal cover of the soil and the presence of charcoal from the superficial fine roots that were partially consumed. For Parsons et al. (2022) and Fernández (2023) consider that the structure of the soil and roots are little altered at this level of severity. For its part, 4.40 % of the evaluated plots presented a high level of severity of burn scars on trunks and branches, with corking greater than half of the total tree height and the crown was partially or totally affected (Flores-Rodríguez et al., 2021).

Forest fires increase the susceptibility to soil erosion and affect the physicochemical properties of the soil (Benito et al. 2014). Also, variables such as flame length, caloric intensity and the scorch effect are considered, along with environmental factors such as slope, exposure, physical-chemical and structural characteristics of the fuel vegetation that make it dependent on the level of severity (Castillo et al. 2019). The repellency percentages at 1 cm depth are between 60 and 80 %, which corresponds to the second class of strongly repellent grade, so it is likely that the fire was of very high intensity, and this may have caused the formation of a water-repellent layer in the first few centimeters of the mineral soil, reducing infiltration capacity and increasing soil erosion and runoff (Xofis et al., 2023). It agrees with Ulloa et al. (2014) who identified higher levels of persistence in water repellency four months after the fire. The appearance of water repellency is attributed to the incorporation of plant biomass into the soil as the vegetation recovers after the occurrence of the forest fire (Bodí et al., 2012)

In this study, the hydrophilic degree ranged from 80 to 100 % of the surface soil samples, covering both the unaffected areas and those affected by the fire, without showing significant differences between the two. For (Mataix-Solera and Guerrero, 2007), this phenomenon is strongly influenced by the characteristics and properties of the soil, which can determine its evolution during the fire. Hydrophobicity is a characteristic that frequently emerges after fires, although its presence is also linked to various types of soils in different regions and climates of the world (Jordán et al. 2010); in hydrophobic soils, the infiltration process can experience a delay or even being prevented, the speed at which water completely infiltrates the soil will depend on the durability of this hydrophobicity (Bodí et al. 2012). For Agbeshie et al. (2022) increased hydrophobicity can make the soil less able to absorb water and more prone to erosion. According to the data obtained, it can be inferred that the soil affected by the fire in the study areas reached a temperature below 270 °C, since according to De Bano (2000), the formation of a water-repellent layer is intensified. at temperatures below this level; In contrast, temperatures close to 400 °C cause the decomposition of most hydrophobic compounds (Badía and Martí, 2003). The soil's ability to repel water, affected by fire, influences the generation of runoff flows and erosion in burned areas. Low severity fires barely affect soil erosion, but high severity fires significantly increase it (Benito et al. 2014).

The soil analysis indicated a decrease in pH of 0.34 units between the affected area (P1) and the unaffected area (P3). According to the literature, the average pH of the area affected by fire is lower than that of the unaffected area (Dhungana et al., 2024). Alva and Manosalva (2019)

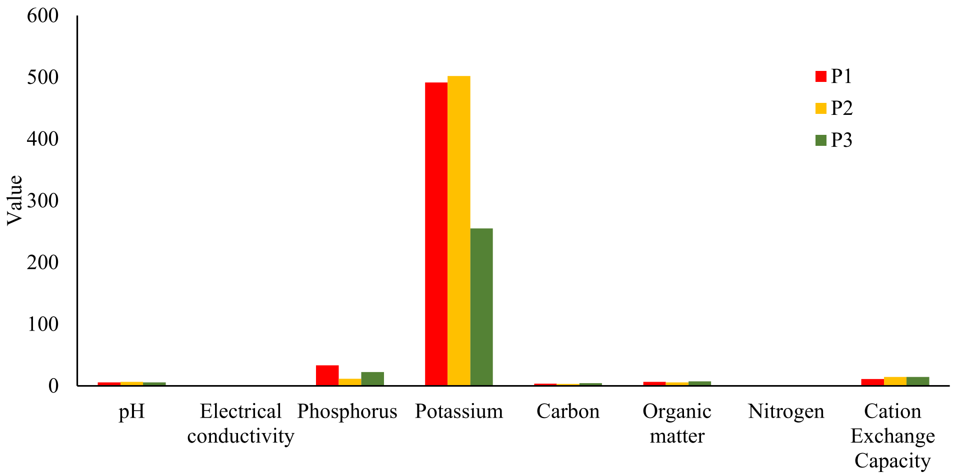

Fig. 7. Distribution of WDPT method by each of the selected plots.

obtained a reduction of 0.27 units for partially affected plots and 0.17 units for fully affected plots. Martínez et al. (1991), attributes this reduction may be related to the washing and dragging of cations during periods of intense rains, which could result in lower values in the impacted area. However, for Denegri et al. (2014) by increasing the burning temperature to 200 °C, the pH progressively decreases in relation to unburned soils. However, the pH values for the scrub samples (P2) increase by 0.78 units. For Capulín et al. (2010) and López et al. (2022) after the occurrence of a fire, it is common for the pH to experience an increase, mainly due to the contribution of ashes that provide oxides, carbonates and basic cations resulting from the burning of organic matter. Martínez et al. (1991) attribute this increase to ashes from fires, since they contain a notable amount of potassium carbonate (K_2CO_3) which, due to its origin as a weak acid and strong base, exhibits an alkaline reaction when hydrolyzed.

The electrical conductivity of sample P1 in relation to sample P3 shows a decrease of 0.02 dS/m, classifying the soil as very slightly saline ($EC < 2dS/m$). Likewise, Domínguez (2016) and Mejía (2023) noted that after the fire, the affected area presented lower values compared to the unaffected area. According to Bodí et al. (2012) these values may return to pre-fire levels and even be lower after one or two years, due to the removal of ash and soot. On the other hand, (Agbeshie et al., 2022) that electrical conductivity increases in burned soils after low intensity prescribed fires due to the release of soluble inorganic ions and the creation of black carbon; However, EC can also decrease in soils exposed to temperatures of about 500 °C, due to the destruction of clay minerals, the formation of oxides and the formation of coarse particles (Xifré-Salvadó et al., 2021).

The comparison between sample P1 and P3 showed that the CEC has decreased by 3.20 meq/100 g, a phenomenon which can be attributed to the reintroduction of organic matter to the soil, which contributes significantly to the CEC after a forest fire (Becerra et al. 2004; Capulín et al. 2010). For both P1 and P2 the organic matter content decreased with respect to the unburned area. This behavior is due to the highest concentration of plant remains present in the first 10 cm of the soil, similar to what was obtained by Alva and Manosalva (2019), this decline is associated with the decrease in both the number of organic residues and the number and activity of microbial populations involved in mineralization and humification processes. The change in organic matter and nitrogen is directly related to the magnitude of soil warming and the severity of the fire. High and moderate fire severities cause the greatest losses in these components (Knoepp et al., 1998).

Phosphorus concentrations in P1 increased by 10.77 ppm, generating a positive effect on the burned soil due to the growth and development of pine forests being improved at low levels, this coincides with what was obtained by Capulín et al. (2010) and Mejía (2023) who showed that the phosphorus content in affected plots increases. Similarly Fernández-García et al. (2021), Huerta et al. (2020) found higher available P in the topsoil of a burned plot compared to an unburned plot after a high-intensity wildfire.

For Caldwell et al. (2002) this increase is associated with the contribution of this element from the ashes, given that in their study the fire had a moderate intensity, the conditions were not conducive to its volatilization and attributed to the mineralization of phosphorus (Afif-Khouri and Oliveira-Prendes, 2006) and its temporary immobilization due to the formation of calcium and/or magnesium phosphates. DeBano (1991) also reported that phosphorus responds differently to fire and only about 60 % of the total is lost by non-particulate transfer when fuels are fully consumed (Raison et al., 2011). Increased concentrations result from substantial amounts of highly available P with ash deposition on the soil surface immediately after fire and combustion of organic matter (Agbeshie et al., 2022; DeBano, 1991). In this sense Raison et al. (2011) indicate that ashes are highly enriched with nutrients and can contain up to 50 times more P than the concentrations in the unburned fuel.

The percentage of carbon showed a decrease of 0.54 and 1.07 % in samples P1 and P2 compared to the unburned one. Domínguez (2016) concluded that the percentage of carbon experienced a reduction of 1.39 to 1.04 %, in the burned area, for the purposes of the eradication of decomposing organic material from the subsoil, due to the activity of necrophytic microorganisms during the burning, leaving the soil more vulnerable to erosion by wind and water. According to Mataix-Solera and Guerrero (2007), in high intensity fires, there is a decrease in the carbon content as a result of the consumption of organic horizons and organic matter in the first centimeters of mineral soil (Urretavizcaya, 2010). Likewise, the decrease in carbon and nitrogen in the burned areas is produced by the combustion of the mulch and soil organic matter, given that the temperature thresholds of carbon and nitrogen are low in relation to temperatures reached by wood fuels, these Nutrients are rapidly volatilized from organic matter during combustion (De Bano, 2000).

Potassium in P1 and P2 increased by 236.33 ppm and 247.07 ppm, respectively compared to the unburned area. For Domínguez (2016) he considers that this could be related to the low volatilization and the contribution of ash from the fire, causing the mineralization of potassium and consequently an increase in its levels. Magnesium in both samples decreases its concentration; this reduction is related to the rapid leaching of this cation from the soil (Soto et al., 1991). Furthermore, Úbeda (2001) and Urretavizcaya (2010) indicated that the availability of calcium in the Soil suffers a substantial decrease in areas of lower fire intensity, but experiences increase in areas of moderate intensity.

The textural composition of the soil has not undergone substantial modifications, since it remains within the range corresponding to the type of soil called Sandy Loam, both in the pine plantation plots and in the scrub plots. These results support the notion that the textural characteristics of the soil were not modified by the passage of the fire in accordance with the results obtained by Alva and Manosalva (2019). Given the type of soil texture, which includes sand, silt and clay with high temperature thresholds, fire generally does not affect them, unless they are exposed to high temperatures at the soil surface (Rosero, 2013b). Some authors, consider that soil temperatures developed under wildfire are not adequate to cause significant changes in soil particle distribution (Giovannini et al., 1988; Xofis et al., 2023) so texture is not easily affected by wildfire, as sand, silt and clay exhibit high temperature thresholds (Agbeshie et al., 2022).

This study made it possible to evaluate the impact of forest fires on the physical and chemical properties of the soil in plots with forest and shrubland species. Among the limitations of the study is the temporal scope, since the soil properties were analyzed only once and in two types of vegetation. Future studies should study the variations in soil recovery trajectories according to the different types of vegetation, climatic conditions after the fire and the identification of areas vulnerable and recurrent to fires that include social and environmental components. In addition, the application of spectral indices, machine learning models and cloud processing for the evaluation of forest fires in high Andean areas of Peru using remote sensing.

5. Conclusions

The level of severity in the Tablón-Perú fire is classified as very low, since the burned soil showed an adequate regeneration process, evidencing the presence of herbaceous plants and ferns. In the areas with plantations with *Pinus radiata* D. Don, regeneration with this species was important. Therefore, fire not only causes adverse effects, but also acts as an agent that accelerates the process of plant regeneration, specifically ignition in conifers helps the cones to release their seeds. Areas impacted by fire, in pine forests and shrublands at a depth of 1 cm were strongly repellent. Whereas, in non-fired areas, the soil behaved hydrophilic. At the level of physical properties such as texture, no variations were reported, in contrast to the chemical characteristics that showed significant variations in the areas with *Pinus radiata* D. Don.

The results of this study show the impact of fire on soil physical and chemical properties. These results can be taken as a baseline and replicated in other high Andean areas of Peru by policy makers and land managers in Peru. This in order to design and implement recovery actions for areas affected by forest fires. In the future, we recommend additional studies that integrate the assessment of areas vulnerable to forest fires, integration of machine learning algorithms to predict fire detection and degraded areas, as well as research that includes social and environmental components to improve the accuracy and management of forest fires in Peru.

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Author contributions

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CRediT authorship contribution statement

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Declaration of competing interest

We, the undersigned authors, declare that there are no conflicts of interest regarding the publication of this article.

Data availability

No data was used for the research described in the article.

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