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A Case Study of the Physical and Hydrological Characteristics of the Soil after the Occurrence of Forest Fires in Durango, Mexico

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Forest fires are disturbances that, in addition to causing effects on vegetation, have an impact on the components and properties of soils. Fires influence soil biota, soil organic matter, macro and micronutrients, and physical properties such as bulk density, porosity, hardness, infiltration, aggregates, color and soil permeability. Therefore, the main objective of this research was to evaluate the physical and hydrological properties of soils affected by forest fires in El Salto, Durango. In particular, two areas damaged by forest fires (2023-2024) were analyzed and compared against an unaffected area to determine the degree of recovery of soil properties after a forest fire. The dominant soil corresponds to the Cambisol type, characterized by being a shallow soil, with the presence of fragmented rocks and the formation of a differentiated profile in horizons. The results indicate that the unaffected area presents optimal conditions in the soil physical properties unlike the observed in the areas were forest fires ocurred; the rates of water infiltration into the soil, apparent density, porosity, aggregate stability, color and mechanical resistance to penetration were significantly modified. The information will be useful to have a better diagnosis of the state of the soil before and after the forest fires occurred, and in this way to be able to make more precise management recommendations of water, soil and vegetation resources.

Keywords: Cambisol, Diagnosis, Water, Vegetation, Fragmented rocks.

1. Introduction

Soil is one of the most important natural resources, as its functions are essential in terrestrial ecosystems and human life. In particular, they are the source of growth for plants and a wide variety of living organisms; it also controls the destination of water in the hydrological system; it recycles the waste and bodies of plants, animals and microorganisms and contributes to the mitigation of climate change through carbon capture (Kopittke, 2022; Nannipieri, 2020). The above can be defined as soil ecosystem services; which are considered as resources and/or goods that people obtain for the satisfaction of multiple needs from the natural environment of the ecosystem (Vega et al., 2015; Hyun et al., 2022) (Fig, 1). In this sense, it is important to highlight that for many years these services were considered inexhaustible, but currently the soil is subjected to different pressures that it is difficult to preserve these services in the best condition, which can trigger other types of ecological, social and economic problems such as erosion, soil salinization, pollution, etc. poverty, disease, migration, famine, etc. (Luna et al., 2022; Somoza and Vázquez, 2023; Cantú and Bejar, 2024; Khalaf-alla et al., 2024).

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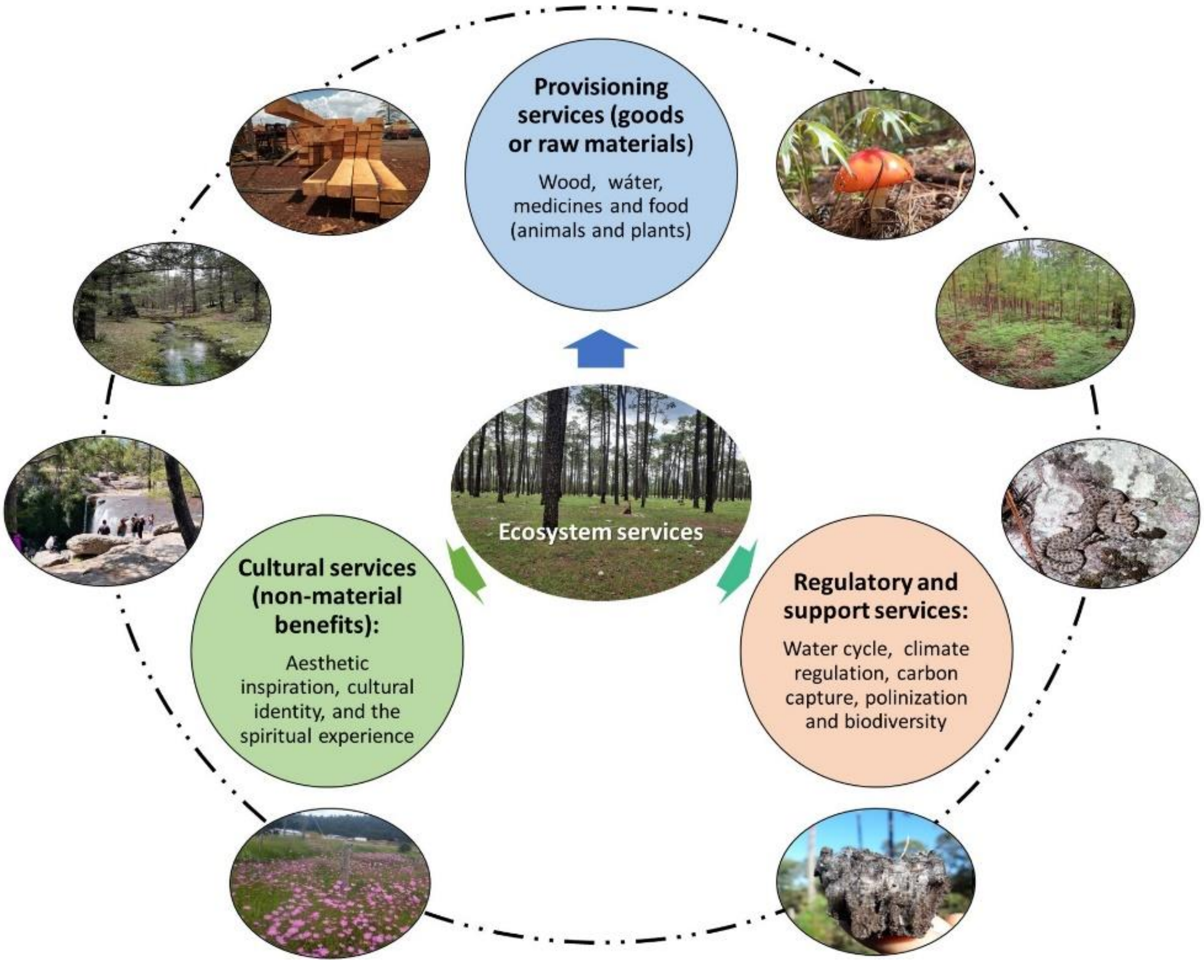

Fig. 1. Ecosystem services flowchart.

Worldwide, forest fires have become a focus of soil degradation since they have increased significantly worldwide, due to changes in environmental, social, and cultural components (Cuesta, 2013; Dhunganaet al., 2024). In particular, the effects of fire on the soil will depend on the characteristics of the site (cover, slope, load of woody fuels, soil moisture, etc.) and the fire itself (time, direction, intensity of warming) (Carrion et al., 2022). For example, in coniferous forest fires, temperatures of 1200 to 1400 °C can be reached during an intense fire within the ignited mass; while on the ground surface it can reach 1000 °C, in bush fires 500 to 700 °C and in grasslands 200 °C (Martínez et al., 1991). In any case, these are temperatures high enough to modify the physical, chemical and biological properties of the soil. In addition to the above, the frequent occurrence of fires mainly degrades soil structure, reduces infiltration, increases erodibility, and decreases soil fertility (Agbeshie et al., 2022; Kastridis et al., 2022).

According to Cerdà et al. (2022) and Su et al. (2022), the impact of fire on the hydrological characteristics of soils is directly caused by the alteration of vegetation and soil cover (organic layer; leaf litter and humus), since, when vegetation temporarily disappears, the interception capacity is drastically reduced, favouring surface runoff. Likewise, Saneugenio et al. (2023) mention that the recovery of the ecosystem after a forest fire depends on the soil and the water stored in it. Where water and nutrients will allow the recovery of vegetation that will slow down erosive processes, and water will allow the basic edaphic processes for the release of nutrients to occur. Without water in the soil, the areas affected by forest fires will begin a path towards degradation that can lead to the desertification of the territory.

In this sense, it is worth highlighting the hydrological importance of temperate forests, which are considered important ecosystems for the recharge of aquifers, since it is estimated that they provide 1.2 billion cubic meters of water at the national level (Torres and Guevara, 2002). And in particular, the forests of the state of Durango are vital for the basins of the Pacific Ocean and the interior of the north-central part of the country (Dueñez et al., 2006). However, forest fires are one of the main agents of degradation of cold temperate forests (Rawat et al., 2022). And according to the National Forest Fire Concentrate of the National Forestry Commission (CONAFOR, 2024), in the last two years the occurrence of forest fires and affected area has increased significantly, and particularly in the state of Durango in 2022, 269 were registered with an affected area of 86, 107 hectares and by 2023 a total of 347 forest fires equivalent to 89,334 hectares affected, which positions it as one of the states with the greatest impact in the country and where the possible cause in most of them was classified as intentional.

Therefore, the main objective of this research was to evaluate the physical and chemical properties in soils affected by forest fires in El Salto, Durango, Mexico. In particular, two areas damaged by forest fires (2023-2024) and compared with an unaffected area will be analyzed to determine the degree of resilience of soil properties. The information will be useful to have a better diagnosis about the state of the soil before and after fire, and in this way to be able to make more precise recommendations on what would be the best management in the ecosystem to avoid the occurrence of forest fires and soil degradation.

2. Materials and methods

2.1. Location of study

The study area is located in experimental forests adjacent to the Instituto Tecnologico de El Salto in Durango, Mexico, at an average altitude of 2,580 m. (Fig. 2). According to the climatic classification of García (2004), the climate that predominates is C(W2), which corresponds to a subhumid temperate. The dominant soil is the Cambisol type, characterized by being a young little developed soil. The B horizon, in formation from the parent material, consists of sandstones, alluviums, limestones and conglomerates. (National Institute of Statistics and Geography [INEGI], 2017; Luna et al., 2024).

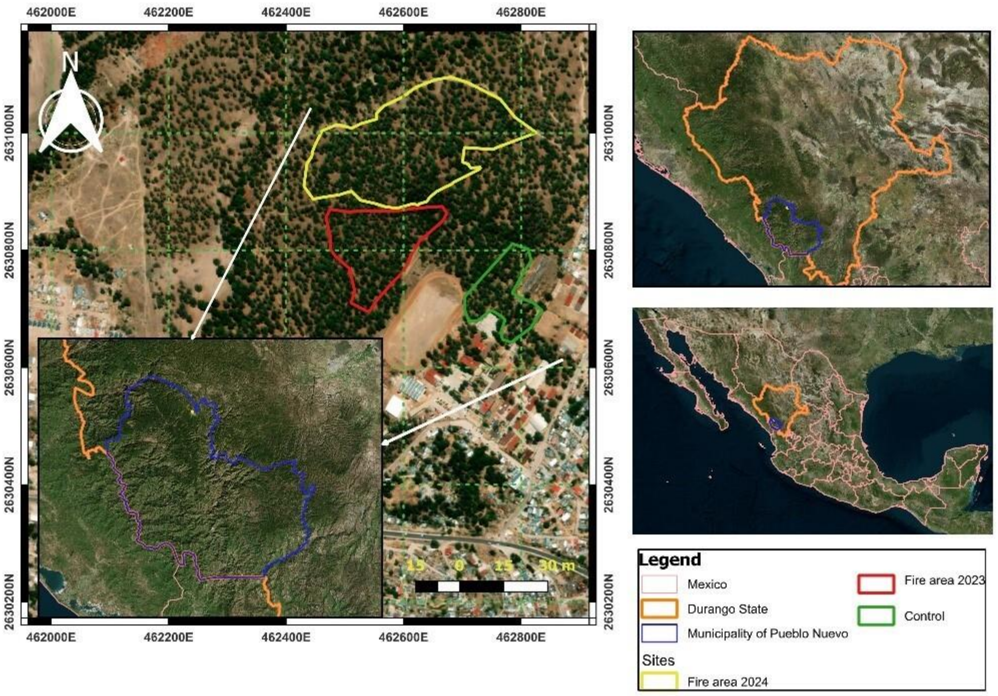

Fig. 2. Location of the evaluated areas in El Salto, Durango, Mexico.

In particular, three areas of peri-urban forest were considered; of which two areas were damaged by fires that spread horizontally on the surface of the land, which mainly affected trunks, grasslands, leaf litter, humus, branches, twigs, shrubs and natural regeneration. Other features are described below:

a) Forest area affected by forest fire in 2023; which has an area of 4.9 hectares, there is a lower stratum made up of mainly annual herbaceous species. The slope is very gentle or non-existent. The presence of leaf litter and humus is scarce, occurring mainly in thin layers around the trees present. b) Area of forest affected by forest fire in the month of April 2024; affected area of 1.9 hectares, the burning of leaf litter is partial, which means a decrease in the volume of the organic fraction and the origin of a significant layer of carbonized waste and ash. c) Forest area unaffected by forest fires in recent years, which has an area of 1.1 hectares, with a greater presence of leaf litter and humus (Control).

2.2. Determining soil infiltration

In each area, four infiltration tests were applied with variable recharges of 150 minutes of evaluation (2.5 hours), for which the double ring infiltrometer (Royal Eijkelkamp®, model M-0904E) was used, the tests were carried out during the month of May 2024. The process consisted of infiltration records (in cm) every 5 minutes until the first hour of evaluation was completed; in the second hour the measurements were made every 10 minutes; Finally, two readings were taken with 15 min of differentiation for a total When the water level reached 8 cm, the inner cylinder was recharged, depositing the water slowly; The outer cylinder was filled when its level decreased. Based on the in situ readings, the variables of the infiltration process were calculated, which are presented in Table 1 (Yáñez et al., 2019).

TABLE 1. Methods of determining the variables of the infiltration process.

Variable	Ecuation	Where
Infiltration rate	$I=\frac{HL\times10\times60}{T}$	I = Infiltration rate (mm h^{-1}) HL = Difference between readings (cm) 10 = Conversion factor from cm to mm 60 = Conversion factor from minutes to hours T = Time period (min)
Initial infiltration	$Ii = V_1$	Ii = Initial infiltration (mm h^{-1}) V1 = Infiltration rate at minute one (mm h^{-1})
Basic infiltration	$Ib=\frac{V_{120}+V_{135}+V_{150}}{3}$	Ib = Basic infiltration rate (mm h^{-1}) V120 = Infiltration rate of the antepenultimate reading (mm h^{-1}) V135 = Infiltration rate of the penultimate reading (mm h^{-1}) V150 = Infiltration rate of the ultimate reading (mm h^{-1})
Accumulated infiltration	$Ia=\sum L$	Ia = Accumulated infiltration (mm) ∑L = Total sum of the volumes of infiltrated water over time of 2.5 h

Simultaneously with the infiltration tests, samples were taken to estimate the moisture content in the soil, for this, a small soil sample (150 to 200 gr) is taken, deposited in paper bags with the data of the sampling area; then it determines the wet weight and then they are taken to the laboratory where they are introduced into the oven at a constant temperature of 105 °C for 24 hours for subsequent weighing. The moisture content (W) of each sample is calculated using the following equation:

$$Hs = \frac{W - D}{D}$$

Where: Hs: Moisture content in %; W: wet soil weight expressed in grams D: soil dry weight expressed in grams

2.3. Permeability

Soil permeability (Ks) was determined using the method proposed by Yáñez et al. (2019), which consisted of extracting eight samples unaltered by depth with the help of metal cylinders of equal dimensions (5 cm high and 3.7 cm in diameter); Subsequently, the samples were subjected to saturation for 24 hours, to finally measure the time in which a column of water crosses the column of saturated soil. Based on the above, the following equation was applied:

$$Ks = 2.3 * \frac{a\ L}{A\ T}\, log_{10}\, \frac{h1}{h2}$$

Where: Ks = soil permeability (cm s^{-1}); a = A = area of the lower and upper cross-section of the cylinders; T = time in seconds; log10; Common logarithm (base 10); h1 = height of both columns (10cm); h2 Saturated column height (5cm). From the above, the equation was simplified as follows:

$$Ks = \frac{3.46}{T}$$

2.4. Determination of the bulk density of the soil

The bulk density was determined by the cylinder method (Woerner, 1989). In each of the areas evaluated, 8 samples unaltered by depth (8 of 0-10 and 8 of 10-20 cm) were extracted with the help of beveled cylinders at the bottom (Woerner, 1989). The method consisted of introducing the cylinders into the ground with the help of a mallet avoiding hitting the center of them, then they were extracted by carefully eliminating with a spatula the excess soil above and below the cylinders; finally they were placed in paper bags where they were labeled and transferred to the laboratory to the multipurpose laboratory of the Technological Institute of El Salto for drying in an oven at 105 °C for 24 hours. Once the samples were dry, the following equation was applied to calculate the bulk density (Woerner, 1989):

$$\mathrm{BD} = \frac{p2 - p1}{vc}$$

Where:
BD = Bulk density (g cm^{-3})
$p2$= dry weight of the sample with the cylinder (g)
$p1$= weight of the cylinder (g)
vc= Cylinder volume (cm^3)

2.6. Estimation of total soil porosity

On the other hand, the total porosity of the soil was estimated from the values obtained of bulk density and assuming a particle density of 2.65 g cm-3, from the above the following formula is adjusted (Lu et al., 2014; McPhee et al., 2015; Yáñez et al., 2019):

$$\mathrm{P\%} = [1\text{-}\ (\frac{\mathrm{BD}}{2.76})]^{*}\ 10$$

Where P = porosity expressed as a percentage; BD = bulk density of the soil

2.7. Mechanical resistance to penetration

The measurement of mechanical resistance to penetration was determined with a push-pull force meter with a digital display (VTSYIQI brand), which was introduced vertically into the ground. The spring compression read on the screen, shows the resistance caused by the hardness of the soil in kg cm^{-2}.

2.8. Soil aggregate stability and soil color

On the other hand, the stability of soil aggregates was determined by the Slake Test method (USDA, 2001); which is based on taking an aggregated soil sample and then placing it on a precipitate aso full of water and with metal mesh in it, with the help of a stopwatch the speed with which the sample decomposes is measured. After 5 minutes, it is observed what percentage of the soil sample has been diluted, finally, based on the above and Table 2, the degree of stability of the aggregates is identified. If the soil structure is stable, water can enter the pores of the soil and displace air without causing the aggregate to break.

TABLE 2. Assessment of the stability of soil aggregates.

Low	Moderate	Strong
The aggregates disintegrate and fall apart in less than 2 minutes.	The aggregates disintegrate and fall apart in 2-10 minutes / a small part of the dough remains intact..	The soil mass disintegrates and falls apart in >10 minutes / a large part of the mass remains intact.

The characterization of the soil, by its color, was carried out in the field comparing a soil sample with the Munsell table, defining the color under three parameters: the hue (Hue), indicating the relationship between red, yellow, green, blue and purple; the value, which indicates the light or darkness with values between 1 and 8; and chroma, which refers to the purity or intensity of color (FAO, 2009; Domínguez et al., 2011).

2.9. Statistical Analysis

The data of the variables of infiltration, bulk density (BD), porosity (P), mechanical resistance to penetration (RMP) and permeability were subjected to normality and goodness of fit tests of Kolmogorov-Smirnov and homogeneity of variances of Levene. Based on the results, the following analyses were performed:

- Analysis of variance (ANOVA) of one factor ($P \leq 0.05$) to the variables initial, basic and accumulated infiltration and soil moisture.
- To detect differences between areas and depths, a two-factor ANOVA ($P \leq 0.05$) was applied to the variables of BD, P, RMP and permeability. Subsequently, for the differentiation of the mean values, Tukey's post hoc test ($P \leq 0.05$) was performed.

All data were analyzed using the SPSS statistical package version 22 (International Business Machines [IBM], 2013).

3. Results

Table 3 presents the results of the tests of normality and homogeneity of variances for the variables considered in this study. Where it can be seen that all the data of the variables met both assumptions.

TABLE 3. Tests for normality and homogeneity of variances.

	Kolmogorov-Smirnov		Levene	
	Statistical	P value	Statistical	P value
N = 9				
Ii (mm h^{-1})	0.273	0.052	4.887	0.055
Ib (mm h^{-1})	0.238	0.151	1.659	0.267
Ia (mm)	0.165	0.200	3.434	0.101
Hs(%)	0.176	0.200	0.434	0.667
N = 48				
BD (g cm^{-3})	0.077	0.200	2.280	0.064
P (%)	0.078	0.200	2.325	0.057
RMP (kg cm^{-2})	0.071	0.200	1.246	0.305
Permeability (cm s^{-1})	0.124	0.064	1.080	0.385

Ii: initial infiltration, Ib: basic infiltration, Ia: cumulative infiltration, Hs: soil moisture, BD: bulk density, P: total porosity, RMP: mechanical resistance to penetration

3.1. Analysis of variance for soil infiltration and moisture variables

Table 4 shows the results of the ANOVA for the variables of initial, basic, accumulated infiltration and soil moisture, where it can be observed that all the variables presented significant differences between areas evaluated with the exception of soil moisture.

TABLE 4. Analysis of variance for infiltration variables.

Variable	Degree of freedom	F value	Sig.
Ii (mm h^{-1})	2	8.482	0.018
Ib (mm h^{-1})	2	6.798	0.029
Ia (mm)	2	5.564	0.043
Hs (%)	2	0.141	0.841

Ii: initial infiltration, Ib: basic infiltration, I: Accumulated infiltration, Hs: Soil mosture (%)

The mean values of the variables that make up the infiltration process, as well as the soil moisture content are shown in Table 5; specifically, it can be observed that after the occurrence of fires in 2023 and 2024, the initial infiltration was reduced by more than 60 and 70% compared to the area considered as a control; while basic infiltration presented decreases greater than 50%. Meanwhile, accumulated infiltrated lamina, in both burned areas was reduced by an average of 57%. The initial soil moisture content between the three areas was statistically similar.

TABLE 5. Mean values of hydrological variables in the different areas.

Areas	Ii (mm hr^{-1})	Ib (mm hr^{-1})	Ia (mm)	Hs (%)
2023	1120b	124.33a	402.33a	7.39a
2024	880b	162.33a	460.33a	8.21a
Control	2820a	329b	1024.30b	8.02a

Ii: initial infiltration, Ib: basic infiltration, Ia: Accumulated infiltration, Hs: soil mosture

The average infiltration behavior is presented in Fig. 3, it can be distinguished that the Core stands out with respect to the burned areas. In general, the infiltration curves show an initial period where the infiltration velocity is high in the first 5 minutes; subsequently, the infiltration decreases gradually (5-30 min) to become asymptotic, which occurs after 60 min of application of the test.

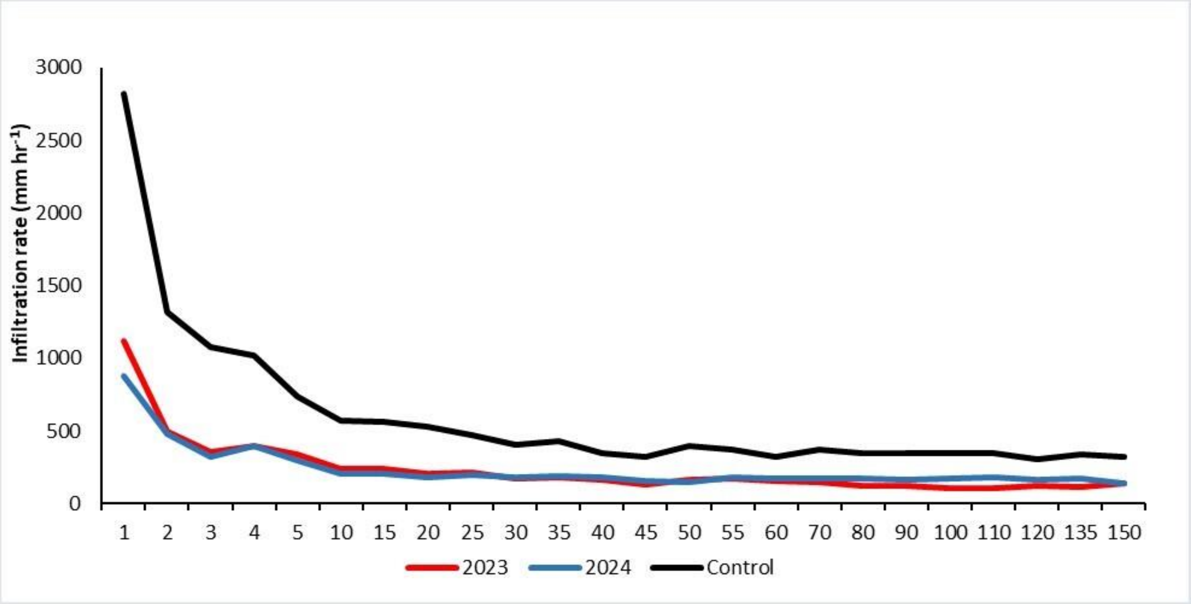

Fig. 3. Average infiltration rate per area assessed.

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3.1. Two-factors analysis of variance for BD, P, permeability and RMP.

The results of the analysis of variance between evaluated areas and depth ranges are shown in Table 6, where it can be identified that all variables presented highly significant differences in both comparison factors (<0.001).

TABLE 6. Two-factor analysis of variance.

Origen		Degree of freedom	F value	Sig.
Area	BD	2	12.323	>0.01
	P	2	12.323	>0.01
	RMP	2	14.728	>0.01
	Permeability	2	8.186	>0.01
Depth	BD	1	21.404	>0.01
	P	1	21.434	>0.01
	RMP	1	64.946	>0.01
	Permeability	1	19.943	>0.01

BD: bulk density, P: total porosity, RMP: mechanical resistance to penetration.

3.1.1. Bulk density

The bulk density values are presented in Fig. 4, where it can be seen that at both depths the burned areas presented an increase in the bulk density of the soil with respect to the control, with the burned area 2024 registering the highest bulk density at the two depths. (from 0-10 cm = 1.20g cm^{-3} and 10-20 cm = 1.30 g cm^{-3}).

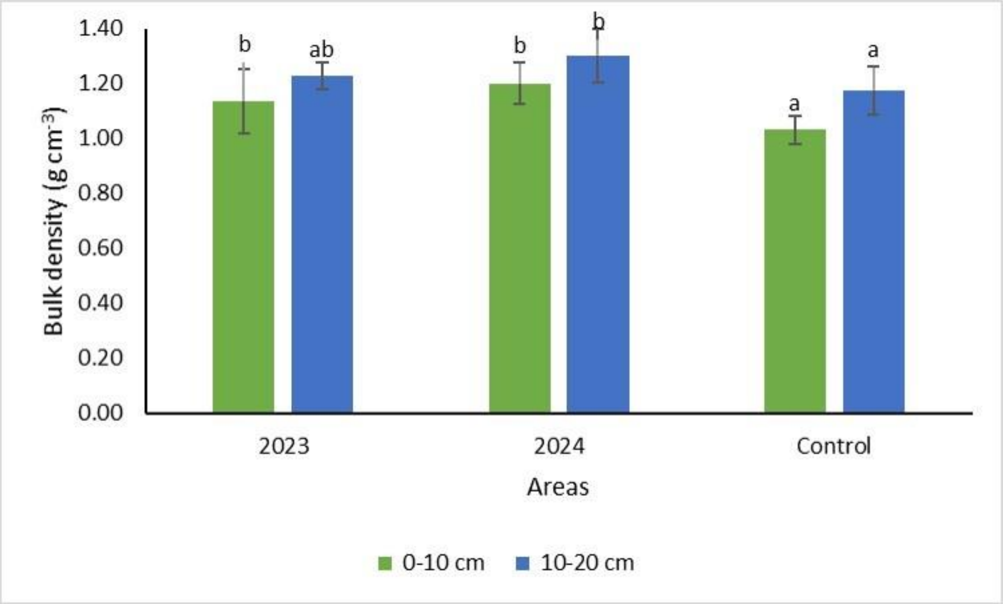

Fig. 4. Bulk density by area and depth.

3.1.1. Total porosity

Otherwise, porosity values for the first depth ranged from a minimum of 56 % to a maximum of 67 % and from 10-20 cm from 52 % to 57 %; it should be noted that in both depth intervals the control and the burned area of 2024 presented the highest and lowest values respectively (Fig. 5). As expected, the relationship between porosity and bulk density values can be influenced by the dispersion, fragmentation and incineration of organic material present in the soil.

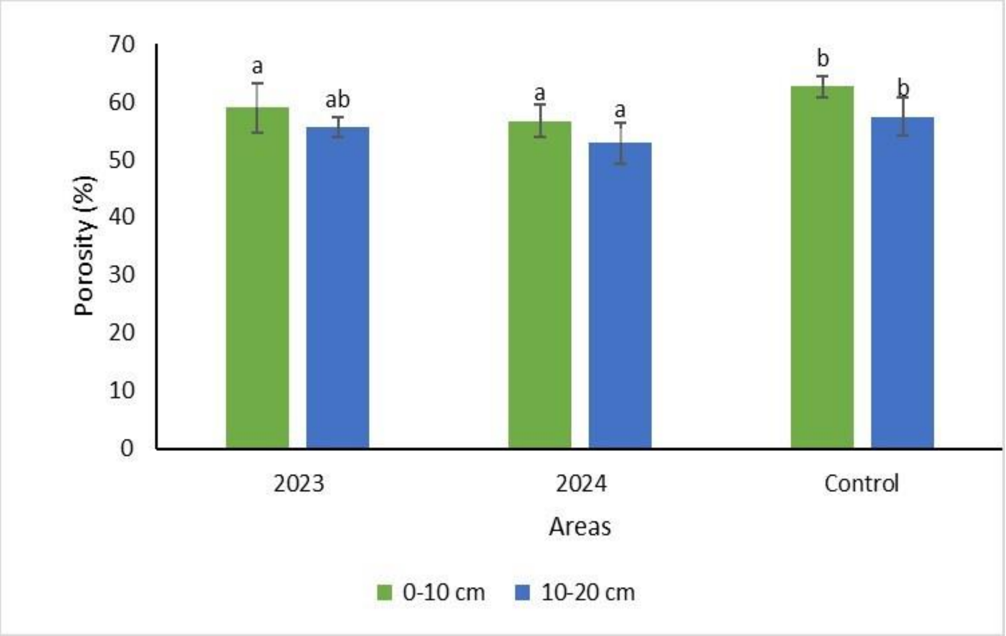

Fig. 5. Total soil porosity by area and depth.

3.1.2. Mechanical resistance to penetration

Table 7 presents the average values corresponding to mechanical resistance to penetration, in the first depth the Core presented the highest value (17.85 Kg cm^{-2}) while the two burned areas presented similar values. For the second depth, the RMP increased significantly in the three areas; The highest and lowest values were presented in the burned areas 2024 and 2023 respectively.

TABLE 7. Mechanical resistance to penetration (RMP) by area and depth.

Areas	RMP (kg cm^{-2})	RMP (kg cm^{-2})	Average (kg cm^{-2})
	0-10 cm	10-20 cm	
2023	13.34 ± 2.30	17.22 ± 1.95	15.27a
2024	13.69 ± 2.89	22.67 ± 1.78	18.17b
Control	17.85 ± 1.70	21.56 ± 3.11	19.70b

3.1.3.Permeability

Table 8 presents the average values of soil permeability, where the 2023 and control areas presented statistically similar records, while the 2024 values were the lowest. Similarly, it can be observed that in the three areas evaluated, soil permeability increased considerably for the second depth.

TABLE 8. Average permeability values by land use .

Area	Depth	Permeability (cm s^{-1})
2023	0-10 cm	0.0012b
	10-20 cm	0.0045b
	Average	0.028b
2024	0-10 cm	0.0004a
	10-20 cm	0.0012a
	Average	0.0008a
Control	0-10 cm	0.0012b
	10-20 cm	0.0040b
	Average	0.026b

3.1.4.Stability of soil aggregates

The results of the aggregate stability test of the three areas and for both depths are shown in Table 9, in general both fires present differences with respect to the control, for example, area 2024 was the one that presented the most evident damage in the first depth with low and moderate stability for the second depth. The 2023 area presented moderate stability for both depths, what it could mean that after one year the soil shows improvements in this physical variable compared to 2024. Finally, the control showed a strong stability at both depths, maintaining its stability after < 20 min of the start of the test.

TABLE9. Aggregate stability test results.

Area	Depth	Stability degree
2023	0-10 cm	Moderate
	10-20 cm	Moderate
2024	0-10 cm	Low
	10-20 cm	Moderate
Control	0-10 cm	Strong
	10-20 cm	Strong

3.1.5. Soil color

The soil colors obtained were brown, for both depths of the control, dark gray for the first depth of the 2023 fire and brown of 10-20 cm, while the area burned in 2024 presented a black color of 0-10 cm and 10-20 cm brown.

4. Discussion

The results of this study corresponding to the control allow us to define the importance of soil cover in the hydrological processes of the ecosystem, since it defines the optimal conditions of the physical properties of the soil such as bulk density, porosity, stability and soil structure that moderate the speed of entry, stay and circulation of water in the soil

(Muñoz-Villers et al., 2015; Lozano-Trejo et al., 2020).
In contrast to what was observed after the occurrence of forest fires; where water infiltration rates in the soil show a tendency to decrease, which coincides with different research that has measured hydrological responses to forest fires (Inbar et al., 2014; Weber & Reyna, 2019; Wagenbrenner et a., 2021), where they point out that the presence of fire can change soil structure, bulk density, and total porosity, and specifically in the event of surface fires as was the case, the size and distribution of pores have a greater negative impact on surface horizons; due to the accumulation of articulated material and ash, which considerably decreases water flows into the soil profile, which can trigger increases in runoff and flooding.

However, it has also been shown that after one year infiltration can present a significant increase (Oswald et al., 2023), however, recoveries can be highly variable depending on the severity and extent of the fire; soil intensity, duration and type, climatic regime, post-fire biological activity, herbaceous regeneration and soil cover density (Hubert et al., 2012; Robichaud et al. 2013; Wine & Cadol, 2016; Pellegrini et al., 2018; Pérez et al. 2021). In this sense, post-fire conditions varied substantially, since the 2023 area presents a more consistent soil cover than that of the 2024 fire where most of the leaf litter, humus and herbaceous plants due to their characteristics disappeared easily despite the fact that the fire was of low severity (Lavoie et al., 2010). In addition to the above, Elliott and Vose (2010), Bates et al. (2011), and Vázquez et al. (2018) point out that it can take 1 to 3 years to recover the levels of soil cover that existed until the previous fire, which leads to stabilizing the hydrological characteristics of the soil, which is consistent with the information presented.

According to Woerner (1989), for the assessment of the bulk density of the soil, they can be categorized from low (control) to medium (fires). Particularly, the trend of bulk density was to increase after the fires of 2023 and 2024, this confirms what has been pointed out by many studies that indicate that the occurrence of forest fires whether in pine forests, oaks, jungles or scrublands; negatively impacts soil bulk density with its consequent effect on soil porosity as it is inversely proportional to bulk density (Granged et al. 2011 ; Jordán et al. 2011 ; Heydari et al. 2017). The response of these two variables is due to the changes caused by the accumulation of ash and clay particles scattered during forest fires that obstruct the pore space, as well as the collapse of soil aggregation and the destruction of soil organic matter; which has a direct impact on hydrological properties such as soil infiltration and permeability (Varela et al., 2015; Downing et al., 2017; Heydari et al., 2017; Alcañiz et al. 2018; Alsaeedi, 2023; Al-Khayri & Khan, 2024), which coincides with the results of the present study.

Soil damage in the most recent fire was evident by reduced soil permeability in both depth ranges, which on average was more than three times lower than the conditions affected in 2024 and the control. This may be attributed to the presence of hydrophobic material, instability of aggregates, increases in bulk density in the surface part, which together can be a factor in reducing the movement of water on and within the soil (Camargo et al., 2012). On the other hand, it was observed that the permeability for the fire that occurred in 2023 presents a recovery of this variable, which may be due to the fact that as time goes by, there is an elimination of ash due to the effect of gravity and wind, leading to re-establishing the potential of these pre-fire variables (Hubbert et al., 2012; González, 2017). Similarly, Strydom et al. (2024) mention that fires significantly reduce permeability in the short term, but return to pre-burn rates approximately one year later; which coincides with the trend of the permeability of both fires with respect to the control.
The mechanical resistance to ground penetration was different between the two intervals of fire and the control, particularly in the most recent fire it decreased significantly, but in the area of 2023 after one year, it increased considerably, which can be attributed to the recovery of bulk density levels, soil porosity, soil organic matter, and aggregate stability (Cass et al., 1984; Hernández et al., 2020; Oswald et al., 2023).

The modifications in the color of the soil after the fire occurred only in the first three centimeters of depth, this can be influenced by the type and intensity of the fire; that being of a superficial type, its affectation is directed to the leaf litter which when burned left charred residues and black ashes three to five centimeters thick; which, when combined with the ground, changed its color to darker tones (Hernández et al., 2020). Likewise, Mataix et al. (2007) point out that this superficial impact of fire may be due to the poor capacity of the soil as a thermal conductor that causes flames and heat to be redirected upwards from the ground. Similarly, the color of the burned ground can be used as a parameter to estimate the severity of fire (Úbeda et al., 2009), and due to its dark or black hue we could infer that the temperature reached ranged between 150 °C - 200 °C categorized as low severity, since as a consequence of high severity the color tends to appear in lighter shades (gray or white) (Pereira et al., 2010).

Agbeshie (2022) and Badía et al. (2014) point out that aggregate stability is affected when soil temperatures exceed 100 °C, as the complete carbonization or oxidation of organic matter leads to the destruction of soil structure through the disaggregation and decomposition of soil macropores (Alcañiz et al., 2018). However, inconsistencies have been presented in the literature on the impact of fire on the stability of soil aggregates, as some studies have not found significant changes in the stability of soil aggregates when low- and medium-severity forest fires occurred (Jordan et al., 2011; Scharenbroch et al., 2012). In contrast, Varela et al. (2015) point out that medium-severity forest fires in a pine forest reduced aggregate stability in a Regosol soil in Spain. These contradictions may be influenced by different factors that influence the intensity of the fire, such as soil organic matter, fuel availability, fuel moisture, temperature, soil type, and soil moisture (Mataix et al., 2011; Murillo, 2022). In this way, the results of this study coincide with the above, since the occurrences of fires coincide with the dry season when soil moisture levels are considerably reduced (<15%) and therefore fuels are more sensitive to ignition, being decisive in the stability of soil aggregates.

5. Conclusion

The occurrence of forest fires significantly modified the physical and hydrological properties of Cambisol.

The change in the physical properties of the soil can be attributed to the accumulation of ash that obstructs the pore space, as well as to the collapse and elimination of soil aggregation and soil organic matter respectively; which gradually affects the hydrological properties of the soil. The infiltration variables showed a tendency to decrease immediately after the fire occurred. The bulk density, porosity and stability of aggregates show a slight recovery after a year after the forest fire occurred. The forest fire mainly affected the first 10 cm of soil depth. As these are peri-urban forests, it is recommended to carry out awareness campaigns to avoid throwing garbage, flammable materials and lit objects.

List of abbreviations:

BD (g cm^{-3}): Bulk density in grams per cubic centimeter
Ii (mm hr^{-1}): initial infiltration in millimeters per hour
Ib (mm hr^{-1}): basic infiltration in millimeters per hour
Ia (mm): accumulated infiltration in millimeters
Hs (%): soil mosture expressed as a percentage
P(%): porosity expressed as a percentage
RMP (kg cm^2): mechanical resistance to penetration in kilogram per centimeter squared
cm s^{-1}: centimeter per second

Declarations

Ethics approval and consent to participate

Consent for publication: The article contains no such material that may be unlawful, defamatory, or which would, if published, in any way whatsoever, violate the terms and conditions as laid down in the agreement.

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