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Evaluation of Soil Physical and Hydrological Properties in Burned Grasslands in Durango, Mexico

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THE SOILS of the state of Durango are diverse and support a wide variety of vegetation types and land uses of significant ecological, social, and economic importance. Grasslands, in particular, are fragile forest ecosystems in the face of wildfires, since fire greatly affects soil properties such as bulk density, porosity, mechanical resistance to penetration, infiltration, and soil permeability. This research aimed to evaluate the effects of fire on the physical and hydrological characteristics of soils in grasslands in the El Salto region of Durango, Mexico. Two plots were identified and established: a) a plot burned in January 2025, with a total impact on grassland biomass; b) a control plot adjacent to the fire, which was not impacted by the fire and presents a characteristic grassland cover. According to the results, the variables showed significant differences between the plots evaluated, except for basic and accumulated infiltration. Specifically, initial infiltration decreased by 65% compared to the control area, while humidity decreased by more than 30%. Baseline infiltration ranged from 32 to 56 mm h^{-1} between the burned and control areas. After the fires, cumulative infiltration decreased by 38%. After the forest fire, the bulk density increased by 16% compared to the control plot (1.05 g cm^{-3}). On the other hand, total porosity behaved inversely to the soil's bulk density. The mechanical resistance to penetration of the burned plot showed a decrease of 25.3%, and the permeability showed the same trend where it was significantly reduced (<55%) with respect to the control plot.

Keywords: Wildfires, Infiltration, Bulk density, Porosity, Mechanical resistance to penetration, Permeability.

1. Introduction

Soil is a complex, diverse and dynamic natural entity, which is considered key to global food security and therefore to human well-being; in this sense, ecosystem services are all the tangible and intangible goods that the soil provides, which are categorized as: provision and maintenance, regulation and cultural (Luna et al., 2022; Cantú and Bejar, 2024). Soil has physical, hydrological, chemical, and biological properties, and its evaluation allows us to diagnose the functioning of ecosystems (Ahmad et al., 2024; Rodríguez et al., 2024). However, the soil is subject to different scenarios such as intensive land use, pollution, fires, climate change, among others, which can have a direct impact on the balance of its properties and therefore on its health (Bai et al., 2018). Specifically, the occurrence of fires generates an immediate impact on the dynamics of water in soils, since the incineration and carbonization of biomass and soil cover generates changes in soil bulk density, porosity, texture, color, moisture content and permeability and surface erosion; it should be noted that damage is a function of a series of factors, such as the severity of the fire, type of vegetation and soil type (Mataix-Solera et al., 2011; Agbeshie et al., 2022; Elakiya et al., 2023; Luna et al., 2024). It is important to mention that the use of fire is a common practice that has been used in different types of vegetation as a tool for pasture management, ecosystem restoration, and agricultural purposes, however, regardless of its use and origin, fire can affect entire ecosystems (Ramos et al., 2024; Kumar et al., 2025); thus deteriorating the quality of the environmental services that these ecosystems provide, cycling of soil nutrients, water retention and storage, carbon sequestration, and erosion control, among others (Guleria et al., 2024).

In particular, grasslands are very important for humanity as they contribute to food and economic security (Fraval et al., 2020); and when sustainable practices are in place, they allow for effective management of water resources and soil (Davies et al., 2015; Stavi., 2019; Talat et al., 2025). But, these ecosystems are subject to different agricultural and livestock uses where it is common to observe burns for the resurgence of tender regrowth for livestock and weed elimination; nevertheless, Casas (2023) indicates that poor fire management practices can lead to significant deterioration of soil resources and ecosystems; therefore, its use must consider important aspects such as the characteristics of the terrain, vegetation, and climatic conditions. For example, the use of fire in grasslands is usually carried out on large areas of land and during times of the year with prolonged

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droughts, so its management must be strictly responsible, considering that these ecosystems are very susceptible to fires, since, if not controlled, their impact can be extensive, in addition to the fact that they can become very intense, mainly due to the forest fuel load present (Rodríguez et al., 2020).

Stavi (2019) and Luna et al. (2024) cite that most fires are man-made; some may be started accidentally, others by deliberate practice of prescribed burning, and some fires are started by arsonists. Specifically, in the state of Durango, fires have annually affected large areas of shrub vegetation and grasslands; and according to National Institute of Statistics and Geography [INEGI] (2017) grasslands represent approximately 40% of the total area of the state (123200 Km^2). In addition, based on statistics from the o National Forestry Commission [CONAFOR] (2025); It can be inferred that this region of the country suffers significantly from the ravages of climate change, which can be inferred by the number of forest fires that are registered annually and by the unusual dates of occurrence, to mention, so far in 2025 (January-February) there have been 5 fires affecting mainly pine forest and natural grassland.

Based on the above, the objective was to evaluate the effects of fire on the physical and hydrological characteristics of the soil in grasslands in the region of El Salto, Durango, Mexico. In the region, it is worth noting that there are many information gaps on the subject under study, so the results will be useful for making decisions aimed at the sustainability of ecosystems and soil resources.

2. Materials and Methods

2.1. Location of study

The study area is located in the Sierra Madre Occidental region in the south of the state of Durango, in the place called "Bajío atascoso" in the ejido José María Morelos, municipality of Pueblo Nuevo; between coordinates 23°50'57" N and -105°18'41" W (Fig. 1). According to González-Elizondo et al. (2012) the dominant tree vegetation is made up of *Pinus cooperi* C. E. Blanco, *P. leiophylla* Schiede ex Schltdl. & Cham., *P. teocote* Schltdl. & Cham., *P. engelmannii* Carrière, *Juniperus deppeana* Steud., *Quercus sideroxyla* Bonpl. and *Q. durifolia* Seemen. While the grasslands are mainly composed of the species of *Muhlenbergia porteri* Scribn. The average annual rainfall varies from 600 to 1 000 mm in the driest parts to the wettest. The predominant soil type is Regosol, which has very specific characteristics, as these are shallow soils with an unstable structure. Therefore, the occurrence of forest fires can alter their physical and hydrological properties. (INEGI, 2010; INEGI, 2017).

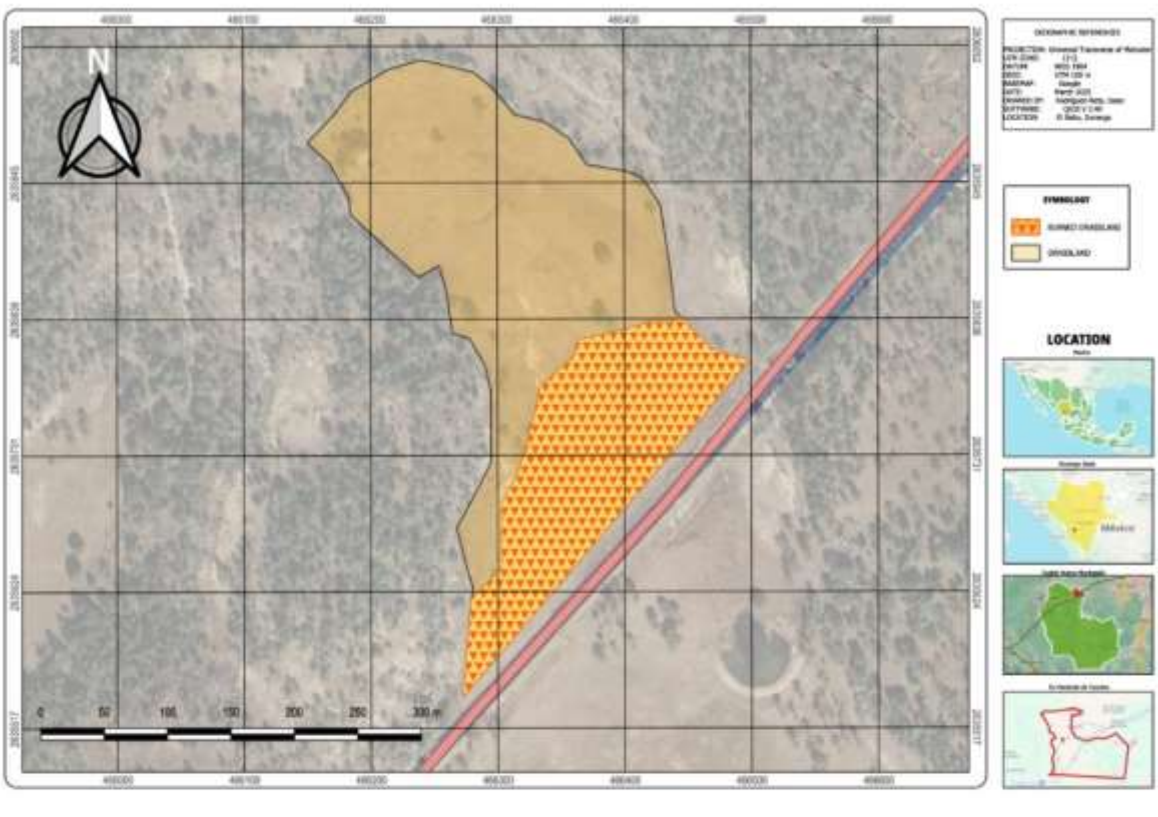

Fig. 1. Location of study area.

2.2. Experimental design

To evaluate the physical and hydrological characteristics of the soil, within the study area, two plots measuring 100 × 100 meters (10000 m^2) separated by a distance of 80 meters, were identified and established, which are described below**: a)** burned plot of 2.4 hectares of surface, damaged by fire in January 2025 and with a total impact on the biomass of the grassland; resulting in a decrease in the organic matter and the formation of a significant layer of charred debris and ash with an average thickness of 2.5 cm. **b)** Control plot: An adjacent 4.9 hectare area, that was unaffected by the fire and retained the typical grassland cover (Fig. 2).

Fig. 2. Grassland areas evaluated.

2.3. Soil analysis

For soil analysis, in situ and ex situ measurements were carried out in each area to determine the physical and hydrological variables of the soil, which are detailed below (Table 1).

Table 1. Variables to be considered in the present study.

Physical	Hydrological
Bulk density	Infiltration*
Total porosity	Soil moisture**
Mechanical resistance to penetration	Permeability

*= From the outside of the soil to the inside of the soil, *= soil surface

2.3.1. Bulk density and total porosity

The bulk density of the soil, expressed in grams per cm^3, was obtained using the cylinder method, which consisted of extracting eight samples (repetitions) of undisturbed soil from each area evaluated at an average depth of 0-15 cm; the samples were placed in paper bags, labelled, and taken to the laboratory for drying and weighing (Woerner, 1989); the following expression was then applied to the data obtained:

(1)

$$\text{Bulk density in grams per cm}^3 = \frac{\text{Dry weight of the soil sample in grams}}{\text{Volume of cylinder in cm}^3}$$

While the total porosity of the soil was estimated using the aforementioned bulk density data; applying the formula suggested by Lu et al. (2014), McPhee et al., (2015) and Yáñez et al. (2019):

(2)

$$\text{Total porosity (\%)} = \left[1 - \frac{\text{Bulk Density}}{2.65}\right] * 10$$

Where: 2.65 = assumed particle density (grams per cm^3)

2.3.2. Mechanical Penetration Resistance

This variable was determined by using a digital push-pull force meter (VTSYIQI brand) (Fig. 3), which is introduced vertically into the ground and the compression of the spring gives an on-screen reading, showing the resistance caused by the hardness of the soil in kg cm^2 (Rodríguez et al., 2024).

Fig. 3. Device for determining mechanical resistance to penetration.

2.3.3. Infiltration

Three infiltration tests were carried out on each plot during February 20 and March 10, 2025; A double-ring infiltrometer (metallic) was used for this purpose, with an inner diameter of 15 cm and an outer diameter of 30 cm and a height of 30 cm. Specifically, the process consisted of stripping the mineral soil, then both cylinders were inserted into the soil at a depth of 5 cm; then a ruler was introduced in the inner cylinder to measure the infiltration, then the water was added in both cylinders and finally the test began recording the readings for a period of 180 minutes, 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 (Luna et al., 2020). Simultaneously with the infiltration tests, soil samples were extracted to determine the gravimetric moisture content (Woerner, 1989).

With the data obtained in the field, the variables that make up the infiltration process were calculated, which are mentioned below:

Infiltration rate: defined as the capacity with which water enters the soil represented in mm h^{-1} based on the depth (in mm) of the sheet of water that manages to penetrate the soil in one hour (Castellanos-Navarrete et al., 2013). The following equation was used for its determination (Zhang et al., 2017):

(3)

$$I = In * t * 600.$$

Where: ***I*** is the infiltration rate (mm $h\text{-}^{1}$); In is the infiltration (cm); ***t*** is the time during the infiltration period (minutes); and ***600*** is a conversion coefficient to mm h^{-1}.

Initial infiltration (mm h^{-1}): corresponds to the first reading of the infiltration test.

Basic infiltration (mm h^{-1}): at which point infiltration reaches a constant value, this condition is achieved when the soil has reached its field capacity (Bejar et al., 2021). This is calculated from the averages of the last three readings of the infiltration test (Yáñez et al., 2019).

Cumulative infiltration (mm): Considered as the sum total of the volumes of infiltrated water in the span of 180 minutes and is expressed in mm (Luna et al., 2024).

2.3.4. Soil moisture

Simultaneously with the infiltration tests, three small soil samples were taken at surface level (150 to 200 grams) at each site, which were deposited in paper bags and their wet weight was recorded, then taken to the laboratory where they were dried in an oven at a constant temperature of 105 °C for 24 hours. Finally, its dry weight was obtained. Based on the above, the moisture content (W) of each sample was determined with the following equation (Woerner, 1989):

(4)

$$Hs = W – D/ D$$

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

2.3.5. Permeability

The soil permeability was obtained from the use of unaltered samples, which were extracted using metal cylinders with dimensions of 5 cm in height and 3.7 cm in diameter; the method consists of subjecting the samples to saturation for 24 hours and then recording the time in which a column of water crosses the column of saturated soil (Fig. 4). The following equation is applied to the results (Yáñez et al., 2019; Luna et al., 2024):

(5)

$$Ks = 3.46 / AT$$

Where: Ks = soil permeability (cm s^{-1}); 3.46 = constant related to the volume of the cylinder (cm^3) A = cross-sectional area of the cylinders (cm^2) t = time in seconds

Fig. 4. Process for determining soil permeability.

2.4. Statistical analyses

The data of the variables of infiltration (initial [mm h^{-1}], basic [mm h^{-1}] and accumulated [mm]), soil moisture (%), permeability (cm s^{-1}), bulk density (grams per cm^3), total porosity (%) and mechanical resistance to penetration (kg cm^{-2}) were subjected to the tests of normality and goodness of fit of Kolmogorov-Smirnov and homogeneity of variances of Levene. Based on the results, the following analyses were performed:

• Student T-test ($P \leq 0.05$) for independent samples or, where appropriate, Mann-Whitney test to determine significant differences in the variables between the areas evaluated.

All data were analysed using SPSS version 22 (International Business Machines [IBM], 2013).

3. Results

According to the results of the normality and homogeneity of variance tests, all variables met both statistical assumptions (Table 2).

Table 2. Statistics of the Kolmovorov test and Levene's test.

	MRP (kg cm^2)	Ks (cm s^{-1})	BD (grams per cm^3)	P (%)	Initial infiltration (mm hr^{-1})	Basic infiltration (mm hr^{-1})	Cumulative infiltration (mm)	Soil moisture (%)
n	**16**	**16**	**16**	**16**	**9**	**9**	**9**	**9**
Kolmovorov-Smirnov								
Statistic value	0.110	0.187	0.135	0.135	0.286	0.231	0.223	0.167
P value	0.200	0.200	0.200	0.137	0.136	0.200	0.200	0.200
Levene Test								
Statistic value	0.261	0.262	0.574	0.574	0.400	1.293	0.139	0.800
P value	0.616	0.619	0.461	0.461	0.516	0.319	0.728	0.422

MRP: Mechanical Resistance to Penetration; Ks: Permeability; BD: Bulk density; P%: Porosity.

3.1. Infiltration

Fig.5 shows the average infiltration curves over the 180-minute test period. Three distinct moments can be identified, corresponding to the initial infiltration period, where the infiltration rate reached its maximum in both areas, remaining constant for a brief period before gradually decreasing until reaching 60 minutes of the infiltration test. Finally, the curves tend to exhibit asymptotic behavior after the 120-minute evaluation period, which is referred to as the basic infiltration capacity of the soil.

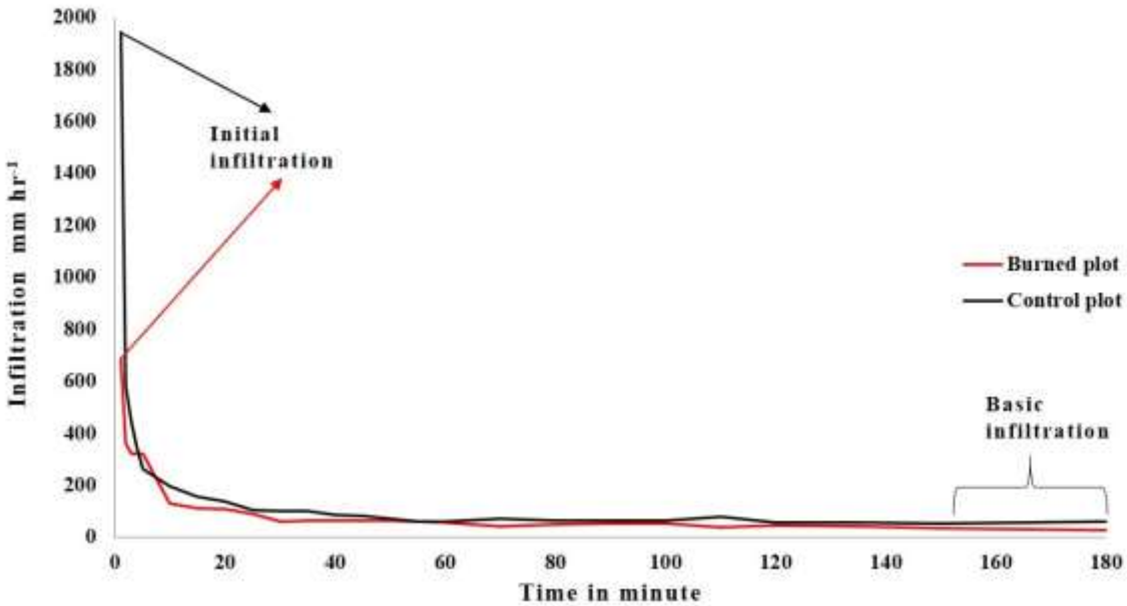

Fig. 5. Average infiltration curves per plot evaluated.

Table 3 presents the descriptive statistics for the variables involved in the infiltration process, as well as soil surface moisture. The statistics for the independent samples t-test are also presented. Only the initial infiltration and soil moisture variables showed significant differences between the evaluated plots. Only the initial infiltration and soil moisture variables showed significant differences between the evaluated plots. In particular, initial infiltration decreased by 65% compared to the control area, while moisture decreased by more than 30%. Basic infiltration ranged from 32 to 56 mm h^{-1} between the burned and control areas, representing a 43% decrease. Cumulative infiltration was similar between the two plots; however, after the fires, this variable decreased by 38%.

Table 3. Descriptive statistics of the infiltration variables.

Variables	Plots	n	Mean	Standard deviation	Mean standard error
Initial infiltration (mm hr^{-1})	Burned	3	680a	34.64102	20
	Control	3	1940b	481.24838	277.84888
Basic infiltration (mm hr^{-1})	Burned	3	32.0444a	10.98308	6.34109
	Control	3	55.7778a	22.33416	12.89463
Cumulative infiltration (mm)	Burned	3	181.6667a	94.93331	54.80977
	Control	3	292.3333a	133.55274	77.10671
Soil mosture (%)	Burned	3	7a	1	0.577350
	Control	3	11b	2	1.15470

Different letters indicate significant differences ($P < 0.05$).

3.2. Bulk density, soil porosity, mechanical penetration resistance and permeability

According to the independent samples t test, all variables showed highly significant differences between the evaluated plots ($P < 0.05$); this allows us to define that the occurrence of the fire led to changes in soil physics (structure, density and soil porosity) derived from the combustion of soil organic matter and vegetation, which results in changes in the internal movements of water in the soil. Fig. 6 describes the behavior of the bulk density, where it can be seen that after the occurrence of the forest fire this soil variable increased significantly (16%), compared to the control plot (1.05 grams per cm^3). On the other hand, the total porosity, being a variable intrinsically related to the bulk density of the soil, presents an inverse behavior, in particular this variable oscillated between 55 (burned plot) and 64 % (control plot).

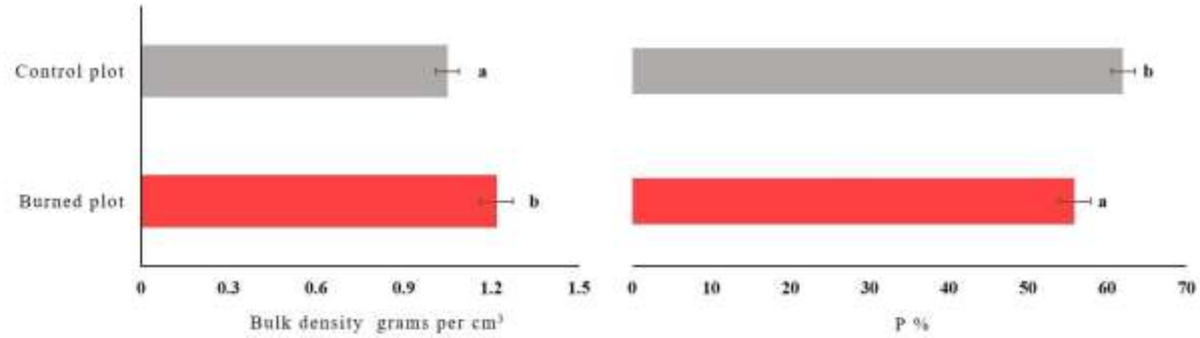

Fig. 6. Bulk density and porosity of the soil per plot evaluated. Different letters indicate significant differences (P < 0.05).

According to Table 4, the mechanical resistance to penetration of the burned plot showed a decrease of 25.3%, and the permeability showed the same trend where it was significantly reduced (<55%) with respect to the control plot. In general, these results indicate that the upper layer of the Regosol type soil presents high sensitivity to the elimination of aerial and superficial cover derived from the occurrence of forest fires, which directly affects the physical and hydrological stability of the soil.

Table 4. Average values of resistance to mechanical penetration and soil permeability.

Variables	Burned plot	Control plot
Mechanical penetration resistance (kg cm^2)	13.95a	18.67b
Permeability (cm s^{-1})	0.0011a	0.0024b

Different letters indicate significant differences (P < 0.05).

4. Discussion

The results of the soil analysis for the present study show that the occurrence of forest fires and grassland ecosystems cause significant differences in the physical and hydrological properties of the soil, which can lead to negatively affecting the functionality of the ecosystem (Luna et al., 2024). This has already been demonstrated in different studies in different ecosystems (temperate forests, lowland rainforests, desert areas, etc.), where the majority agree that the elimination of vegetation and soil cover has an immediate impact on water flows in the soil and its aggregation (Ravi et al., 2009; Stavi., 2019; Garcia et al., 2023; Dhungana et al., 2024). Although the effects of fires on the soil depend on multiple factors such as vegetation type, land cover and meteorological conditions, which can be enhanced by climate change, land use changes, proximity to urban areas and human intervention (Reyes and Balcázar, 2021); for all or the above, its comprehensive assessment is of utmost importance in order to define actions that lead to restoring and improving its pre-fire condition.

According to the infiltration results, the variable that showed a notable change was the initial infiltration, registering a considerable decrease compared to the control, which was attributed to the changes caused by the occurrence of the fire; where the physical variables in the first centimeters of the soil are significantly modified by its disaggregation, by the accumulation of charred remains and ashes and by the erosive effect of the wind, which directly affects water flows in the soil (Stavi., 2019; Carrà et al., 2021). In this sense, Luna et al. (2024) mentíos that the effects of surface fires are immediately reflected in the size and distribution of soil pores; because the characteristics of the fire residues that combine with soil particles tend to increase their repellency (hydrophobicity) preventing the transit of water from the surface part to the interior of the soil profile (Copaja et al., 2023; Garcia et al., 2025), which can lead to flooding, runoff, contamination of water bodies and floods (Vázquez et al., 2018; Carrà et al., 2022).

On the other hand, the basic and accumulated infiltration in the burned plot presented a similarity with respect to the control plot, which may be subject to the type of fire, which due to its characteristics can be categorized as low intensity, presenting only an affectation in the superficial layer of the soil due to the accumulation of hydrophobic material, which is reflected in the behavior of the initial infiltration variable (Saneugenio et al., 2023; Luna et al., 2024). Subsequently, this resistance was reduced, thus improving the soil's capacity to infiltrate water, which is reflected in the results of the present study. Based on the basic infiltration rate classes recognized by the United States Department of Agriculture's Natural Resources Conservation System (USDA. 2001), in the control plot was categorized as moderate (50 to 120 mm hr^{-1}) and in the burned plot it was defined as moderately slow (15 to 50 mm hr^{-1}). Soil moisture contents showed a significant variation attributed to the fact that the removal of soil cover and vegetation caused by forest fires leads to a reduction in the capacity to intercept, retain and evaporate water levels (Rodriguez et al., 2014), in addition to the modification of soil conditions that sometimes, due to the type of fire, can form an impermeable layer on the soil surface that potentially affects infiltration and also favors surface runoff (González-Pelayo et al., 2024).

According to Woerner (1989), the bulk density of the soil in the control plot was categorized as very low, after the occurrence of the fire this variable increased slightly to a low status (> 1.20 g cm-3). This trend has been reported by multiple studies where they mention that fire, whether in any type of ecosystem (pine forests, oak, jungles, scrublands and grasslands) and land use, causes significant modifications in the density of the soil and therefore other variables such as soil porosity, permeability and water infiltration into the soil are modified (Granged et al. 2011; Jordán et al. 2011; Heydari et al. 2017; Kumar et al., 2025). This can be attributed to the obstruction of micro and macro pores by the presence, accumulation, and dispersion of ash and clays generated by fires (Alcañiz et al., 2018; Luna et al., 2024). On the other hand, Strydom et al. (2024) point out that fire reduces soil permeability in the short term, which was reflected in the present study. Despite, this variable tends to recover after one or two years due to the solubilization, leaching, runoff, and wind erosion of ash from the soil. Mechanical resistance to soil penetration decreased significantly after the fire; Agbeshie et al. (2022) and Luna et al. (2024) mention that this variable tends to decrease; due to the loss of soil organic matter, which weakens the structure and aggregation of the soil, which also makes it more susceptible to erosion; although, its degree of affectation directly depends on the intensity and type of fire.

5. Conclusions

In summary, our results indicate that the soil's physical and hydrological properties showed changes following the occurrence of the wildfire. This impact was evident in the soil's bulk density, porosity, mechanical resistance to penetration due to the presence of ash, particulate matter, and changes in soil aggregation. These changes together caused significant changes in the soil's pore space and, consequently, in water movement both within and above the soil profile. From a conservation perspective, the control plot remains intermediate in the assessment of the soil's physical and hydrological properties, making it possible to clearly distinguish the effects of the wildfire. Vegetation is a key factor in soil health, as maintaining soil cover regulates the soil's physical and hydrological processes. The results obtained can be useful in decision-making for those responsible for the region, considering that fires have gradually increased over the last five years.

List of abbreviations:

MRP (kg cm^{-2}): Mechanical Resitence to Penetration
Ks (cm s^{-1}): Permeability in centimeter per second
BD (grams per cm^3): Bulk density in grams per cubic centimeter
P%: Porosity as a percentage
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.

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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