CONTROLLED BURNS EFFECT ON SOIL CHEMICAL PROPERTIES

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Resumo

Efeito de queimadas controladas nas propriedades químicas do solo. Queimadas têm sido utilizadas por séculos no manejo de pastos, florestas e áreas agrícolas. Defendidas por alguns e criticadas por outros, até hoje não há um consenso na comunidade científica acerca dos seus efeitos no solo. Este estudo teve por objetivo analisar o efeito do fogo controlado nas seguintes propriedades químicas do solo: pH, H+Al, Al^{3+}, Na^+, K^+, P, M.O., Ca^{2+}, Mg^{2+} e N. Para tal, duas áreas de pastagens foram queimadas e tiveram a intensidade do fogo quantificada. O solo das áreas queimadas e de uma área controle foram amostrados em três distintos momentos: imediatamente, um e seis meses após as queimas. O fogo, durante os experimentos, apresentou baixa intensidade, variando de 23,7 a 30,91 kJ m^{-1} s^{-1}. Imediatamente após a queima, os valores de pH, Na^+, Ca^{2+}, K^+ e P, aumentaram e diferiram significativamente dos valores da área não queimada, sendo que no sexto mês após a queima, apenas os valores de K^+, P e Ca^{2+} apresentavam valores significativamente superiores em relação à área controle. Apesar dos valores de N e H+Al nas áreas queimadas e controle terem sido similares imediatamente e um mês após as queimas, após seis meses a quantidade de N foi significativamente maior em uma das áreas queimadas e de H+Al significativamente maior na área controle. As quantidades de Mg^{2+}, M.O. e Al^{3+} não sofreram interferência pelo fogo durante o período avaliado. Os resultados sugerem que queimadas de baixa intensidade podem reduzir a acidez do solo e incrementar, em curto prazo, a quantidade de determinados nutrientes essenciais ao desenvolvimento das plantas.
Palavras-chave: Manejo do Fogo; Fertilização; Nutrientes no solo; Mineralização.

Abstract

Controlled burns have been used to manage pastures, forests and agricultural fields for centuries. Defended by some and criticized by others, until today, there is still no consensus in the scientific community about the effects caused by fire on soil. This study had the objective to analyze the effect of controlled burns on soil pH, H+Al, Al^{3+}, Na^+, K^+, P, O.M., Ca^{2+}, Mg^{2+}, and N. For this propose, two different pasture plots were burned and had the fire intensity quantified. The burned soil, and from an adjacent control plot, were collected at three different moments: immediately, one and six months after the burns. The burns presented low intensity ranging from 23,7 to 30,91 kJ m^{-1} s^{-1}. Immediately after the burns the values of pH, Na^+, Ca^{2+}, K^+ and P increased in the burned plots and were significantly different from the control plot. However, six months after the burns, only the amounts of K^+, P and Ca^{2+} remained significantly larger than the control. Despite the values of the N and H+Al in burned and control areas were similar immediately and one month after the burns, after six months the amount of N was significantly larger in one of the burned plot, while the H+Al was significantly bigger in the control plot. The amounts of Mg^{2+}, O.M. and Al^{3+}did not change during the study period. The found results suggest that low-intensity controlled burns can reduce soil acidity and be effective in increasing some essential nutrients for plant development in short term.
Keywords: Fire Management; Fertilization; Soil Nutrients; Mineralization.

INTRODUCTION

The use of controlled burns as a silvopastoral management technique is a highly controversial topic. Although this technique has been employed by humans for thousands of years, its frequency has increased in recent decades, leading to direct and indirect environmental impacts.

In Brazil, as well as in many other parts of the world, controlled burns are deeply ingrained in the culture and difficult to replace. They are commonly employed for purposes such as clearing agricultural and forest areas, renewing pastures, expanding agricultural and livestock frontiers, facilitating pre-harvest management of crops like sugarcane, and controlling pests and diseases (REDIN *et al.*, 2011; WHITE, 2018). In Brazil, despite federal regulations that restrict the use of fire (the federal law 12.651/2012 only permits controlled burns with prior approval from the state environmental agency in specific locations or regions where fire is justified for agricultural or forestry practices), the reality is that the majority of burns are conducted without proper authorization, making them illegal (BRAZIL, 2012; WHITE, 2018).

Occasionally, controlled burns escalate into wildfires, where the fire spreads uncontrollably and consumes vast areas generating even more significant environmental consequences. Data collected by Santos *et al.* (2006) indicate that controlled burns accounted for approximately 24% of the wildfires registered in Brazil during the studied period, highlighting the need for better control over the use of fire as a management technique.

The burning of vegetation, whether through controlled burns or wildfires, causes a series of chemical, physical, and biological modifications to the soil (REDIN *et al.*, 2011). Despite the surface of the soil being significantly affected by fire, sometimes reaching temperatures of over 1.000 °C, the impacts on the soil below 20 cm in depth are small or even non-existent, due to the soil's excellent thermal insulation properties (WHITE *et al.*, 2013).

In addition to the immediate effect of fire on the organisms living near the soil surface, as the peak temperature during a fire is usually lethal to most living beings, fire usually affects the soil's pH and the availability of organic matter, indirectly impacting the entire soil fauna (WHITE *et al.*, 2013). During the burning process, organic matter is mineralized, releasing various nutrients into the soil. These nutrients can be reused by surviving organisms that establish themselves in the burned area or can be lost through rainfall and wind erosion. In some cases, all the mineralized organic matter can be rapidly lost, particularly in exposed sandy areas (REDIN *et al.*, 2011; SOARES; BATISTA, 2007).

Given the significant variability in the effects of fire on different environments, there is ongoing scientific debate on this subject. The intensity of the fire, its frequency, the vegetation type, the duration of the fire, soil characteristics, the presence of organisms in the soil, and other factors all influence the resulting impacts (SOARES; BATISTA, 2007; WHITE *et al.*, 2013). Therefore, establishing general patterns becomes challenging. While some authors argue that controlled burns can be beneficial when executed with care, others propose more cautious regulations and limitations on this practice due to sustainability concerns.

This study aims to analyze the effects of controlled burns on specific soil properties, including pH; potential acidity (H+Al); organic matter content (O.M.); exchangeable aluminum (Al^{3+}), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+) and potassium (K^+); phosphorus (P); and nitrogen (N). By increasing the understanding of this topic, it will be possible to contribute to the ongoing debate regarding the sustainability of controlled burn practices.

MATERIAL AND MÉTHODS

Characterization of the study area

The municipality of Nossa Senhora da Glória is located in the *Alto Sertão Sergipano* region, encompassing an area of 758.4 km² dominated by the *Caatinga* biome and with an average altitude of 291 m (Figure 1) (IBGE, 2020). The climate is classified as "As" (Equatorial with Dry Summer), with an average annual temperature of 23.4 °C and an average annual precipitation of 763 mm, with rainfall concentrated from March to August (CLIMATE-DATA, 2020).
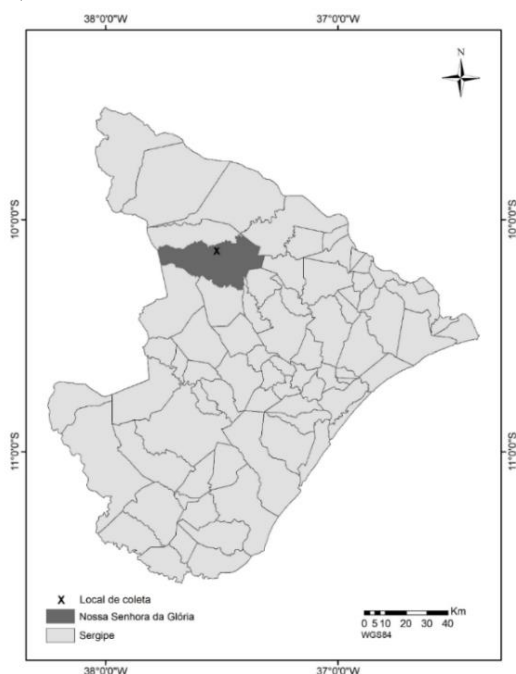

Figure 1. Location of the Nossa Senhora da Glória (SE) municipality and from the data collection site.
(Elaboration: The author).
Figura 1. Localização do município de Nossa Senhora da Glória, SE e da área de coleta dos dados.
(Elaboração: O autor).

The landscape is characterized by rocky outcrops, rugged terrain, exposed regolith, scattered shrubby *Caatinga*, and areas of herbaceous vegetation. The natural vegetation cover is relatively small, with pastures being the predominant land use (SANTOS *et al.*, 2019).

The soil is classified as Eutrophic Lithic Neosols (RLe), which is commonly found in semi-arid regions with rocky outcrops. These soils are characterized by their poor development, shallow depth, non-hydromorphic nature, and the presence of either a shallow A horizon directly over the rock or a thin C horizon. As a result, the soil has limited agricultural potential and is highly susceptible to erosion (SANTOS *et al.*, 2018).

Nossa Senhora da Glória is renowned as one of the municipalities in the dairy basin of Sergipe, supplying milk and its derivatives to neighboring municipalities in Sergipe, Bahia, and Alagoas. Additionally, the region encompasses vast areas dedicated to corn cultivation (IBGE, 2017).

Evaluation of the effects of fire

In the municipality of Nossa Senhora da Glória, it is common for farmers and ranchers to take advantage of the dry vegetation in January, as the months of October, November, and December are the driest of the year (CLIMATE-DATA, 2020), and employ controlled burns for land clearing during this period. To accurately describe the effects of vegetation fires as they typically occur in the region, experimental burns were conducted in January, utilizing the downwind burning technique.

Two pasture areas, each measuring 100 m^2, were selected for being burned at coordinates 10º05'03" S and 37º31'50" W. The areas have an altitude of 190 m and are spaced 15 meters apart at their edges. Both areas exhibited similar characteristics in terms of topography, with flat terrain and no significant slopes, and vegetation composition, consisting of herbaceous plants and some shrub species. According to information provided by the landowner, the last fire management had been carried out three years prior. Following that fire, the area had been used as pasture for one year and subsequently left unmanaged for the past two years (Figure 2). Prior to the burns, measurements of air temperature, air relative humidity, and wind speed were taken using a portable thermometer/hygrometer/anemometer (AKROM - KR825).

Figure 2. Photograph illustrating the beginning of vegetation burning experiment in one of the plots.
Figura 2. Fotografia ilustrando o início da queima da vegetação durante o experimento em uma das parcelas.
(Photograph: The author).
(Fotografia: O autor).

An adjacent area, located approximately 25 meters away from the burned plots and sharing the same characteristics in terms of size, topography, soil, and vegetation, was designated as the control area. Soil samples were collected from both the burned areas and the control area immediately after the burn, one month after the burn, and six months after the burn. No management activities were carried out in any of the areas following the burns, allowing natural ecological succession to occur.

The collected soil samples were sent to the Soil Remediation Laboratory at the Federal University of Sergipe for analysis. The following parameters were determined for each of the three sampling period: pH, H+Al, O.M., Ca^{2+}, Mg^{2+}, Al^{3+}, P, Na^+, K^+ and N.

Distribution of Plots for Soil Analysis

After the burn, a transect line was established in both the burned and control plots. The line divided the plots in half, extending from the point where the fire was initiated to the final edge. Along each transect, 10 points

were marked at one-meter intervals. At each marked point, simple soil samples weighing approximately 50 g were collected from the surface layer (0-5 cm depth) using an auger and placed in a clean bucket. Subsequently, all samples from the same area were homogenized to create a composite sample weighing approximately 500 g, which was then separated and sent to the laboratory. As a result, three soil samples, one from each burned area and one from the control area, were analyzed for each of the three sampling time intervals.

Determination of Fire Intensity

Fireline intensity refers to the amount of energy released per unit area along any point of the fire perimeter. While it cannot be measured directly, it can be calculated using mathematical equations, such as the equation developed by Byram (1959) (Equation 1). Fireline intensity is a measurement of the heat experienced by a person in close proximity to the flames and serves as a crucial variable for planning firefighting activities and assessing the environmental impacts of fire (BYRAM, 1959; WHITE *et al.*, 2016).

$$IB = H * W * R \qquad \qquad (Equação\ 1)$$

Where: IB = Byram's fireline intensity (kJ m^{-1} s^{-1});
H = Fuel heat content (kJ kg^{-1});
W = Fuel consumed by the fire (kg m^{-2});
R = Fire rate of spread (m s^{-1}).

The fuel heat content, which represents the amount of heat energy contained within a given mass of fuel, was established at 8.000 BTU lb^{-1} or 18.622 kJ kg^{-1}. This value is considered standard for live and dead fuel and is widely used in fire behavior modeling software, such as BehavePlus (SCOTT; BURGAN, 2005). Minor adjustments to this value can be made through specific studies to achieve higher precision (SCOTT; BURGAN, 2005; WHITE *et al.*, 2013). However, for the purpose of this study, the standard value was considered acceptable for measuring fire intensity in the burned plots.

To determine the amount of available fuel prior to burning, ten randomly selected 1 m² plots were chosen in each of the areas designated for burning, and had the fuel collected and weighed using destructive sampling methods (BYRAM, 1959; WHITE *et al.*, 2013). Since the fuel load is determined on a dry weight basis, sub-samples of the pre-burn fuel were taken to the laboratory for drying until reaching a constant weight and had their moisture content calculated. The same procedure was performed immediately after the burn, where the unburned fuel was collected, and its dry weight and moisture content were determined. By calculating the difference between the measured fuel load before and after the burn, the amount of fuel consumed by the fire during the experiment was determined.

During the burn, the fire rate of spread was calculated by using a stopwatch and a measuring tape to determine the time it took for the flames to cover the entire burned area.

Laboratory analyses

In the laboratory, soil samples were dried in an oven with air circulation at an average temperature of 40 °C. After drying, they were ground in a hammer mill, passed through a 2 mm diameter sieve, and then sent for analysis following the methodologies proposed by Silva (2009).

To determine the average values of the soil chemical characteristics evaluated in this study, the samples from each area (approximately 500 g) were divided into five replicates and analyzed individually. These replicates were essential because the analyses performed use a small quantity of soil, which can lead to variations when working with material from a single sample.

The quantification of soil acidity (pH) was conducted using distilled water at a soil-to-water ratio of 1:2.5, with 10 cm³ of soil and 25 ml of distilled water. The samples were stirred with a glass rod for one minute and allowed to settle for one hour. After one hour, they were stirred again, and the pH electrode was inserted into the homogenized suspension to obtain the indicated value.

Soil organic matter (M.O.) was quantified using the modified Walkley-Black method, which involves the oxidation of soil organic carbon by potassium dichromate ($K_2Cr_2O_7$) in a strongly acidic medium, resulting in the formation of carbon dioxide and water.

The determination of available phosphorus (P) in the soil was performed by measuring the intensity of blue coloration using a photometer. The chemical extractant used for the available P analysis was the Mehlich-1 or North Carolina extractant. The Mehlich solution is a mixture of hydrochloric acid (0.05 mol L^{-1}) and sulfuric acid (0.0125 mol L^{-1}). By comparing the readings of the soil samples with the P standard curve, the content of available P in the soil was calculated.

The measurement of exchangeable potassium and sodium in the soil (K^+ and Na^+) was carried out using the same extract obtained for phosphorus analysis, with the extract being filtered prior to analysis. The quantification of these elements in the soil extract was performed by flame spectrophotometry using a previously established standard curve.

Exchangeable calcium and magnesium (Ca^{2+} and Mg^{2+}) were extracted with a 1 mol L^{-1} potassium chloride (KCl) solution and jointly determined by complexometry using ethylenediaminetetraacetic acid (EDTA) as a chelating agent in the presence of the indicator eriochrome-T. The same extraction for the determination of Ca^{2+} + Mg^{2+} was also used to calculate the individual exchangeable calcium by adding potassium hydroxide, ascorbic acid, acid-calcon-carbonate indicator, and sodium sulfate to the extract. The extract was then titrated with 0.0125 mol L^{-1} EDTA until a color change from pink to blue occurred. With the determination of individual calcium, magnesium was obtained by the difference between the values of Ca^{2+} + Mg^{2+} and Ca^{2+}, and it was also expressed in $cmol_c$ dm^{-3}.

Exchangeable aluminum was quantified using a concentrated solution of potassium chloride (1 mol L^{-1}) to displace and keep the adsorbed aluminum ions in solution. Subsequently, aluminum was determined by titration in the presence of bromothymol blue indicator.

The potential acidity (H + Al) was determined using a buffered solution at pH 7.0 of calcium acetate and titration with sodium hydroxide in the presence of phenolphthalein as an indicator.

The total nitrogen analysis was performed using the Kjeldahl method, in which the sample is digested with concentrated sulfuric acid under heating at 350 °C, converting all organic nitrogen into ammonium ions. In a subsequent step, the obtained solution is alkalized with concentrated sodium hydroxide, and the ammonia produced in this step is distilled and captured by a boric acid solution, which is then titrated with standardized hydrochloric acid.

Statistical analysis

Initially, the mean values, variance, and standard deviation were determined for each of the chemical parameters evaluated in this study. The non-parametric Kruskal-Wallis test was used to verify significant differences among the means of the parameters for each sampling time interval and between the burned areas and the control area. All tests were performed at a 5% significance level using the JMP statistical package (version 10.0).

RESULTS

At 4:00 p.m. on January 17, 2019, the experimental burns were conducted. Immediately prior to the burns, the air temperature was at 28 ºC, the relative humidity 58%, and the wind speed 5 km/h. The moisture content of the live and dead fuel, measured to determine the amount of fuel consumed by the fire, had average values of 70% and 12%, respectively. In both controlled burns, the areas had a low amount of available fuel load, resulting in a low rate of fire spread and consequently, low intensity (Table 1).

Table 1.   Fuel load consumed by the fire; fuel heat content; fire rate of spread; and, fireline intensity, for the two burned sites.
Tabela 2.   Quantidade de material combustível consumida pelo fogo; poder calorífero do material combustível; velocidade de propagação do fogo; e, intensidade da linha do fogo, para as duas áreas queimadas.

Variable	Site 01	Site 02
Fuel load consumed by the fire (kg m^{-2})	0.19	0.20
Dead and live fuel heat content (kJ kg^{-1})	18,622	18,622
Fire rate of spread (m s^{-1})	0.0067	0.0083
Fireline intensity (kJ m^{-1} s^{-1})	23.7	30.91

Most of the soil chemical parameters evaluated in this study underwent some changes, either over time or when comparing the burned areas to the control area (unburned). Only the values of organic matter (O.M.), Mg^{2+}, and Al^{3+} did not vary significantly between the burned and unburned areas and across the different time intervals assessed (Table 2).

Table 2.   Mean values of the chemical parameters evaluated in this study in the two burned sites and in the control area. The values are categorized according to the time of the sampling procedure.

Tabela 2. Valores médios dos parâmetros químicos avaliados neste estudo nas duas áreas queimadas e na área controle. Os valores estão categorizados de acordo com o momento da coleta.

Parameter evaluated	Site	Immediately after the burn	1 month after the burn	6 months after the burn
pH (in water 1:2,5)	Burned 01	$6{,}97^{\updownarrow a}_{\leftrightarrow a}$	$7{,}00^{\updownarrow a}_{\leftrightarrow a}$	$6{,}22^{\updownarrow a}_{\leftrightarrow b}$
	Burned 02	$7{,}02^{\updownarrow a}_{\leftrightarrow a}$	$6{,}72^{\updownarrow a}_{\leftrightarrow a,b}$	$6{,}11^{\updownarrow a}_{\leftrightarrow b}$
	Controlled	$6{,}21^{\updownarrow b}_{\leftrightarrow a}$	$6{,}11^{\updownarrow b}_{\leftrightarrow a}$	$6{,}09^{\updownarrow a}_{\leftrightarrow a}$
H+Al ($cmol_c.dm^{-3}$)	Burned 01	$1{,}37^{\updownarrow a}_{\leftrightarrow a}$	$0{,}85^{\updownarrow a}_{\leftrightarrow b}$	$0{,}64^{\updownarrow a}_{\leftrightarrow b}$
	Burned 02	$1{,}28^{\updownarrow a}_{\leftrightarrow a}$	$0{,}90^{\updownarrow a}_{\leftrightarrow a,b}$	$0{,}66^{\updownarrow a}_{\leftrightarrow b}$
	Controlled	$1{,}26^{\updownarrow a}_{\leftrightarrow a,b}$	$1{,}02^{\updownarrow a}_{\leftrightarrow a}$	$1{,}40^{\updownarrow b}_{\leftrightarrow b}$
Al^{3+} ($cmol_c.dm^{-3}$)	Burned 01	$0^{\updownarrow a}_{\leftrightarrow a}$	$0^{\updownarrow a}_{\leftrightarrow a}$	$0^{\updownarrow a}_{\leftrightarrow a}$
	Burned 02	$0^{\updownarrow a}_{\leftrightarrow a}$	$0^{\updownarrow a}_{\leftrightarrow a}$	$0^{\updownarrow a}_{\leftrightarrow a}$
	Controlled	$0^{\updownarrow a}_{\leftrightarrow a}$	$0^{\updownarrow a}_{\leftrightarrow a}$	$0^{\updownarrow a}_{\leftrightarrow a}$
Na^+ ($cmol_c.dm^{-3}$)	Burned 01	$0{,}21^{\updownarrow a}_{\leftrightarrow a}$	$0{,}15^{\updownarrow a}_{\leftrightarrow a,b}$	$0{,}10^{\updownarrow a}_{\leftrightarrow b}$
	Burned 02	$0{,}18^{\updownarrow a}_{\leftrightarrow a}$	$0{,}15^{\updownarrow a}_{\leftrightarrow a,b}$	$0{,}11^{\updownarrow a}_{\leftrightarrow b}$
	Controlled	$0{,}10^{\updownarrow b}_{\leftrightarrow a}$	$0{,}07^{\updownarrow b}_{\leftrightarrow a}$	$0{,}08^{\updownarrow a}_{\leftrightarrow a}$
K^+ ($cmol_c.dm^{-3}$)	Burned 01	$1{,}40^{\updownarrow a}_{\leftrightarrow a}$	$0{,}98^{\updownarrow a}_{\leftrightarrow b}$	$0{,}90^{\updownarrow a}_{\leftrightarrow b}$
	Burned 02	$1{,}85^{\updownarrow a}_{\leftrightarrow a}$	$1{,}20^{\updownarrow a}_{\leftrightarrow b}$	$0{,}92^{\updownarrow a}_{\leftrightarrow b}$
	Controlled	$0{,}60^{\updownarrow b}_{\leftrightarrow a}$	$0{,}57^{\updownarrow b}_{\leftrightarrow a}$	$0{,}49^{\updownarrow b}_{\leftrightarrow a}$
P ($mg.dm^{-3}$)	Burned 01	$159{,}00^{\updownarrow a}_{\leftrightarrow a}$	$184{,}54^{\updownarrow a}_{\leftrightarrow a}$	$164{,}65^{\updownarrow a}_{\leftrightarrow a}$
	Burned 02	$136{,}10^{\updownarrow a}_{\leftrightarrow a}$	$171{,}49^{\updownarrow a}_{\leftrightarrow b}$	$159{,}31^{\updownarrow a}_{\leftrightarrow a,b}$
	Controlled	$48{,}07^{\updownarrow b}_{\leftrightarrow a}$	$65{,}24^{\updownarrow b}_{\leftrightarrow a}$	$56{,}60^{\updownarrow b}_{\leftrightarrow a}$
O.M. ($g.kg^{-1}$)	Burned 01	$39{,}63^{\updownarrow a}_{\leftrightarrow a}$	$40{,}25^{\updownarrow a}_{\leftrightarrow a}$	$37{,}16^{\updownarrow a}_{\leftrightarrow a}$
	Burned 02	$37{,}11^{\updownarrow a}_{\leftrightarrow a}$	$51{,}53^{\updownarrow a}_{\leftrightarrow a}$	$48{,}69^{\updownarrow a}_{\leftrightarrow a}$
	Controlled	$44{,}00^{\updownarrow a}_{\leftrightarrow a}$	$48{,}69^{\updownarrow a}_{\leftrightarrow a}$	$45{,}40^{\updownarrow a}_{\leftrightarrow a}$
Ca^{2+} ($cmol_c.dm^{-3}$)	Burned 01	$6{,}69^{\updownarrow a,b}_{\leftrightarrow a}$	$7{,}00^{\updownarrow a}_{\leftrightarrow a,b}$	$8{,}07^{\updownarrow a}_{\leftrightarrow b}$
	Burned 02	$7{,}80^{\updownarrow b}_{\leftrightarrow a}$	$6{,}58^{\updownarrow a}_{\leftrightarrow a}$	$7{,}92^{\updownarrow a}_{\leftrightarrow a}$
	Controlled	$5{,}35^{\updownarrow a}_{\leftrightarrow a}$	$4{,}16^{\updownarrow b}_{\leftrightarrow a}$	$5{,}90^{\updownarrow b}_{\leftrightarrow a}$
Mg^{2+} ($cmol_c.dm^{-3}$)	Burned 01	$2{,}63^{\updownarrow a}_{\leftrightarrow a}$	$2{,}70^{\updownarrow a}_{\leftrightarrow a}$	$2{,}31^{\updownarrow a}_{\leftrightarrow a}$
	Burned 02	$2{,}55^{\updownarrow a}_{\leftrightarrow a}$	$2{,}82^{\updownarrow a}_{\leftrightarrow a}$	$2{,}04^{\updownarrow a}_{\leftrightarrow a}$
	Controlled	$2{,}28^{\updownarrow a}_{\leftrightarrow a}$	$2{,}53^{\updownarrow a}_{\leftrightarrow a}$	$1{,}95^{\updownarrow a}_{\leftrightarrow a}$
N ($g.kg^{-1}$)	Burned 01	$1{,}53^{\updownarrow a}_{\leftrightarrow a,b}$	$1{,}31^{\updownarrow a}_{\leftrightarrow a}$	$1{,}81^{\updownarrow a,b}_{\leftrightarrow b}$
	Burned 02	$1{,}48^{\updownarrow a}_{\leftrightarrow a}$	$1{,}68^{\updownarrow a}_{\leftrightarrow a}$	$2{,}04^{\updownarrow b}_{\leftrightarrow b}$
	Controlled	$1{,}59^{\updownarrow a}_{\leftrightarrow a}$	$1{,}47^{\updownarrow a}_{\leftrightarrow a}$	$1{,}62^{\updownarrow a}_{\leftrightarrow a}$

*Note: Different letters indicate significantly different means according to the Kruskal-Wallis test. Superscript letters preceded by the symbol "↕" are for the three different areas within the same time interval (vertical). Subscript letters preceded by the symbol "↔" are for the same area across the three different time intervals (horizontal).

DISCUSSION

Controlled burns conducted in this study had a low intensity, as according to the classification adopted by Andrews (1982), burns with fireline intensity below 350 kJ m^{-1} s^{-1} are classified as low intensity. This low intensity was attributed due to the low fuel load available in the areas, which had been abandoned and regenerating for only two years, and also due to the small size of the burned areas. Larger burns would result in more heating of the air and, consequently, a greater movement of air masses, which could positively influence fire spread and intensity. Therefore, it is essential to consider the fire intensity when analyzing and discussing the results obtained in this study.

Below, all the measured chemical parameters will be individually presented and discussed, aiming to evaluate if the fire had any influence on its values, as well as to compare the obtained data with other published studies.

pH: Immediately after burning, the average pH of the burned areas significantly increased compared to the unburned soil, remaining significantly higher in the first month after the burn. However, after six months, the pH of the burned soils decreased and was no longer significantly different from the control plot. This reduction may be attributed to the loss of exchangeable bases from the soil, which were mineralized during vegetation burn. These results are consistent with findings in the literature, which state that organic matter burn produces alkaline compounds such as oxides and carbonates, reducing soil acidity, especially near the soil surface. This alkaline reaction can stimulate nitrification and vegetative growth, but the duration of the effect varies depending on fire intensity; soil and vegetation characteristics; and other parameters (HERINGER *et al.*, 2002; LORENZON *et al.*, 2014; SOARES; BATISTA, 2007). In a study conducted in native grassland areas subjected to prolonged fire management activities, Heringer *et al.* (2002) concluded that the pH tends to be higher in burned native fields compared to other treatments.

H + Al: There was no significant difference in the average potential acidity between the burned and control areas immediately after burning. However, in the burned areas, there was a gradual reduction in potential acidity over time, resulting in the average potential acidity of the burned areas being significantly lower than the control area in the sampling performed 6 months after the use of fire. Vegetation burn typically results in higher aluminum saturation and potential acidity of the soil (HERINGER *et al.*, 2002). However, there are also studies that do not report changes or even a reduction in soil potential acidity due to fire. For example, Magallanes *et al.* (2020) found no significant difference in potential acidity 24 hours after a controlled burn in the Brazilian Cerrado. The variation in potential acidity observed in different periods in this study may be associated with external interferences such as precipitation events.

Al^{3+}: No exchangeable aluminum was detected in any of the samples, as soils with a pH above 5.5 rarely have exchangeable Al^{3+} (NATALE *et al.*, 2012). The presence of calcium carbonate in the soil and low rainfall favor the absence of high acidity in the region's soils.

Na+: The average values of exchangeable sodium were higher in soil samples obtained immediately after the burns and one month later, compared to the control area. However, after six months, the sodium content in both burned areas significantly decreased from the values obtained immediately after the burns, reaching a value close to and no longer significantly different from the one obtained in the control plot. These findings are similar to those described by Nghalipo *et al.* (2019) when analyzing the effect of fire in a savannah area in Namibia. According to the authors, the levels of P, K^+, Na^+, Mg^{2+}, and Ca^{2+} increase immediately after the fire due to their presence in the ash deposited on the soil after the burn and consistently decrease over time. Although most studies report an initial increase in Na^+ after the fire, diverse results can be found. Pereira *et al.* (2017), for example, reports that low intensity burning in grassland areas in Lithuania did not result in a significant variation in the amount of Na^+.

K^+: Immediately after the burn, the amount of exchangeable potassium in the soil of the burned areas significantly increased (on average 2.7 times compared to the control area), and although its values decreased over time in the burned areas, it remained significantly higher six months later compared to the controlled value. Several studies report an increase in exchangeable K^+ in the soil immediately after fire due to the high concentration of this nutrient in the ash (e.g., Nghalipo *et al.*, 2019; Redin *et al.*, 2011). Unlike nitrogen, cations such as Ca^{2+}, Mg^{2+}, K^+, and Na^+ are not volatilized by fire. However, this increase tends to disappear in the medium term through soil leaching by rainfall (Soares & Batista, 2007).

P: The amount of phosphorus increased after the burn (on average 3 times). However, it did not decrease over time and remained significantly higher 6 months after the burn compared to the control plot. In a literature review involving 139 soil studies and 39 litter studies, Butler *et al.* (2018) concluded that fire leads to higher levels of mineral P in the soil, as well as significantly lower C:P and N:P ratios. According to the same authors, these results demonstrate that fire has a P rich signature in the soil-plant system that varies with the type of vegetation.

O.M.: Regarding the effect of fire on soil organic matter (O.M.), the results obtained in this study did not indicate any significant modification. It is know that several variables influence the amount of available O.M. in the soil after the burn, as fire intensity, vegetation type, and soil texture (Soares & Batista, 2007). Therefore, different results regarding this aspect can be found in literature, ranging from total consumption of the O.M. to virtually no change. In a study conducted in a natural pasture area in Rio Grande do Sul, comparing a site managed through burns for 100 years and a control plot managed without fire, the O.M. levels in the soils of both areas also remained unchanged (Heringer *et al.*, 2002). In contrast, a study conducted in Spain on shrubland areas subjected to controlled burns observed a significant reduction in the amount of O.M. in the top 3 cm of the soil (Armas-Herrera *et al.*, 2016).

Ca^{2+}: The average amount of Ca^{2+} in the burned areas was higher than the values in the control area during all time intervals evaluated. As previously mentioned, most studies examining the effects of controlled burns on the quantity of available nutrients in the soil report an increase in Ca^{2+} after fire, as the ash contains a large amount of this nutrient (Redin *et al.*, 2011). However, it should be noted that studies investigating the effects of repeated burns over several years state that fire, in the long term, increases soil acidity and reduces availability of nutrients such as Ca^{2+}, Mg^{2+}, and K^+, as the exposed soil, without vegetation cover, becomes susceptible to the impact of raindrops, greatly increasing the risk of nutrient losses through erosion (Heringer *et al.*, 2002).

Mg^{2+}: Although the average amount of exchangeable Mg^{2+} in the soil during the three collection periods was slightly higher in the burned areas, this difference was not statistically significant. Most studies involving controlled and low-intensity burns report an increase in both Ca^{2+} and Mg^{2+} in the mineralized superficial layer of the soil (Pereira *et al.*, 2017). The small and nonsignificant variation in the amount of Mg^{2+} between the burned areas and the control plot in this study suggests that due to the small amount of burned fuel and the low intensity of the fires, only a small and nonsignificant amount of this nutrient was mineralized and made available on the soil surface.

N: The average total nitrogen did not vary significantly between the burned areas and the control area immediately after the burn and 1 month after the burn. However, Area 02 showed a significant difference compared to the control area after 6 months. According to Soares and Batista (2007), there is a reduction in the total nitrogen content on the soil surface after fire, which is proportional to the fire intensity. However, the same authors also state that the activity of nitrogen fixing soil microorganisms is intensified after a burn, leading to a subsequent increase in mineralized nitrogen. Thus, although fire volatilizes part of the total nitrogen, the increased activity of nitrogen fixing organisms after the burn can replenish this loss. For savannah and forest areas subject to frequent burning over several years, Pellegrini *et al.* (2018) stated that both N and C quantities were significantly reduced over time. They reported a 38% reduction in N in burned areas compared to fire-protected areas. The results of this study suggest that low-intensity burning has little effect on nitrogen volatilization. The increase in total N in burned Area 02, in the sixth-month sampling, may indicate an increase in the activity of nitrogen fixing microorganisms after the fire.

Based on the data obtained in this study and the analysis of existing publications on the subject, there is a wide variety of distinct results regarding the effects of fire on soil chemical parameters. Therefore, it is suggested that all studies aiming to quantify such effects provide a precise description of the components that can interfere with the results, including soil and burned vegetation type; fire intensity; time since the last burn; post-burn soil management; and environmental conditions, particularly rainfall, between the burn event and soil sampling for analysis. Only with an adequate description of all parameters that can influence the effects of fire on soil chemical properties, it will be possible to establish patterns and increase knowledge on the subject.

CONCLUSIONS

- Fire, even at low intensity (ranging from 23.7 to 30.91 $kJ\ m^{-1}\ s^{-1}$), was responsible for altering the chemical proprieties of the soil. Immediately after the burn, pH, Na^+, Ca^{2+}, K^+, and P values increased and differed from those of the unburned area. Six months after the burns, the K^+, P, and Ca^{2+} values still remained significantly higher compared to the unburned control area.
- Although N and H+Al values in the burned and control areas were similar immediately and one month after the burns, after six months, the amount of N was significantly higher in one of the burned areas, and H+Al was significantly higher in the control area, suggesting the possibility of long-term effects of fire on these parameters.
- The amounts of Mg^{2+}, organic matter (M.O.), and Al^{3+} were not affected by the fire during the evaluated period.
- Due to similar soil characteristics, vegetation, management practices and climate, both burned areas did not present significant differences in the soil chemical proprieties when compared to each other. This

emphasizes the importance of analyzing such independent factors in studies involving the effect of fire on the soil, and the need for caution when comparing the results obtained in this study with others.

- It is highly recommended that future studies evaluating the effect of fire on soil chemical properties also quantitatively measure the fire intensity. Only this way it will be possible to elucidate the intrinsic relationship between both variables.

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REFERENCES

ANDREWS, P. L. **Charts for interpreting wildland fire behavior characteristics**. Ogden: USDA Forest Service, Intermountain Forest and Range Experiment Station., 1982. (General Technical Report INT-131)

ARMAS-HERRERA, C. M.; MARTÍ, C.; BADÍA, D.; ORTIZ-PERPIÑÁ, O.; GIRONA-GARCÍA, A.; PORTA, J. Immediate effects of prescribed burning in the Central Pyrenees on the amount and stability of topsoil organic matter. **Catena**, [S.l.], v. 147, p. 238-244, 2016. DOI: https://doi.org/10.1016/j.catena.2016.07.016

BRASIL. **Lei nº 12.651, de 25 de maio de 2012**. Dispõe sobre a proteção da vegetação nativa; altera as Leis nos 6.938, de 31 de agosto de 1981, 9.393, de 19 de dezembro de 1996, e 11.428, de 22 de dezembro de 2006; revoga as Leis nos 4.771, de 15 de setembro de 1965, e 7.754, de 14 de abril de 1989, e a Medida Provisória no 2.166-67, de 24 de agosto de 2001; e dá outras providências. Diário Oficial da União, Brasília, DF, 28 de maio de 2012. Disponível em: <http://www.planalto.gov.br/ccivil_03/_ato2011-2014/2012/lei/l12651.htm> Acesso em: 24 de junho de 2022.

BUTLER, O. M.; ELSER, J. J.; LEWIS, T.; MACKEY, B.; CHEN, C. The phosphorus-rich signature of fire in the soil–plant system: a global meta-analysis. **Ecology letters**, Oxford, v. 21, n. 3, p. 335-344, 2018. DOI: https://doi.org/10.1111/ele.12896

BYRAM, G. M. Combustion of Forest Fuels. In: DAVIS, K. P. (ed.). **Forest Fire**: Controlled and Use. New York: McGraw-Hill, 1959, p. 61-89.

CLIMATE-DATA. **Nossa Senhora da Glória Clima (Brasil)**. 2020. Disponível em: <https://pt.climate-data.org/america-do-sul/brasil/sergipe/nossa-senhora-da-gloria-42976/> Acesso em: 07 nov. 2020.

HERINGER, I.; JACQUES, A. V. Á.; BISSANI, C. A.; TEDESCO, M. Características de um Latossolo Vermelho sob pastagem natural sujeita à ação prolongada do fogo e de práticas alternativas de manejo. **Ciência Rural**, Santa Maria, v. 32, n. 2, p. 309-314, 2002. DOI: https://doi.org/10.1590/S0103-84782002000200021

IBGE – Instituto Brasileiro de Geografia e Estatística. **Área da unidade territorial**: Área territorial brasileira. Rio de Janeiro: IBGE, 2020.

IBGE - Instituto Brasileiro de Geografia e Estatística. **Censo Agropecuário**. Rio de Janeiro: IBGE, 2017.

LORENZON, A. S.; BRIANEZI, D.; VALDETARO, E. B.; DE SOUZA, C. M.; MARTINS, S. V.; RIBEIRO, C. A. A. S.; JACOVINE, L. A. G. Análise química de um solo florestal após ocorrência de fogo. **Revista Brasileira de Agropecuária Sustentável,** Campos dos Goytacazes, v.4, n.2, p.142-147, 2014. DOI: https://doi.org/10.21206/rbas.v4i2.269

MAGALLANES, S. R. S.; GIONGO, M.; CARVALHO, E. V. D.; ROTILI, E. A.; FERNANDES, A. C.; CACHOEIRA, J. N.; SANTOS, G. R. D. Immediate Effects of Prescribed Burning on Chemical Properties of the Cerrado Soil. **Floresta e Ambiente**, Seropédica, v. 27, n. 3, 2020. DOI: http://dx.doi.org/10.1590/2179-8087.025318

NATALE, W.; ROZANE, D. E.; PARENT, L. E.; PARENT, S. É. Acidez do solo e calagem em pomares de frutíferas tropicais. **Revista Brasileira de Fruticultura**, São Paulo, v. 34, n. 4, p. 1294-1306, 2012. DOI: https://doi.org/10.1590/S0100-29452012000400041

NGHALIPO, E.; JOUBERT, D.; THROOP, H.; GROENGROEFT, A. The effect of fire history on soil nutrients and soil organic carbon in a semi-arid savanna woodland, central Namibia. **African journal of range & forage science**, Pietermaritzburg, v. 36, n. 1, p. 9-16, 2019. DOI: https://doi.org/10.2989/10220119.2018.1526825

PELLEGRINI, A. F. *et al.* Fire frequency drives decadal changes in soil carbon and nitrogen and ecosystem productivity. **Nature**, London, v. 553, n. 7687, p. 194-198, 2018. DOI: https://doi.org/10.1038/nature24668

PEREIRA, P. *et al.* Short-term low-severity spring grassland fire impacts on soil extractable elements and soil ratios in Lithuania. **Science of the Total Environment**, Amsterdam, v. 578, p. 469-475, 2017. DOI: https://doi.org/10.1016/j.scitotenv.2016.10.210

REDIN, M.; SANTOS, G. D. F. D.; MIGUEL, P.; DENEGA, G. L.; LUPATINI, M.; DONEDA, A.; SOUZA, E. L. D. Impactos da queima sobre atributos químicos, físicos e biológicos do solo. **Ciência Florestal**, Santa Maria, v. 21, n. 2, p. 381-392, 2011. DOI: https://doi.org/10.5902/198050983243

SANTOS, H. G.; JACOMINE, P. K. T.; ANJOS, L. H. C.; OLIVEIRA, V. A.; LUMBRERAS, J. F.; COELHO, M. R.; CUNHA, T. J. F. **Sistema brasileiro de classificação de solos**. Brasília: Embrapa, 2018.

SANTOS, R. S.; LIRA, D. R.; SANTOS C. A.; PINTO J. E. S. S. Unidades de Paisagem no Alto Sertão Sergipano. In: PINHEIRO, L. S.; GORAYEB, A. (org.). **Geografia Física e as Mudanças Globais**. Fortaleza: Editora UFC, 2019.

SCOTT, J. H.; BURGAN, R. E. **Standard fire behavior fuel models**: a comprehensive set for use with Rothermel's surface fire spread model. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 2005.

SILVA, F. C. **Manual de análise química de solos, plantas e fertilizantes**. Brasília: Embrapa Solos, 2009.

SOARES, R. V.; BATISTA, A. C. **Incêndios florestais: controle, efeitos e uso do fogo**. Curitiba: Universidade Federal do Paraná, 2007.

WHITE, B. L. A; WHITE, L. A. S.; RIBEIRO, G. T.; SOUZA, R. M. Empirical models for describing fire behavior in Brazilian commercial eucalypt plantations. **Cerne**, Lavras, v. 22, n. 4, p. 397-406, 2016. DOI: https://doi.org/10.1590/0104776020162204222

WHITE, B. L. A.; RIBEIRO, G. T.; MELO E SOUZA, R. Efeito do fogo na população de artrópodes e seu uso como bioindicadores para conservação ambiental. In: SOUZA, R. M.; SILVA M. S. F. (org.) **Conservação Ambiental e Planejamento Territorial**. Porto Alegre: Redes, 2013, p. 19-28.

WHITE, B. L. A.; RIBEIRO, A. S.; RIBEIRO, G. T.; SOUZA, R. M. Building fuel models and simulating their surface fire behavior in the "Serra de Itabaiana" National Park, Sergipe, Brazil. **Floresta**, Curitiba, v. 43, n. 1, p. 27-38, 2013. DOI: http://dx.doi.org/10.5380/rf.v43i1.28034

WHITE, B. L. A. Spatiotemporal variation in fire occurrence in the state of Amazonas, Brazil, between 2003 and 2016. **Acta Amazonica**, Manaus, v. 48, n. 4, p. 358-367, 2018. DOI: https://doi.org/10.1590/1809-4392201704522