Revista Brasileira de Geomorfologia

v. 27, nº 3 (2026)

http://dx.doi.org/10.20502/rbg.v27i3.2769

https://rbgeomorfologia.org.br/
ISSN 2236-5664

Research Article

Short-term post-fire changes in soil properties and soil suction responses over time in forested soil affecting shallow landslides: field experiments in Nova Friburgo, SE-Brazil

Efeitos imediatos do fogo nas propriedades do solo e respostas da sucção ao longo do tempo em solo florestal e implicações em deslizamentos translacionais: experimentos de campo em Nova Friburgo, SE-Brasil

Letícia Bolsas [1], Ana Luiza Coelho Netto [2]

[1] Universidade Federal do Rio de Janeiro, Programa de Pós-Graduação em Geografia, Rio de Janeiro, Brasil. E-mail: leticiabufrj@gmail.com
ORCID: https://orcid.org/0000-0002-0144-1380

[2] Universidade Federal do Rio de Janeiro, Programa de Pós-Graduação em Geografia, Rio de Janeiro, Brasil. E-mail: ananetto@acd.ufrj.br
ORCID: https://orcid.org/0000-0003-0158-0994

Received: 18/11/2025; Accepted: 13/08/2026; Published: 25/08/2026

Abstract: Rainfall-induced shallow landslides are frequent hazards in mountainous regions. Although several factors influence their occurrence, the role of fire in triggering such events remains poorly explored, particularly in tropical environments. This study investigated fire as a conditioning factor for shallow landslides through an experimental fire at a 12 m² site covered with degraded Atlantic rainforest. Soil suction was monitored at different depths for two years after the fire at both burned and unburned sites. Soil texture, bulk density, total porosity, organic matter, and true density were analyzed before the fire and 2, 15, and 30 days after, down to 50 cm; bulk density was also assessed at 8 months. Results showed short-term changes in soil properties within 2 days, limited to the soil surface (<5 cm). Changes in soil suction were observed 3 months post-fire in the upper soil and at depth after 6 months. Suction at the burned site was up to five times higher than at the control site. This response is hypothesized to be linked to rapid post-fire vegetation recovery - indirectly observed in the field and through soil temperature data – in addition to the short-term changes in soil properties investigated at the study site. These findings demonstrate that fire can significantly modify parameters critical for slope stability.

Keywords: wildfire; vegetation; slope stability; field monitoring; pore water pressure.

Resumo: Deslizamentos translacionais induzidos por chuva são ameaças frequentes em regiões montanhosas. Embora diversos fatores influenciem sua ocorrência, o papel do fogo na deflagração desses eventos permanece pouco explorado, especialmente em ambientes tropicais. Este estudo investigou o fogo como fator condicionante para deslizamentos rasos por meio de um experimento de queima em uma área de 12 m² coberta por Mata Atlântica degradada. A sucção do solo foi monitorada em diferentes profundidades por dois anos após o fogo, tanto no local queimado quanto em área controle. A textura do solo, densidade aparente, porosidade total, matéria orgânica e densidade real foram analisadas antes da queima e 2, 15 e 30 dias depois, até 50 cm de profundidade; a densidade aparente também foi avaliada após 8 meses. Os resultados mostraram alterações de curto prazo nas propriedades do solo dentro de 2 dias, limitadas à superfície do solo (<5 cm). Mudanças na sucção do solo foram observadas 3 meses após o fogo nas camadas superficiais e, em profundidade, após 6 meses. A sucção no local queimado foi até cinco vezes maior do que no local controle. Essa resposta é hipotetizada como estando relacionada à rápida recuperação da vegetação pós-fogo - observada indiretamente em campo e por meio de dados de temperatura do solo - além das mudanças de curto prazo nas propriedades do solo investigadas na área de estudo. Esses achados demonstram que o fogo pode modificar significativamente parâmetros críticos para a estabilidade de encostas.

Palavras-chave: incêndio; vegetação; estabilidade de encostas; monitoramento de campo; poropressão de água.

1. Introduction

Extreme rainfall-induced landslides are natural phenomena in mountainous domains and play an essential role in landscape evolution (Korup et al. 2010; Coelho Netto et al. 2013). In Southeast Brazil, slope lowering and retreat are primarily related to shallow translational, debris flows, and rock fall mechanisms (Lacerda 2007), which are related to different combinations of variable controls such as local geology, geomorphology, soil, vegetation, and human interference. However, ongoing climate change, marked by the progressive increase in periods of drought and extreme rainfall (IPCC 2021; Alves et al. 2021) combined with changes in vegetation since the Holocene (Facadio et al. 2024), and, more recently, with human-induced changes in land use, has been affecting the recurrence time-intervals of this natural phenomenon (Gariano and Guzzetti 2016) and increasing the magnitude of socio-environmental impacts (Coelho Netto et al. 2013; Alcantara et al. 2023; Silva et al. 2024).

In the mountainous domain of the Serra do Mar, in the state of Rio de Janeiro, Southeast Brazil, such droughts have favored the occurrence of wildfires, especially around urban areas, which then spread uphill and along watersheds (Bolsas et al. 2022). In recent years, fire has been identified as a possible key driver in increasing the triggering of shallow landslides (Rengers et al. 2020; Lei et al. 2022; Abdollahi et al. 2023; Coelho Netto et al. 2024; Ramirez et al. 2024).

Many authors indicate the role of fire in altering the physical properties of soils and its effects on hydrological and hydro-erosive processes. Fire can lead to changes in the soil-water-vegetation interface by promoting alterations in the organic matter content, texture, bulk density, stability of soil aggregates, hydrophobicity, infiltration, and surface erosion (DeBano 2000; Doerr et al. 2000; Shakesby and Doerr 2006). In addition to post-fire changes in hydro-erosive processes, there is well-established literature investigating post-fire debris flows initiated by runoff erosion due to overland flow (Wells, 1987; Cannon et al. 2003; Wall et al. 2020). However, studies investigating shallow landslides after wildfires have only begun to develop in recent years (Rengers et al. 2020; Lei et al. 2022; Abdollahi et al. 2023).

Despite the increasing scientific research on this topic (Akosah and Gratchev 2025), there are still few studies that effectively investigate the effects of fire on the hydromechanical behavior of soils in relation to the triggering of shallow landslides based on field data, especially in tropical regions. Thus, uncertainty remains in linking the triggering of shallow translational landslides in burned areas directly to fire effects due to limited data availability on this topic (Parise and Cannon 2012).

Recent studies in temperate regions, mainly covered by pine forest, indicate that there is a time window in which landscapes are more susceptible to shallow translational landslides, which is between 2 and 3 years after fire (Rengers et al. 2020; Lei et al. 2022; Abdollahi et al. 2023). These authors suggest that the landscape would be more prone to shallow landslides when vegetation is in the initial regrowth stage, which allows more water into the soil through infiltration and there is increased soil moisture due to decreased evapotranspiration (Helvey 1980; Megahan 1983), in addition to there being a lack of soil anchorage by roots.

Although most studies address an increase in soil moisture after fire, in a tropical region, in post-fire herbaceous-shrubby vegetation, Coelho Netto et al. (2024) reported a delayed increase in soil suction at a depth of 150 cm around six months after a fire at the end of the drier season. This increase in soil suction would confer an apparent stability to the soil. However, the latter authors suggest that shallow landslides could be triggered by rapid soil suction loss during the following rainy season, increasing pore water pressure to trigger shallow landslides.

In this context, it is not well understood what effects fire has on the hydromechanical behavior of soil that could favor the triggering of shallow translational landslides. In addition, since landslides are among the most significant hazards capable of causing disasters, it is crucial to understand the role of fire effects on landslide triggers to effectively mitigate their impact and reduce damage. Therefore, this study aims to investigate the impact of fire on soil properties that may affect slope stability. To achieve this goal, the following questions are addressed: (1) How does soil suction respond to fire over time? (2) How deep can this effect spread into the soil profile? and (3) Can post-fire soil characteristics and properties contribute to these effects?

2. Methods

2.1. Study site

The study area is located in the Serra do Mar mountainous domain, at an altitude of 1,050 m, in the southeast of the municipality of Nova Friburgo (22°19'7.57" S, 42°16'57.37" W) in the state of Rio de Janeiro, Brazil. The original vegetation cover was dominated by Upper Montane Atlantic Rainforest, which has been substituted by secondary forest with a high degree of degradation and fragmentation (Ribeiro et al. 2009; Fundação SOS Mata Atlântica and INPE 2021), resulting from long-term slash-and-burn practices. The mean annual temperature is 16°C, and the mean annual rainfall is 1,469.3 mm (Coelho Netto et al. 2024). Rainfall is mainly concentrated during the summer months, between December and March, and the driest months usually occur between June and September. Long-term daily rainfall records (1950-2020) indicate a secular trend of an increasing number of dry days per year (Coelho Netto et al. 2024).

Fire is a recurring phenomenon in Nova Friburgo, where an average of 316 occurrences per year has been recorded by the 6th Military Fire Department, considering the records between 2014 and 2024 (Coelho Netto et al. 2024; Bolsas et al. 2019). The most critical years were 2014 and 2024, with 488 and 516 occurrences recorded, respectively. Fires occur predominantly at the end of the dry period, between August and October, and can exceed 150 occurrences in just one month. According to previous studies, these fires are caused by humans, typically ignited near roads and streets where the vegetation is drier, before spreading upslope, reaching long distances through the ridges (Bolsas et al. 2022).

2.2. Experimental Setting

Field investigations were conducted near the foot of a rocky escarpment, within a convex-straight interfluve, characterized by an east-facing slope of around 20° overlapped by a thin (~2 m deep), block-rich colluvial deposit (Figure 1). The slope is covered by a degraded patch of secondary forest, which is approximately 40 years old and developed after agricultural use of slash-and-burn type. The surrounding matrix is dominated by grass and cattle grazing. Two sampling sites were established along the forest edge, one being the burned site, where the controlled burning experiment was conducted, and the other being the control site that remained unburned. The experiment is representative of slopes covered by one type of vegetation, which was affected by landslides in the last extreme rainfall event in 2011, and that is also affected by wildfires in the municipality (Silva et al. 2022; Coelho Netto et al. 2013).

It is worth mentioning that the study area presents a volume of 30.64 $m^3 ha^{-1}$ of coarse woody debris (Oliveira et al. to be published), which is higher than values found in the interior of the same fragment (10.08 $m^3 ha^{-1}$) and other studies from secondary Atlantic Forest fragments (Villanova et al. 2019). This elevated amount of deadwood is likely associated with the strong wind exposure at the forest edge, which increases tree mortality and promotes the accumulation of woody debris on the forest floor. Therefore, the site naturally exhibits a high potential fuel load compared to more sheltered forest interiors.

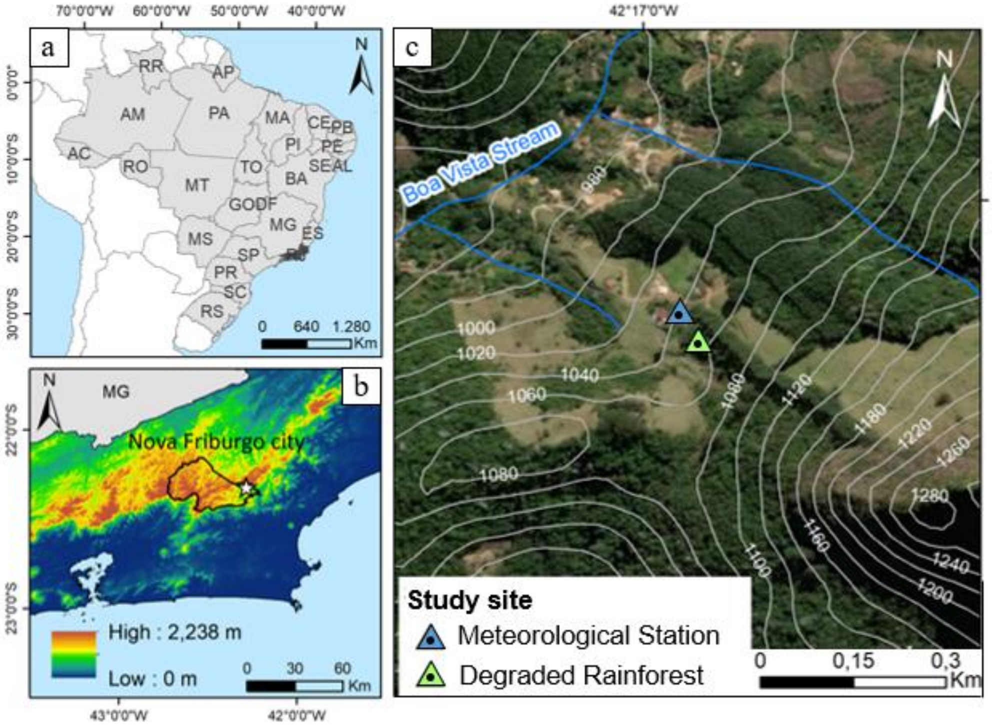

Figure 1. Location of the study area: a) in Southeast Brazil, within the state of Rio de Janeiro; b) situated in the city of Nova Friburgo, in the Serra do Mar mountain region; and c) the specific study site covered by degraded Rainforest and the location of the meteorological station, both at a drainage headwater in the upper sub-basin of the Boa Esperança River, near the Boa Vista Stream.

The burning experiment consisted of applying a controlled fire within an area of 3 × 4 m (Figure 2a). To prepare the terrain for burning, the smaller trunks (DBH < 5 cm) of the individual trees were cut at breast height to prevent the flames from spreading through the forest canopy (Fig. 2b). The thinner material cut from the tree canopy, such as branches and leaves, was used as fuel for burning (Figure 2c). Although the exact dry mass of the added biomass was not quantified, the material used originated exclusively from the individuals already present within the experimental plot and with small diameter. Thus, no external fuel was introduced into the system.

The addition and surface redistribution of this biomass were designed to simulate an extreme but plausible scenario of fuel availability. Considering the edge condition of the fragment and its recurrent exposure to strong winds, it is reasonable to assume situations in which branches and recently fallen woody debris accumulate on the ground. Merganič et al. (2022) recorded a high volume of deadwood in wind-disturbed forests in Europe, supporting the plausibility of high fuel accumulation following strong wind events. In this sense, the experiment does not aim to represent a typical low-intensity understory burn, but rather a high-intensity surface fire under conditions of elevated fuel load.

This preparation was carried out 15 days before the experiment to allow the fuel to lose moisture. Finally, a 1 m firebreak was made around the experimental setting on the day of the burning to prevent the fire from spreading beyond the limits of the experiment. These practices were carried out entirely by two rural farmers with knowledge of burning techniques and experience in this management practice.

Figure 2. Experiment site a) before the experiment; b) during land preparation before controlled burning, showing the cutting of individual trees; and c) thinner material cut from the tree canopy, such as branches and leaves, left to dry in the air to use as fuel for burning.

The experiment was carried out on August 06, 2022, with a total duration of 2 hours of active flames to simulate a high-severity fire (Figure 3a). It started at 4 p.m. and ended at 6 p.m. On that day, the meteorological conditions included an average temperature of 15.0 °C, 0.4 mm of daily rainfall, windless conditions, and 95.0% relative humidity. Even with the active flames ending after 2 hours, the next day, embers were observed at the ground surface within the study plot (Figure 3c).

The flame temperature during the experiment was measured using an infrared laser thermometer (Figure 3b). Readings were taken at different points within the plot at approximately 2-minute intervals, totaling 68 measurements by the end of the experiment. The soil temperature was measured using one K-type thermocouple sensor at depths of 0, 5, 10, and 15 cm. These sensors were connected to a data logger (HOBO 4-Channel Thermocouple) recording data every second (Figure 3b). The sensors were mounted on a 15 cm stainless steel rod, positioned horizontally at the specified depths along the wall of a small trench dug at the edge of the plot. The sensor cables were covered with a ceramic blanket to protect them from high temperatures.

After the fire, vegetation recovery was observed monthly through field observations. In addition to photographs, vegetation recovery was indirectly assessed using soil temperature data described in the next topic.

Figure 3. Experiment site a) during the controlled burning experiment; b) soil temperature recording at different depths; and c) lit embers the day after the experiment, d) hardened soil blocks collected at the soil surface (0 – 20 cm depth), promoting cracks on the soil surface.

2.3. Soil Characteristics

To analyze the effects of fire on soil properties, triplicate samples of both disturbed and undisturbed soil were collected at different depths using volumetric rings (100 cm^3) at 0–5, 5–10, 10–15, 15–20, 30–35, and 50–55 cm. Soil samples were collected at both the control and burned sites at the following time intervals: 2 days, 15 days, 30 days, and 8 months. Soil characterization followed the methodologies described in Teixeira et al. (2017). The particle size distribution was determined through a combination of sieving to separate fine and coarse sand and sedimentation with pipetting to distinguish clay from silt. Prior to the granulometric analysis, all the samples underwent pre-treatment with 30-volume hydrogen peroxide (H_2O_2) to remove organic matter and fine roots.

The bulk density of the undisturbed soil samples was determined using the oven-drying method. Particle density was measured using the volumetric flask method. The total organic matter content in the soil was determined through incineration in a muffle furnace. The samples, which were macerated and sieved to 80 mesh, were dried in an oven at 65 °C for 24 hours and weighed. They were then incinerated in a muffle furnace at 600 °C for 6 hours and weighed again.

2.4. Soil Suction

Soil suction was monitored in the field using granular matrix sensors (Watermark, Irrometer), which operate based on the principle of electrical resistance and have a measurement range between 0 and -239 kPa. A total of seven sensors were installed at different depths (0–10, 10–20, 20–30, 30–40, 40–50, 90–100, and 140–150 cm), along with a temperature sensor at 10–20 cm, at both sampling sites. The shallow depths (<20 cm) were investigated aiming to observe post-fire direct changes, since it's wide known through literature that fire effects on soil properties rarely extent beyond the 20 cm depth; deeper depths (> 100 cm) were investigated aiming to observe post-fire indirect changes at the surface that are a common landslide failure zone; intermediate depths were investigated aiming to observe if changes progressively occur along the depth over time.

All eight sensors were connected to a data logger (Watermark 900M), programmed to collect data at 15-minute intervals, resulting in 96 daily records. Monitoring began on July 16, 2022, at the control site, and on September 06, 2022, at the burned site, and continued until September 06, 2024, the study period considered. Installation of the sensors followed the recommendations of Rix et al. (2021). Soil suction data were correlated with data from a weather station located less than 10 m from the sampling sites to assess sensor responses to temperature and rainfall variations across different temporal scales.

2.5. Statistical analysis

The soil properties data were subjected to the Shapiro-Wilk normality test to determine which statistical tests would be used. To verify whether there was a difference between treatments, time interval, and depth, the data for bulk density, true density, porosity, and organic matter were subjected to a one-way analysis of variance (ANOVA) and the Tukey test to compare the mean values at a significance level of $P < 0.05$. Statistical analyses were performed using PAST 4.03 software.

Due to temporal autocorrelation in the soil suction time series, statistical comparisons between burned and control sites were performed for selected representative periods using paired t-tests at the 10–20 cm and 140–150 cm depths. Additionally, a bootstrap resampling approach (10,000 iterations) was used to estimate the mean increase factor in soil suction and its 95% confidence interval.

3. Results

3.1 Fire behavior and soil temperatures

The fire flames within the experimental setting were spatially non-uniform and the average temperature was 390.8°C with a standard deviation of 196.1°C; the extreme temperature values (>600°C) were reached 30% of the total time of the experiment. Soil temperature during the experiment reached 231.8 °C on the soil surface (0 cm), 352.5 °C at 5 cm, and 75.1 and 55.18 °C at 10 and 15 cm, respectively.

In Figure 4, it can be observed that the soil surface temperature remained above 100°C for approximately 11 hours from the beginning of the experiment, but fluctuated over the total monitoring time, with three main peaks. The first peak reached 220 °C at the end of the experiment; a second peak at 220°C occurred 5 hours after the end of the experiment; and a third peak (~200°C) occurred after 7 hours, at 1 am on August 07.

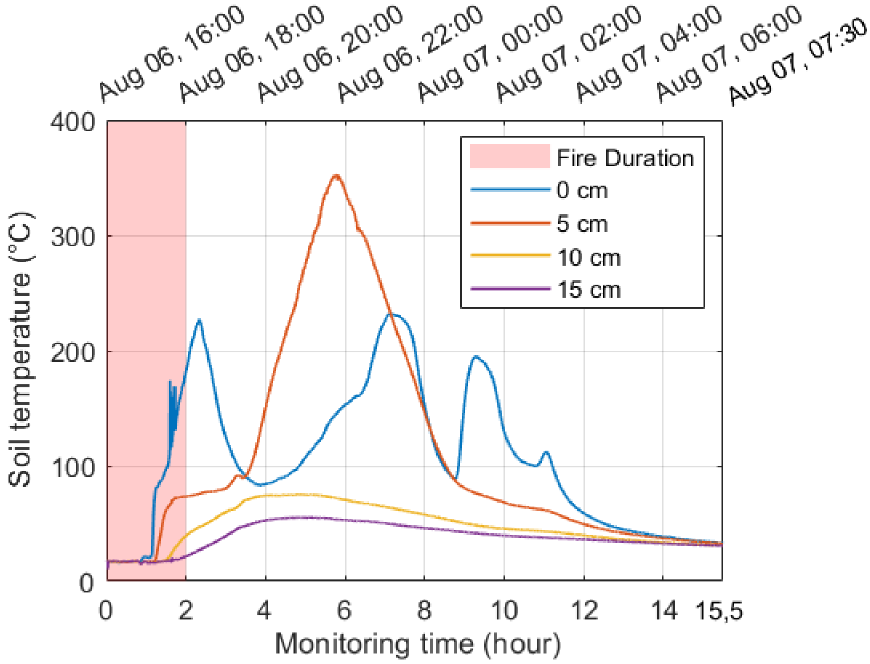

Figure 4. Variation in soil temperature at depths of 0, 5, 10, and 15 cm was monitored from 16:00 on August 06, 2022, to 07:30 on August 07, 2022. The red section highlights the experimental burning period, during which flames were active for a total of 2 hours.

The highest temperatures occurred at 5 cm depth, with a small rise (to 70°C) during the fire, which stabilized for approximately 2 h. The soil temperature then rose for 2 h, reaching a peak of 352.5°C; subsequently, it rapidly decreased to 80°C over 2 h 30 m, decelerating at the end of the monitoring period. Temperature variations at depths of 10 and 15 cm occurred after the end of the experiment and remained below 100°C, reaching a maximum of 80°C at 10 cm and 50°C at 15 cm.

3.2 Post-fire vegetation recovery

Immediately after the experiment, the burned site showed a layer of white ash on the soil surface, which was washed away by rain over the following 14 days, leaving a layer of black ash (Figure 5). Until 3 months after the experiment, little vegetation had returned at the burned site, with just a little regrowth at the edges of the plot that did not exceed 20 cm in height. At around 7 months, the vegetation had reached around 1 meter in height and was growing into the plot, although with the continued presence of black ash. Approximately 1 to 1.5 years after the fire, the vegetation reached 1.5 m in height and the soil surface was already completely covered by litter.

Figure 5. Vegetation recovery at the burned site over a 1.5-year period after the experimental fire. Red arrow indicates datalogger location.

3.3 Fire effects on soil characteristics

The soil was classified as Cambisol according to the Brazilian Soil Classification System (Santos et al. 2018) and sandy clay loam at most depths, but with increasing clay content with depth, the classification changed to sandy clay at 50 cm. Although statistical hypothesis tests were not performed for the granulometric data due to sample constraints, descriptive variations in particle size distribution over time suggested a localized trend on the soil surface (0 – 5 cm), where clay content gradually decreased after the fire, dropping from 289.8 g kg^{-1} before the fire to 271.2, 225.8, and 211.9 g kg^{-1} at 2-, 15-, and 30-days post-fire, respectively (Table 1). Simultaneously, at the same depth, coarse sand content increased gradually, rising from 439.4 g kg^{-1} before the fire to 423.2, 517.7, and 533.9 g kg^{-1} at 2-, 15-, and 30-days post-fire, respectively. At deeper soil layers, no perceptible changes were observed following the fire.

Table 1. Granulometric composition of forest soil before and 2, 15, and 30 days after fire at different depths.

Depth (cm)	Clay (g kg^{-1})			
	Pre-Fire	2 days	15 days	30 days
0 - 5	289.8	271.2	225.8	211.9
5 - 10	256.9	247.6	247.4	261.4
10 - 15	276.2	287.0	266.6	241.5
15 - 20	274.1	325.9	300.5	190.7
30 - 35	331.4	348.3	311.5	253.8
50 - 55	343.7	357.2	356.0	323.7
Depth (cm)	Silt (g kg^{-1})			
	Pre-Fire	2 days	15 days	30 days
0 - 5	184.9	217.4	172.9	171.5
5 - 10	121.0	113.7	121.2	85.1
10 - 15	107.5	100.3	115.8	136.6
15 - 20	109.4	106.5	116.0	196.0
30 - 35	124.2	119.8	118.8	144.5

Depth (cm)				
50 - 55	135.0	131.2	139.1	126.9
Depth (cm)	Fine Sand (g kg^{-1})			
	Pre-Fire	2 days	15 days	30 days
0 - 5	85.8	88.3	83.3	82.8
5 - 10	104.3	83.7	99.5	112.7
10 - 15	101.3	140.0	97.8	95.9
15 - 20	115.2	101.8	106.2	110.6
30 - 35	101.9	94.6	85.0	107.4
50 - 55	94.3	115.3	104.6	83.6
Depth (cm)	Coarse Sand (g kg^{-1})			
	Pre-Fire	2 days	15 days	30 days
0 - 5	439.4	423.2	517.7	533.9
5 - 10	517.8	555.1	531.9	540.8
10 - 15	514.9	472.7	519.8	526.1
15 - 20	501.3	465.8	477.3	502.7
30 - 35	442.5	437.3	484.7	494.3
50 - 55	427.0	396.4	400.3	465.7

The soil bulk density showed a significant increase with depth in the pre-fire samples, ranging from 0.57 g cm^{-3} in the first 5 cm to 0.98 g cm^{-3} at 50 cm (Table 2). After the fire, there was a progressive increase in soil surface bulk density (0 – 5 cm) that was statistically significant 30 days after, compared to the pre-fire value. As time progressed and surface values increased, the soil profile no longer showed significant differences in depth, particularly after 15 days post-fire. However, after 8 months, soil bulk density values begin to decrease by 0.87 g cm-3.

Table 2. Mean soil bulk density ± standard deviation (g cm^{-3}) before and after fire.

Depth (cm)	Pre-fire	2 days	15 days	30 days	8 months
0 – 5	0.57 ± 0.12^{aA}	0.78 ± 0.08^{abA}	0.94 ± 0.04^{abA}	1.03 ± 0.13^{bA}	0.87 ± 0.11^{abA}
5 – 10	0.84 ± 0.05^{aAB}	1.02 ± 0.06^{aB}	0.99 ± 0.11^{aA}	1.03 ± 0.08^{aA}	0.97 ± 0.07^{aA}
10 – 15	0.84 ± 0.08^{aAB}	0.99 ± 0.06^{aAB}	1.00 ± 0.02^{aA}	1.07 ± 0.04^{bA}	1.02 ± 0.03^{abA}
15 – 20	0.88 ± 0.05^{aAB}	1.03 ± 0.06^{aB}	1.02 ± 0.04^{aA}	1.04 ± 0.03^{aA}	0.94 ± 0.06^{aA}
30 – 35	0.95 ± 0.00^{aB}	0.91 ± 0.07^{aAB}	1.03 ± 0.05^{aA}	1.08 ± 0.08^{aA}	0.95 ± 0.03^{aA}
50 – 55	0.98 ± 0.02^{aB}	0.95 ± 0.03^{aAB}	0.96 ± 0.06^{aA}	1.04 ± 0.04^{aA}	0.95 ± 0.03^{aA}

Note: Different lowercase letters indicate significant differences at different time intervals at the same soil depth at $p < 0.05$. Different uppercase letters indicate significant differences at different soil depths in the same time intervals at $p < 0.05$.

The particle density in the surface depth (0 – 5 cm) did not differ between pre- and post-fire conditions, but there was a significant difference between soil collected after 2 days and 30 days (Figure 6). However, soils collected at 5 – 10, 10 – 15, and 15 – 20 cm showed differences between pre- and post-fire conditions. At the last depth analyzed (30 – 35 cm), true soil density did not differ. Total porosity decreased after the fire, being more noticeable at depths of 0 – 5 cm, with reductions of 9.93% at 2 days after the fire, 15.65% at 15 days, and 17.96% at 30 days after the fire.

Organic matter content showed a significant increase immediately after the fire (2 days) on the soil surface (0 – 5 cm), whereby values increased from 56.77 ± 0.90 to 67.06 ± 3.69 g kg-1, but with a decrease after 15 and 30 days of 54.49 ± 1.35 and 45.62 ± 2.26, respectively (Figure 6). At the lower depth (5–10 cm), no significant variation in organic matter content was observed 2 days after the experiment, remaining at 54.08 g kg^{-1}. However, at 15 and 30 days, a marked decrease was recorded, with concentrations dropping to 38.08 g kg^{-1} and 42.18 g kg^{-1}, respectively. Deeper layers did not show significant changes in organic matter content following the fire.

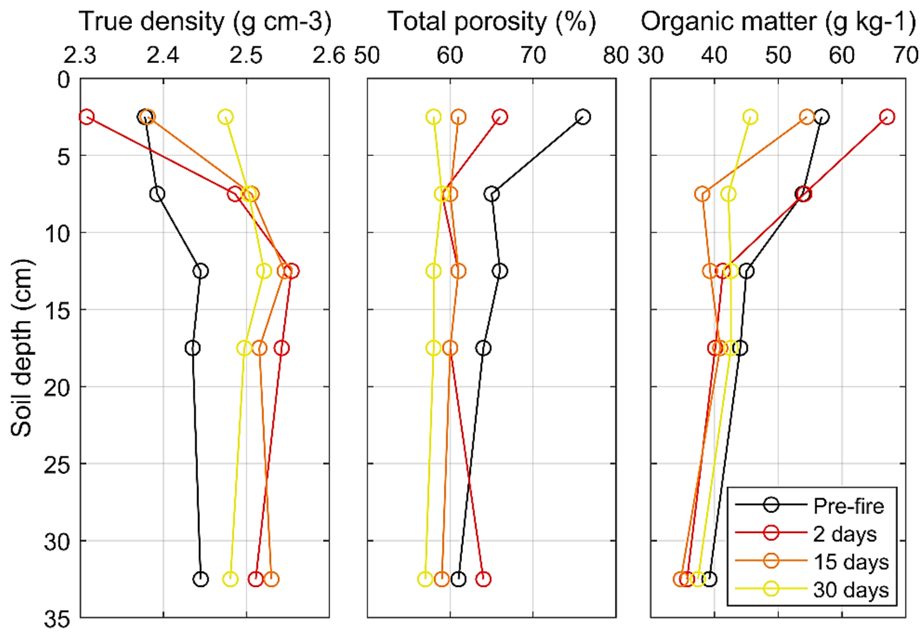

Figure 6. Soil properties studied before and after fire at different time intervals and by depth.

3.4 Fire effects on soil suction over time

The variation in soil suction over the sampling period followed rainfall distribution (Figure 7). Shallow depths responded more quickly to incoming and outgoing water, except at 0 – 10 cm, which maintained lower suction values in both areas compared to 10 – 20 cm. The suction at depths below 1 meter showed a more significant increase during drought periods, especially between June and October, remaining close to saturation during the wetter months between December and March. Nevertheless, there is a noteworthy difference in the range of suction values between the control site and the burned site, whereby, the increase in suction in the latter occurs at more accentuated rates and at higher values.

Soil temperatures at both sites followed air temperatures, increasing during the warmer months between December 2022 and March 2023. The mean soil temperature at the burned site was higher than at the control site, averaging 18.2 °C compared with 16.9 °C at the control site over the entire period. The variation range was 6.9°C and 8.3°C, respectively. In addition, the temperature difference between the two sites reached a maximum of 4.3°C in December 2022, four months after the fire, and gradually decreased to 2.8°C in December of the following year.

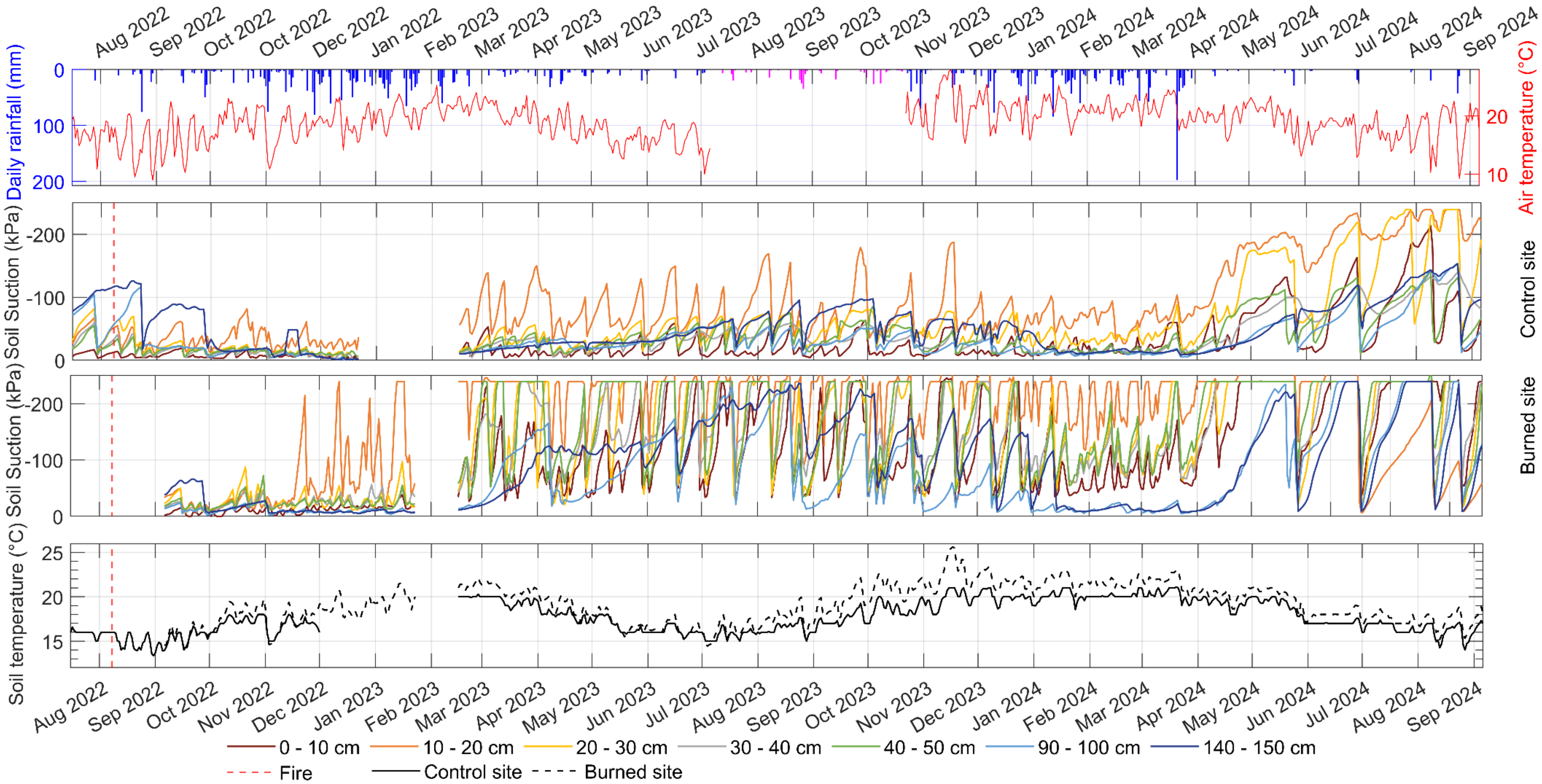

Figure 7. Data distribution throughout the sampling period: a) daily accumulated rainfall and mean air temperature; b) mean soil suction values (n=96/day) at different depths at the control site; c) mean soil suction values (n=96/day) at different depths at the burned site; and d) soil temperature at the control site (continuous black line) and the burned site (dashed black line). The dashed red line on all the graphs indicates the day of the controlled fire (August 06, 2022) at the burned site.

Based on a monthly analysis, Figure 8 shows that the burned area exhibited soil suction behavior similar to that of the control site for about 3 months after the fire. However, 3 months after the fire, the 10 – 20 cm depth began showing higher soil suction than the control site, even during the wetter months. This increase in soil suction in the burned area occurred at other depths, but much later, as observed at depths of 1.0 and 1.5 m around 6 months after the fire and at the beginning of the first dry period following the fire. These differences were statistically significant ($p < 0.05$) at the 10 – 20 cm depth between November 18 and 23, 2022, and at the 140 – 150 cm depth between May 15 and July 15, 2023. In the next humid period, between December 2023 and February 2024, the suction values at these depths returned to showing similar behavior, but there was once again a difference between the areas in the following dry period, with the burned site showing higher values.

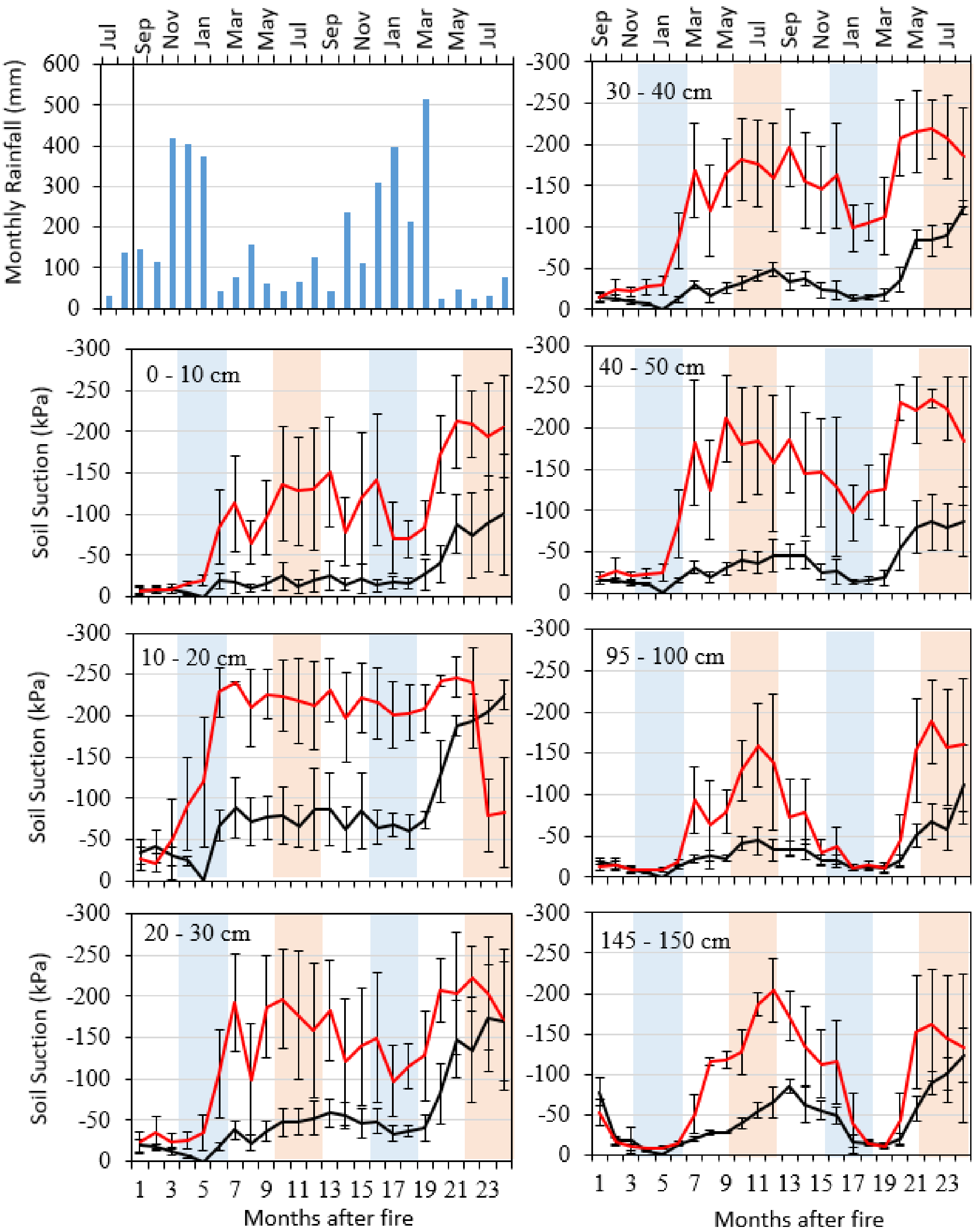

Figure 8. Comparison between monthly soil suction values at the control (black) and burned (red) sites over 24 months after the fire. The monthly rainfall also includes the month of the fire (August 2022) and the month before (July 2022). The orange rectangles indicate the driest months (June, July, and August) and the blue rectangles indicate the wettest months (December, January, and February). The black bars indicate the standard deviation in soil suction for each month.

The first rain event that demonstrated this sudden increase in soil suction at a depth of 10 – 20 cm occurred between November 15 and 30, 2022. The event accumulated 222.8 mm and had a 7-day dry period from November 17 to 23. Between November 18 and 23, the burned site showed an increase in suction values at a depth of 10 – 20 cm, averaging 32.8 kPa per day, compared with 6.0 kPa at the control site (Figure 9). This observation resulted in a direct amplification factor of 5.47 times, corroborated by bootstrap analysis estimating a mean amplification factor of 5.67 (95% CI = [3.94, 8.78]), with a statistically highly significant difference between the groups (paired t-test p-value = 0.0003). In addition, it can also be observed that the suction increase curve rises in steps during this period. Based on the analysis at a daily scale, it was possible to perceive that soil suction at this depth showed standard behavior on the dry days that accompanied the time of day, gradually increasing at the beginning of the day, followed by an exponential increase and, finally, a stationary phase (Figure 10).

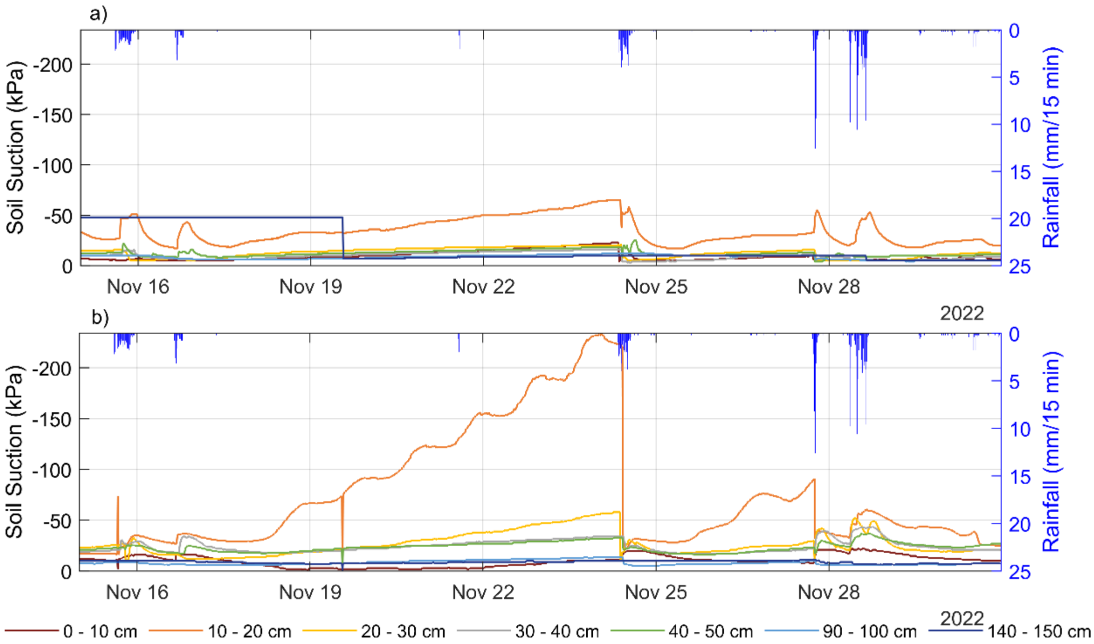

Figure 9. Relationship between soil suction and rainfall at 15-minute intervals during a 7-day dry period between November 17 and 23, 2022, at the sampling sites: a) burned site and b) control site.

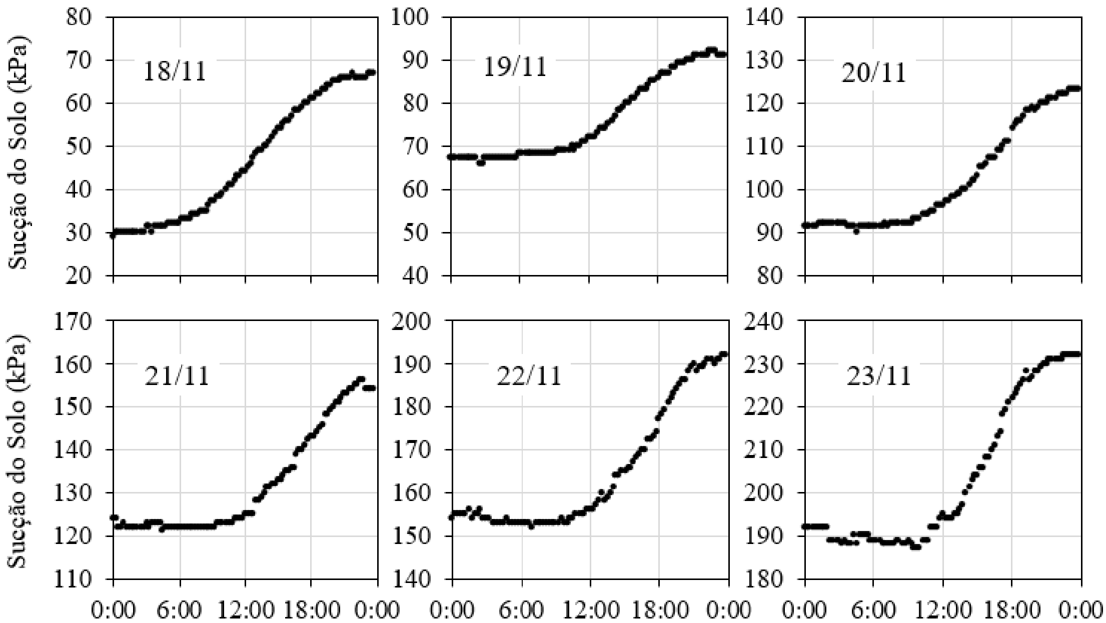

Figure 10. Soil suction curve behavior at 15-minute intervals at a depth of 10 – 20 cm at the burned site throughout the day during the dry period between November 17 and 23, 2022.

4. Discussion

The experimental fire showed that soil temperature changes not only with depth but also over time. The fluctuations at the soil surface can be explained by new ignitions even after the end of the experiment, as confirmed by embers still burning on the ground the day after the fire (Figure 3c). These reignitions could have been caused by wind, since the study site is more prone to such effects due to its location near the edge of the forest fragment. The high values of soil temperature recorded at 5 cm (~350 °C) represent an extreme heating scenario that is unusual compared to the majority of data recorded in literature, where heat decreases rapidly with depth due to the low thermal conductivity of soil (DeBano, 2000; Certini, 2005). In low-intensity fires, soil temperatures rarely exceed 100 °C at the surface or 50 °C at a 5 cm depth (Neary et al. 1999). In this study, however, these elevated temperatures can be directly contextualized by the high potential fuel load characteristic of the site. The forest edge naturally exhibits a significant accumulation of coarse woody debris (30.64 m3 ha-1), driven by wind exposure and increased tree mortality.

The experimental design simulated an extreme but plausible manifestation of this environment by adding and redistributing the canopy material (branches and leaves) cut from the plot onto the soil surface, creating a high-intensity surface fire scenario. Under such high fuel loads of heavy materials, similar to slash residues, the duration of burning and heat residence time can significantly increase, allowing high temperatures to penetrate deeper into the profile. Certini (2005) discuss that under heavy fuel conditions, severe soil heating can occur, where soil temperatures can reach 250 °C at 10 cm and exceed 100 °C as deep as 22 cm. In addition, the deep increase in soil temperature could be explained by a localized collapse of the ground surface observed the day after the fire. This structural failure could physically transport burning fuel material downward, closer to the buried sensors, thereby contributing to the elevated temperatures recorded in the subsurface layers.

The maximum temperatures reached at and near the soil surface, 231.8°C at 0 cm and 352.5°C at 5 cm, were sufficient to cause changes in the properties of the studied soil, while temperatures of 75.1°C at 10 cm and 55.2°C at 15 cm were not shown to be capable of altering the physical properties of the soil in the study area.

The burned site showed differences in soil texture, bulk density, and organic matter in the top 5 cm of soil just 2 days after the fire. The observed trend of increase in sand content and the decrease in clay content at the soil surface are expected outcomes observed across different climatic conditions (Li et al. 2021; Coaguila et al. 2025). This behavior could be related to the selective removal of fine particles through surface erosion, in addition to the formation of new aggregates induced by fire (Certini 2005). The rainfall distribution during the first month after the experiment corroborates the hypothesis of fine particle removal, since the accumulated rainfall at 2 days was 0.0 mm; at 15 days it was 25.0 mm; and at 30 days it was 141.8 mm, with an increase in sand and a decrease in clay occurring only after 15 days.

The absence of rainfall may also explain the increase in organic matter after the first 2 days, when the fuel added to the experiment had not yet been washed away by water. Despite the addition of fuel for the experiment, increased organic matter is also observed in moderate-to-high intensity wildfires, where at least 60% of the canopy is dead, due to external input of heat damaged foliage and burnt materials (Li et al. 2021). With the rain in the following days, the organic matter decreased.

The significant progressive increase in soil bulk density until 30 days from the surface to 5 cm can be explained by different mechanisms, as attested by Certini (2005), due to the collapse of aggregates in response to the burning of organic matter, in addition to the clogging of pores by deposited ash (Figure 5). However, given the observed increase in organic matter within the first two days after the fire, the collapse of aggregates is unlikely to have been the dominant mechanism in this case. Eight months after the fire, the bulk density of the top 5 cm of soil decreased, suggesting partial recovery toward its pre-disturbance state.

The 17.96% decrease in total porosity after 30 days and the increase in soil density reduced water infiltration into the soil and, consequently, lowered moisture conditions. Changes in physical properties after the fire do not appear to have played a significant role, since these changes were observed as early as two days after the fire. Moreover, the increase in suction values occurred only after 3 months at the soil surface and at about 6 months at greater depths. Therefore, other variables appear to govern the effects of fire on changes in soil suction.

The observed increase in suction rates occurs within a timeframe that aligns with local vegetation regrowth. By the time regrowth started and reached 20 cm in height within three months, suction rates were approximately five times higher than those at the unburned site. As shrubby vegetation developed, reaching 1 meter in height in 6 months, suction also increased at greater depths. While this temporal pattern suggests that vegetation recovery may influence soil suction via increased evapotranspiration rates, direct measurements would be required to confirm these mechanisms. Increased evapotranspiration rates were observed by Poulos et al. (2021) at post-fire regenerated shrublands in southeast Arizona. These authors emphasize that the composition of regenerating vegetation plays a more important role than fire severity in controlling evapotranspiration after fire.

In this study, vegetation recovery at the burned site is also supported indirectly by soil temperature data, as the difference between the burned and control site gradually decreases over time, from a maximum of 4.3°C in the first year to 2.8°C in the second year post-fire, likely due to increasing shading and protection from solar radiation. A similar trend was reported by Demir et al. (2025), who also finds a difference of 3.2°C at the first year after fire and decreasing over time, when comparing areas near unburned and burned trees.

The increase in soil suction does not seem fully explained by greater solar incidence at the burned site due to canopy thinning, as also observed by White et al. (2020), since the 0 – 10 cm depth does not lose suction before the 10 – 20 cm depth. However, the soil suction behavior throughout the day in Figure 10 demonstrates that the exponential increase in soil suction begins at 12:00 PM and starts to decrease after 6:00 PM, coinciding with the period of greatest solar radiation, which also governs evapotranspiration. In addition, the black ash on the soil surface until 7 months after the fire may have acted to decrease the surface's solar reflection capacity, as rightly pointed out by Veraverbeke et al. (2012). This suggests greater water loss in the burned area, even during wet periods (Figure 8).

Contrary to the findings of most studies in temperate regions, where post-fire increases in soil moisture are attributed to reduced evapotranspiration following plant mortality (Neary et al. 1999; Shakesby and Doerr 2006; Abdollahi et al. 2023), this study observed the opposite pattern during the sampling period. A similar pattern was reported by Coelho Netto et al. (2024) on a slope with herbaceous–shrubby vegetation burned in 2019 at Rio de Janeiro, where suction showed high values at depths of 100 and 150 cm in the soil for months after the fire, at values that were not observed in previous years of monitoring.

Finally, blocks of very hardened soil measuring approximately 10 x 20 x 20 cm (height, length, and width, respectively) were also observed, which could be associated with cracks in the soil, facilitating the entry of solar rays (Figure 3d). On the other hand, these same cracks could facilitate the entry of water into the soil during the rainy season and promote a rapid drop in suction, as also pointed out by Bordoloi (2020). This increase in soil suction in the first moment after fire, followed by a rapid decrease in the rainy season, was also reported by Demir et al. (2025) through 4-year monitoring field data at Washington (USA).

Findings from temperate regions also suggest that soils are more susceptible to shallow landslides approximately 2–3 years after fire (Rengers et al. 2020; Lei et al. 2022), primarily due to reduced soil cohesion caused by root mortality and increased hydraulic conductivity resulting from macropores left by decomposed roots. In contrast, in the present study, post-fire changes in soil suction occurred over a shorter timescale, with alterations detected early, within 3 months at the surface and 6 months at depths of up to 1.5 m (Figure 11). Therefore, in addition to considering the timescale of fire effects (Vahedifard et al. 2024), it is essential to account for the dynamics of vegetation recovery following fire.

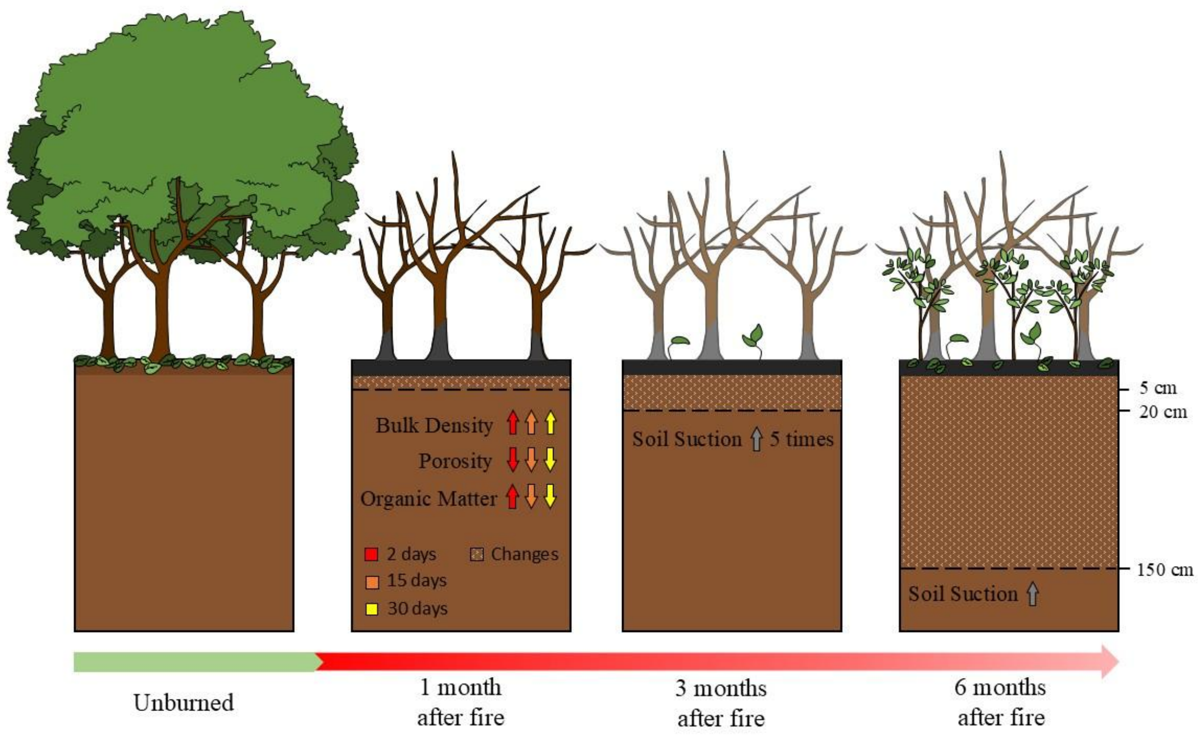

Figure 111. Short-term fire effects on soil properties and temporal changes in soil suction.

5. Conclusions

The fire caused short-term alterations in the studied soil properties, particularly within the top 5 cm. Although properties such as organic matter were affected by the fire, they remained highly influenced by rainfall events, except for soil bulk density. Despite these post-fire changes, the observed variations in soil properties (bulk density, porosity, and organic matter) do not appear to directly influence suction behavior. Changes in these soil properties were detected only 2 days after the fire, whereas substantially higher suction values, approximately five times greater in the burned area, were recorded around 3 months after the fire near the surface (20 cm depth) and 6 months after at depth (1.5 m).

This temporality in soil suction is hypothesized to be linked to the dynamics of vegetation return after the fire, given that regrowth was observed within similar time intervals. However, it remains to be seen whether this rapid increase in post-fire suction could trigger an abrupt drop in suction at depth through soil fissures during extreme rainfall events, leading to a decrease in soil cohesion and consequent slope instability.

The results of this study indicate that the soil system in a tropical environment can have a distinct response in comparison to temperate environments, potentially influenced by the faster regrowth of herbaceous-shrub vegetation after fire. Therefore, in addition to considering the timescale of fire effects and climatic seasonality, it is crucial to pay more attention to the dynamics and composition of vegetation recovery after fire. These findings highlight the importance of accounting for the temporal dynamics of parameters used in slope stability analysis and susceptibility mapping, particularly in humid tropical regions, where post-fire recovery phase can induce changes in the soil-water-vegetation interface over time.

Author's contributions: Conception, Bolsas, L. and Coelho Netto, A. L.; methodology, Bolsas, L. and Coelho Netto, A. L.; formal analysis, Bolsas, L.; research, Bolsas, L. and Coelho Netto, A. L.; data preparation, Bolsas, L.; article writing, Bolsas, L.; revision, Coelho Netto, A. L.; supervision, Coelho Netto, A. L.; acquisition of funding, Coelho Netto, A. L.

Funding: This study was financed through the grants awarded by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) – Brasil [Finance Code 001 and Grant No. 88887.622325/2021-00], Fundação de Amparo à Pesquisa do Estado do Rio de Janeiro (FAPERJ) – Brasil [Grant No. E-26/202.503/2022 (277633)] and through the PRONEX (Support Program for Centers of Excellence, No. 262164/2016) and CNE (Scientists from Our State, No. 246469/2019) projects. CNPq (Brazilian National Research Council) and FAPERJ (Rio de Janeiro State Research

Foundation) through PRONEX (Support Program for Centers of Excellence, No. 262164/2016) and CNE (Scientists from Our State, No. 246469/2019) projects.

Acknowledgments: The authors would like to thank the State Environment Institute of Rio de Janeiro (INEA) for providing the Authorization for Scientific Research in the Conservation Unit (No. 035/2022). The authors would also like to thank Janete Leal, Delair Leal, Lieber Leal, Karoline Ishimine, and Tomás Duek for their support in the field, and Luana Costa for support with laboratory analyses.

Conflict of Interest: The authors declare not having any conflict of interest. The funders had no interference in the development of the study; in the collection, analysis, or data interpretation; in the writing of the manuscript, or in the decision to publish the results.

References

1. ABDOLLAHI, M.; VAHEDIFARD, F.; TRACY, F. T. Post-wildfire stability of unsaturated hillslopes against rainfall-triggered landslides. Earth's Future, v. 11, 2023. DOI: https://doi.org/10.1029/2022EF003213.
2. AKOSAH, S.; GRATCHEV, I. Systematic review of post-wildfire landslides. GeoHazards, v. 6, n. 12, 2025. DOI: https://doi.org/10.3390/geohazards6010012.
3. ALCANTARA, E. et al. Deadly disasters in southeastern South America: flash floods and landslides of February 2022 in Petrópolis, Rio de Janeiro. Natural Hazards and Earth System Sciences, v. 23, p. 1157–1175, 2023. DOI: https://doi.org/10.5194/nhess-23-1157-2023.
4. ALVES, L. M. et al. Assessment of rainfall variability and future change in Brazil across multiple timescales. International Journal of Climatology, v. 41, p. E1875–E1888, 2021. DOI: https://doi.org/10.1002/joc.6818.
5. BOLSAS, L.; FACADIO, A. C.; COELHO NETTO, A. L. Classificação de áreas suscetíveis a incêndios na Bacia do Córrego d'Antas, Nova Friburgo (RJ): uma proposta metodológica. 2022.
6. BOLSAS, L.; FREITAS, L. E.; COELHO NETTO, A. L. Análise espaço-temporal dos incêndios em Nova Friburgo: subsídios ao estudo da suscetibilidade de terreno frente aos deslizamentos. In: XVIII Simpósio Brasileiro de Geografia Física Aplicada. 2019.
7. BORDOLOI, S.; NI, J.; NG, C. W. W. Soil desiccation cracking and its characterization in vegetated soil: a perspective review. Science of The Total Environment, v. 729, 2020. Artigo 138760. DOI: https://doi.org/10.1016/j.scitotenv.2020.138760
8. CANNON, S. H.; BIGIO, E. R.; MINE, E. A process for fire-related debris flow initiation, Cerro Grande fire, New Mexico. Hydrological Processes, v. 15, p. 3011–3023, 2001. DOI: https://doi.org/10.1002/hyp.388.
9. CERTINI, G. Effects of fire on properties of forest soils: a review. Oecologia, v. 143, p. 1–10, 2005.
10. COAGUILA, L. et al. Soil degradation evidence following a wildfire in Arequipa's Andean region, Peru. Spanish Journal of Soil Science, v. 15, 2025. DOI: https://doi.org/10.3389/sjss.2025.13983.
11. COELHO NETTO, A. L. et al. Vegetation changes through recurrent fire affect soil water behavior and enhance landslides in the mountainous region of Rio de Janeiro state, southeast Brazil. Catena, v. 241, 2024. DOI: https://doi.org/10.1016/j.catena.2024.108028.
12. COELHO NETTO, A. L. et al. January 2011: The extreme landslide disaster in Brazil. Berlin: Springer, 2013.
13. DEBANO, L. F. The role of fire and soil heating on water repellency in wildland environments: a review. Journal of Hydrology, v. 321–322, p. 195–206, 2000.
14. DEMIR, M.; GUERRA, J. C.; VAHEDIFARD, V.; ROBICHAUD, P. R.; AKIN, D. 2025. Temporal changes in soil water retention in burned and unburned areas after a wildfire and implications for slope stability. *Canadian Geotechnical Journal*. **62**: 1-16. https://doi.org/10.1139/cgj-2025-0234
15. DOERR, S. H.; SHAKESBY, R. A.; WALSH, R. P. D. Soil water repellency: its causes, characteristics and hydro-geomorphological significance. Earth-Science Reviews, v. 51, p. 33–65, 2000.
16. FACADIO, A. C. C. et al. Holocene hillslope evolution through extreme rainfall-induced landslides in the mountainous region of Rio de Janeiro, Brazil: geochronology and paleoenvironmental evidence. Earth Surface Processes and Landforms, 2024.
17. FUNDAÇÃO SOS MATA ATLÂNTICA; INPE. Atlas dos remanescentes florestais da Mata Atlântica: período 2019/2020: relatório técnico. São Paulo, 2021.
18. GARIANO, S. L.; GUZZETTI, F. Landslides in a changing climate. Earth-Science Reviews, v. 162, p. 227–252, 2016.

19. HELVEY, J. D. Effects of a north central Washington wildfire on runoff and sediment production. Water Resources Bulletin, v. 16, p. 627–634, 1980.
20. IPCC. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, 2021.
21. KORUP, O.; DENSMORE, A. L.; SCHLUNEGGER, F. The role of landslides in mountain range evolution. Geomorphology, v. 120, p. 77–90, 2010. DOI: https://doi.org/10.1016/j.geomorph.2009.09.017.
22. LACERDA, W. A. Landslide initiation in saprolite and colluvium in southern Brazil: field and laboratory observations. Geomorphology, v. 87, p. 104–119, 2007. DOI: https://doi.org/10.1016/j.geomorph.2006.03.037.
23. LEI, M. et al. Temporal evolution of the hydromechanical properties of soil–root systems in a forest fire in China. Science of the Total Environment, v. 809, 2022. DOI: https://doi.org/10.1016/j.scitotenv.2021.151165.
24. LI, Q. et al. Post-fire impacts of vegetation burning on soil properties and water repellency in a pine forest, South Korea. Forests, v. 12, p. 708, 2021. DOI: https://doi.org/10.3390/f12060708.
25. MEGAHAN, W. F. Hydrologic effects of clearcutting and wildfire on steep granitic slopes in Idaho. Water Resources Research, v. 19, p. 811–819, 1983.
26. MERGANIČ, J.; MERGANIČOVÁ, K.; VLČKOVÁ, M.; DUDÁKOVÁ, Z.; FERENČÍK, M.; MOKROŠ, M.; JUŠKO, V.; ALLMAN, M.; TOMČÍK, D. Deadwood Amount at Disturbance Plots after Sanitary Felling. *Plants* **2022**, *11*, 987. https://doi.org/10.3390/plants11070987
27. NEARY, D. G. et al. Fire effects on belowground sustainability: a review and synthesis. Forest Ecology and Management, v. 122, p. 51–71, 1999.
28. PARISE, M.; CANNON, S. H. Wildfire impacts on the processes that generate debris flows in burned watersheds. Natural Hazards, v. 61, p. 217–227, 2012. DOI: https://doi.org/10.1007/s11069-011-9769-9.
29. POULOS, H. M. et al. Wildfire severity and vegetation recovery drive post-fire evapotranspiration in a southwestern pine-oak forest, Arizona, USA. Remote Sensing in Ecology and Conservation, v. 7, p. 579–591, 2021.
30. RAMIREZ, R. A.; JANG, W.; KWON, T.-H. Wildfire burn severity and post-wildfire time impact mechanical and hydraulic properties of forest soils. Geoderma Regional, v. 39, e00856, 2024.
31. RENGERS, F. K. et al. Landslides after wildfire: initiation, magnitude, and mobility. Landslides, v. 17, p. 2631–2641, 2020. DOI: https://doi.org/10.1007/s10346-020-01506-3.
32. RIBEIRO, M. C. et al. The Brazilian Atlantic Forest: how much is left, and how is the remaining forest distributed? Implications for conservation. Biological Conservation, v. 142, p. 1141–1153, 2009.
33. RIX, J.; LO, H.; GHOLSON, D.; HENRY, M. Irrometer Watermark Series: Installation Procedures. Publication 3540, p. 1–21, 2021.
34. SANTOS, H. G.; JACOMINE, P. K. T.; ANJOS, L. H. C.; OLIVEIRA, V. A.; LUMBRERAS, J. F.; COELHO, M. R.; ALMEIRADA, J. A.; ARAUJO FILHO, J. C.; OLIVEIRA, J. B.m CUNHA, T. J. F. Brazilian Soil Classification System. Brasília, DF: Embrapa, 2018.
35. SHAKESBY, R. A.; DOERR, S. H. Wildfire as a hydrological and geomorphological agent. Earth-Science Reviews, v. 74, p. 269–307, 2006.
36. SILVA, R. P. Modelagem da suscetibilidade de terreno à deflagração de escorregamentos translacionais rasos: uma abordagem geo-hidroecológica aplicada à engenharia geotécnica. Rio de Janeiro: Universidade Federal do Rio de Janeiro, 2022.
37. SILVA, R. C.; MARENGO, J. A.; LEMES, M. R. Analysis of extreme rainfall and landslides in the metropolitan region of the Paraíba do Sul River Valley and North Coast of São Paulo, Brazil. Theoretical and Applied Climatology, v. 155, p. 3927–3949, 2024.
38. TEIXEIRA, P. C. et al. Manual de métodos de análise de solo. 3. ed. Brasília, DF: Embrapa, 2017.
39. VAHEDIFARD, F. et al. Interdependencies between wildfire-induced alterations in soil properties, near-surface processes, and geohazards. Earth and Space Science, v. 11, 2024. DOI: https://doi.org/10.1029/2023EA003498.
40. VERAVERBEKE, S. et al. Assessment of post-fire changes in land surface temperature and surface albedo, and their relation with fire-burn severity using multitemporal MODIS imagery. International Journal of Wildland Fire, v. 21, p. 243–256, 2012.

41. VILLANOVA, P. H.; TORRES, C. M. M.; JACOVINE, L. A. G.; SOARES, C. P. B.; SILVA, L. F.; SCHETTINI, B. L. S.; ROCHA, S. J. S. S.; ZANUNCIO, J. C. Necromass Carbon Stock in a Secondary Atlantic Forest Fragment in Brazil. Forests, 2019, 10, 833. DOI: 10.3390/f10100833.
42. WALL, S. A.; ROERING, J. J.; RENGERS, F. K. Runoff-initiated post-fire debris flow, Western Cascades, Oregon. Landslides, v. 17, p. 1649–1661, 2020. DOI: https://doi.org/10.1007/s10346-020-01376-9.
43. WELLS, W. G. The effects of fire on the generation of debris flows in Southern California. In: COSTA, J. E.; WIECZOREK, G. F. (eds.). Debris flows/avalanches: process, recognition, and mitigation. GSA Reviews in Engineering Geology, p. 105–114, 1987.
44. WHITE, D. A. et al. The effect of wildfire on the structure and water balance of a high conservation value Hualo forest in central Chile. Forest Ecology and Management, v. 472, 2020. DOI: https://doi.org/10.1016/j.foreco.2020.118219.

This work is licensed under the Creative Commons License Atribution 4.0 Internacional (http://creativecommons.org/licenses/by/4.0/) – CC BY. This license allows for others to distribute, remix, adapt and create from your work, even for commercial purposes, as long as they give you due credit for the original creation.