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Slope position controls prescribed fire effects on soil: a case study in the high-elevation grassland of Itatiaia National Park

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ABSTRACT: There is a need for greater knowledge about the medium- and long-term effects of prescribed fire management on soil in ecosystems prone to wildfires and more vulnerable to climate change. This study examined the short- and medium-term effects of prescribed fire on soil chemical properties and chemical fractions of soil organic matter (SOM) in two positions of the landscape in a high-elevation grassland environment. The ecosystem is located in the mountain peaks of southeastern Brazil associated with the Atlantic Forest biome. Prescribed fire was conducted in 2017 to reduce understory vegetation and thus prevent potential severe wildfires. Soil samples were collected at the layers of 0.00-0.10, 0.10-0.20, and 0.20-0.40 m, at eight composite sampling. The composite samples were collected on five different occasions: before the prescribed fire, and 10, 30, 90, and 240 days after the prescribed fire. Soil chemical properties, total organic carbon, labile C, and chemical fractionation of SOM were analyzed. All soil properties investigated were affected by the prescribed fire, with variations in landscape position, duration of effect, and soil layer. In the backslope area, the medium-term effect of fire was negative and induced soil degradation and induced soil degradation. In the footslope area, the system showed greater resilience to the effects of fire, as indicated by the recovery of the soil's chemical properties. These results can help assess the suitability of controlled burning of vegetation for managing risks of fire in mountainous regions, such as high-elevation grasslands.

Keywords: Histosols, soil indicators, organic matter, soil management, *Campos de Altitude*.

INTRODUCTION

Large areas of savannah and forests are affected annually by wildfires in various regions of the world. Fire is an important factor in environmental changes in an ecosystem and can affect nutrient compartments and soil organic matter dynamics (Alcañiz et al., 2018; Ayoubi et al., 2021; Babur et al., 2022). In the Atlantic Forest Biome, the areas most affected by the fire are the high-elevation grasslands, an ecosystem restricted to the mountains of the Southeast region with significant ecological relevance, due to their high degree of endemism and biodiversity. This ecosystem is subject to a greater effect of climate change than in the lower parts of the continent. They have soils characterized by a great accumulation of organic matter and peatland (Soares et al., 2016; Silva Neto et al., 2018) and, for this reason, are unstable and may be more sensitive to changes caused by ecological management with fire (Saenger et al., 2015; Assis and Mattos, 2016). Despite their greater vulnerability, biological importance, and role in maintaining ecosystem services, studies on the impacts of prescribed fires on soil properties conducted in Brazilian tropical mountains are rare.

Prescribed fire is the planned use of fire for the purpose of conservation, research and management of combustible materials in fire-prone environments/ecosystems. To allow this practice to be carried out, predefined goals, environmental conditions, and techniques are required in a specific fire plan (Brasil, 2018). In the prescribed fire, the fire pattern is predicted based on the local factors that influence its behavior and monitored until its extinction to achieve the planned goals. It is a strategy that can be used for the reduction or elimination of combustible material to prevent the occurrence of high-intensity and severe wildfires and has been used in different protected areas worldwide, such as in the USA (Hubbert et al., 2006; Knapp et al., 2009; Thompson et al., 2019), Europe (Fernandes et al., 2013; Inbar et al., 2014; Alcañiz et al., 2016), Australia (Andersen et al. 2005; Bennet et al., 2014), and among other countries. In addition to reducing the risk of wildfires, prescribed fires can be useful for habitat restoration, increasing biodiversity, controlling competition among plant species and communities, and eliminating problems with diseases or insects (Hamman et al., 2008; Valkó et al., 2016).

Studies conducted in recent decades in different ecosystems around the world indicate that the effect of fire on soil properties is widely variable and depends on several factors such as the type, intensity, and duration of the fire and its position in the landscape (González-Pérez et al., 2004; Afifi and Oliveira, 2006; Neill et al., 2007; Shakesby, 2011; Bento- Gonçalves et al., 2012; Brown et al., 2013; Inbar et al., 2014; Oliver et al., 2015; Fultz et al., 2016; Alcañiz et al., 2018). Some studies found an increase in pH and nutrient availability after prescribed fire (Kennard and Gholz, 2001; Úbeda et al., 2005; Scharenbroch et al., 2012) and a reduction in soil organic matter (SOM) (Muqaddas et al., 2016), while others have found no significant changes (Meira-Castro et al., 2014; Valkó et al., 2016). In addition, little is known about the effect of prescribed fires on soil C compartments, especially in colloidal fractions, and on the quality and quantity of humic materials. Still, little research has been carried out concerning the long-term variations on the ground surface after burning in mountain area (Úbeda et al., 2005; Meira-Castro et al., 2014; Alcañiz et al., 2016; Valkó et al., 2016).

In Brazil, experiments with prescribed fires began in the 1980s in the IBGE reserve in Brasília and, the following decade, at the Parque Nacional das Emas conservation unit (CU) (França et al., 2007). In 2014, prescribed fire was implemented in three CUs located in the Cerrado Biome, which is highly affected by forest wildfires annually (Schmidt et al., 2016). All studies were concentrated in the Cerrado, with little information available on its use in soil and vegetation in other Brazilian biomes. Studies on high-elevation grassland environments are rare and report only the short-term impact of wildfires on vegetation (Safford, 2001; Aximoff and Rodrigues, 2011; Aximoff et al., 2016).

In the high-altitude grasslands of the INP, the fire regime is variable, with the main cause being human activities for various purposes. The frequency of burning varied from 2 to 15 years in the different landscapes of the park. In the area of this study, a fire occurred ten years prior to sampling. The occurrence of fires in high-altitude fields is at the peak in the dry season (from June to September), resulting in fires of high intensity and severity (Aximoff et al., 2016).

There is a need for greater knowledge about the medium- and long-term effects of prescribed fire management on soil in ecosystems prone to wildfires and more vulnerable to climate change. Developing a better understanding of resilience and ability to respond to such disturbances is necessary. It is also necessary for forest management to identify points or positions in the landscape of greater vulnerability, considering the type and regime of fires (Piqué et al., 2011). In addition, it is important to identify the recurrence of the use of fire to complement the knowledge about the time required for a new burning to be carried out in the area so that there is no damage to the soil (Jones et al., 2015). In the current context of climate change, these studies are even more relevant, as it is predicted that the number and size of wildfires will increase, and wildfire regimes will change (with a higher number of high-severity wildfires during longer wildfire seasons) (Turco et al., 2017; Francos et al., 2018).

The main objective of this study was to determine the short- and medium-term effects of prescribed fire on soil chemical properties and organic matter fractions in two positions on the landscape in the high-elevation grassland environment of Itatiaia National Park (RJ, Brazil). As an initial hypothesis, it is assumed that the prescribed fire carried at the end of the wet season and beginning of the dry season, where there is high water content in the soil (February to April in the high-altitude fields of INP), will have a different impact based on the position in the landscape and on the affected soil layer.

MATERIALS AND METHODS

Study area

The study area is located in the Southeast Region of Brazil, in the Serra da Mantiqueira, Itatiaia massif, at the boundary of Minas Gerais and Rio de Janeiro States, within Itatiaia National Park, a full conservation unit covering an area of 225.54 km^2. This study was undertaken in a zone at a higher altitude range, which is characterized by mountainous and rugged terrain (Figure 1), with altitudes ranging from 2,000 to 2,791 m, culminating in Agulhas Negras Peak (Barreto et al., 2013). The climate is classified as Cwa, a subtropical climate with hot and rainy summers and cold and dry winters, with an average annual temperature of 16 °C and an average annual rainfall of 2,300 mm. In the Agulhas Negras peak, frost occurs, and temperatures can reach -10 °C from June to August (Barreto et al., 2014).

Effects of prescribed fire on soil properties were evaluated in the upper and lower slope positions (backslope and footslope) in an area of approximately 42 ha (22° 22’ 17.1” S and 44° 41’ 32.5” W), with an average altitude of 2,470 m and slope ranging from 3 to 30 %. There is a flat relief on the footslope with the predominance of Typic Haplosaprists (Soil Survey Staff, 2014), (*Organossolo Fólico Sáprico típico* - Santos et al., 2018), with impeded imperfect drainage. On the backslope, the average slope is 25 %, with the occurrence of Lithic Udifolists associated with Lithic Dystrudepts and Lithic Udorthents (Soil Survey Staff, 2014), (*Neossolos Litólicos Hísticos típicos* – Santos et al., 2018) and rock outcrops.

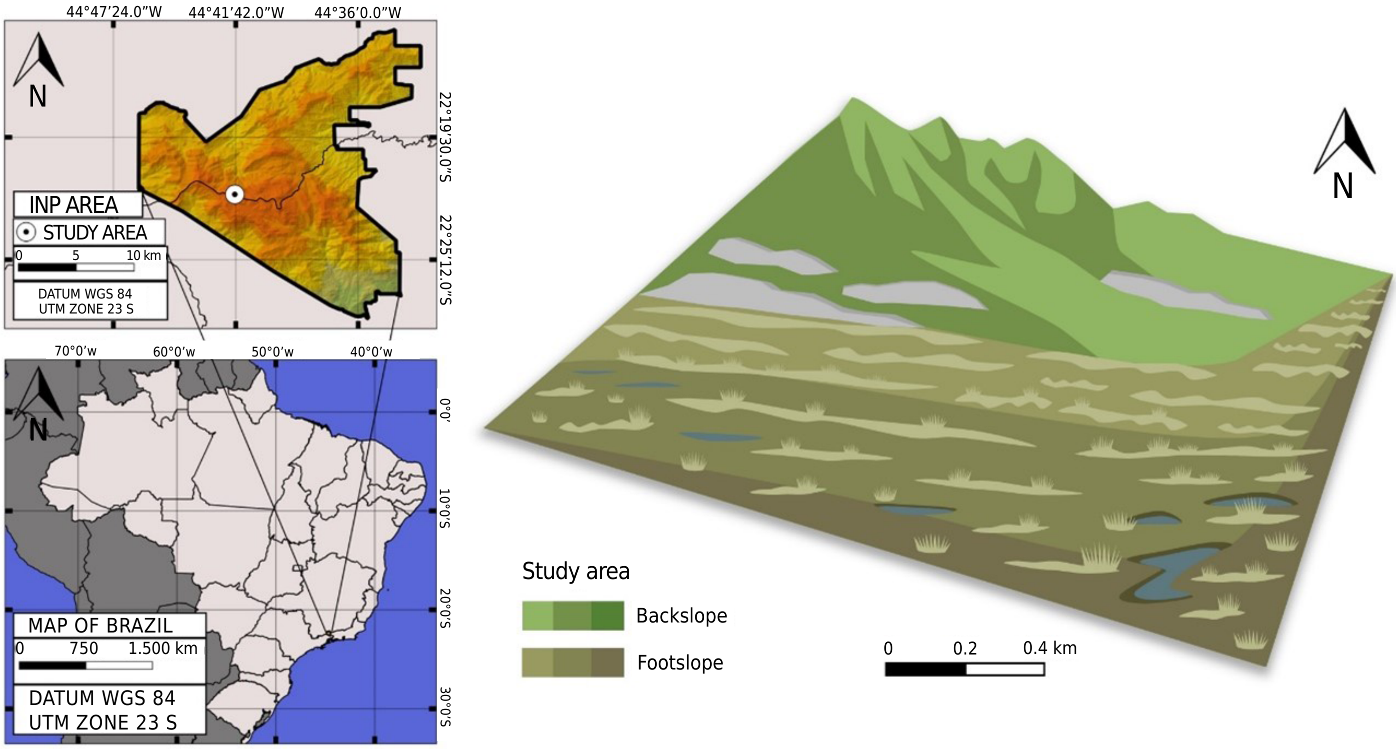

Figure 1. Location of the study area in the upper part of the Itatiaia National Park in the Southeastern region of Brazil.

Physiognomy, defined as altitude fields, is composed of a mosaic with different plant forms and variable structures and may contain variable densities of pteridophytes, herbs, shrubs, and trees, distributed in a graminoid matrix, small fragments of dense Ombrophylous Forest (Umbrophylous Forest), and islands of vegetation on rocks (Figure 2). In the study area, the vegetation was classified as fire-prone. On the backslope, the vegetation is composed of grassy and herbaceous species with a predominance of Cyperaceae and Poaceae, with Cortaderia modesta, Chusquea spp., and Machaerina ensifolia showing the highest dominance (Schmidt et al., 2016). On footslope, there is a greater diversity of groups of plant species, with a predominance of shrubs, including species of the genera Baccharis, Vernonia, and Myrtaceae (Safford et al., 2001; Silva Neto et al., 2018)

The prescribed fire was carried out in April 2017, with air temperatures ranging between 14 and 18 °C, relative humidity between 60 and 90 %, weak winds (3 to 13 km h^{1}), and cloud cover between 0 and 70 %, that is, adequate conditions for controlled burning (Figure 2). Firebreaks around the study area were previously built by removing vegetation and fire defense (crew) to prevent fire escape. The purpose of the burning was to construct a firebreak (preventive protection line) to prevent the spread of wildfires. The fire started at the highest points of the terrain, with the fire front spreading predominantly against the wind and contrary to the slope (backfire). For the backfire, the propagation speed was less than 1.0 m min^{-1}, with a maximum flame length of 1.5 m, and for the headfire, the propagation speed was >1.0 and <2.0 m min^{-1}, with a maximum flame length of 3.0 m.

Figure 2. Prescribed fire carried out in high-elevation Grassland Ecosystem within the Itatiaia National Park (RJ, Brazil). Source: Irgílio Ferraz.

Soil sampling, laboratory, and data analysis

Soil samples were collected before the prescribed fire (control of the original condition), and 10, 30, 90, and 240 days after the prescribed fire (DAPF). On each collection date, samples were collected at four points (pseudo-replicates) spaced 15–30 m apart at each slope position. At each point, three soil pits of 0.40 m depth were opened and samples were collected at layers of 0.00-0.10, 0.10-0.20 and 0.20-0.40 m. The collection of the three soil pits (at each sampling point) and their respective depths comprised one composite sample. The samples were placed in plastic bags, taken to the laboratory, and air-dried and sieved (2 mm mesh).

Chemical characterization of the soil was performed through the following analyses: pH in water (1:2.5), sorption complex (Ca^{2+}, Mg^{2+}, Al^{3+}, K^{+}, Na^{+}, H+Al) (KCl 1 mol L^{-1}) and P (Mehlich-1). The cation exchange capacity (CEC) and base saturation (V%) were calculated (Teixeira et al., 2017). The C and N contents were quantified by dry combustion in a CHN elemental analyzer (TrueSpec Series: Carbon, Hydrogen, Nitrogen Elemental, Macro). Chemical fractionation of humic substances was performed according to the method recommended by the International Humic Substances Society, adapted by Benites et al. (2003), to assess the C content of the humin (C-Hum), humic acid (C-HA), and fulvic acid (C-FA) fractions to determine the C-FA/C-HA and C-Hum/C-AE ratios (AE, alkaline extract = C-HA+C-FA).

Soil labile organic carbon (LOC) was obtained by the organic matter OM oxidation method (POXC) in reaction with $KMnO_7$ 0.2 mol L^{-1} established by the methodology developed by Culman et al. (2012), in which 0.5 g (± 0.01 g) of sample was mixed with 8 mL of distilled water, subjected to manual shaking and left at rest for 16 h; after this period, 2 mL of $KMnO_7$ 0.2 mol L^{-1} solution was added to each sample and subjected to horizontal shaking for 10 min. After the procedure, sample readings were performed using spectrometry based on a $KMnO_7$ concentration curve previously calibrated at 550 nm.

Statistical analyses

Descriptive statistical analysis (mean and standard deviation) and multivariate analysis (principal component analysis) were used for data analysis, as this was a measurement study. Analyses were performed using R (R Development Core Team, 2018). Statistical treatment in the Principal component analysis (PCA) was performed using the CANOCO statistical package (Braak and Smilauer, 2002).

RESULTS

Soil chemical properties

Chemical properties of the soil before and after the prescribed fire (PF) in the three layers of the footslope and backslope areas are shown in figures 4 and 5. In both landscape positions (backslope and footslope), the variations in the evaluated chemical properties were higher in the surface layer (0.00-0.10 m), indicating that it is more sensitive to the effects of fire. For the pH, small variations were observed in both landscape positions. In the footslope area, before the prescribed fire (BPF), the mean was 3.7±0.02, with reductions at 10 days after pre-scribe fire (DAPF) (pH = 3.7±0.02) and 240 DAPF (pH = 3.6±0.03), resulting in 4 % decrease when analyzing BPF and 240 DAPF. In the backslope area, the mean pH decreased by 5 % (BPF to 240 DAPF), from 3.9±0.02 (before PF) to 3.7±0.03 (Figure 3).

For basic cations (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}), different patterns of variation were observed in the landscape compartments (Figure 3). In the footslope area, the contents of Ca^{2+}, Na^{+} and K^{+} decreased immediately after the prescribed fire, with mean of Ca^{2+} = 0.6±0.1 $cmol_c$ kg^{-1}, Na^{+} = 0.17±0.04 $cmol_c$ kg^{-1} and K^{+} = 0.60±0.28 (before PF), and Ca^{2+} = 0.2±0.01 $cmol_c$ kg^{-1}, Na^{+} = 0.06±0.01 $cmol_c$ kg^{-1} and K^{+} = 0.21±0.06 $cmol_c$ kg^{-1} (10 DAPF). After this stage, the contents of these nutrients gradually increased, reaching a mean of Ca^{2+} = 0.5±0.1 $cmol_c$ kg^{-1}, Na^{+} = 0.18±0.02 $cmol_c$ kg^{-1} and K^{+} = 0.71±0.25 $cmol_c$ kg^{-1} (240 DAPF). The variation in percentage of these properties (before PF to 240 DAPF) were respectively -16, 5, and 18 %, respectively. For Mg^{2+}, a different pattern was observed, with a trend of increasing over the standard time observed in both the footslope and backslope areas. In the footslope area, the mean of Mg^{2+} increased 140 %, from 0.5±0.1 (before PF) to 1.2±0.1 $cmol_c$ kg^{-1} (240 DAPF), and in the backslope area 75 %, from 0.8±0.1 (before PF) to 1.4±0.1 $cmol_c$ kg^{-1} (240 DAPF). In the backslope, Ca^{2+} contents also decreased immediately after the prescribed fire (0.2±0.1 $cmol_c$ kg^{-1}), followed by an increase until 240 DAPF (0.5±0.1 $cmol_c$ kg^{-1}), with a mean value decreasing 17 % (BPF to 240 DAPF). For Na^{+} in the backslope area, a 129 % increase was observed at 240 DAPF, with the mean ranging from 0.07±0.01 (before PF) to 0.16±0.01 $cmol_c$ kg^{-1} (240 DAPF). For K^{+}, there was a trend of increase after the prescribed fire in the backslope area, ranging from 0.22±0.05 (before PF) to 0.60±0.14 $cmol_c$ kg^{-1} (240 DAPF), a 124 % increase.

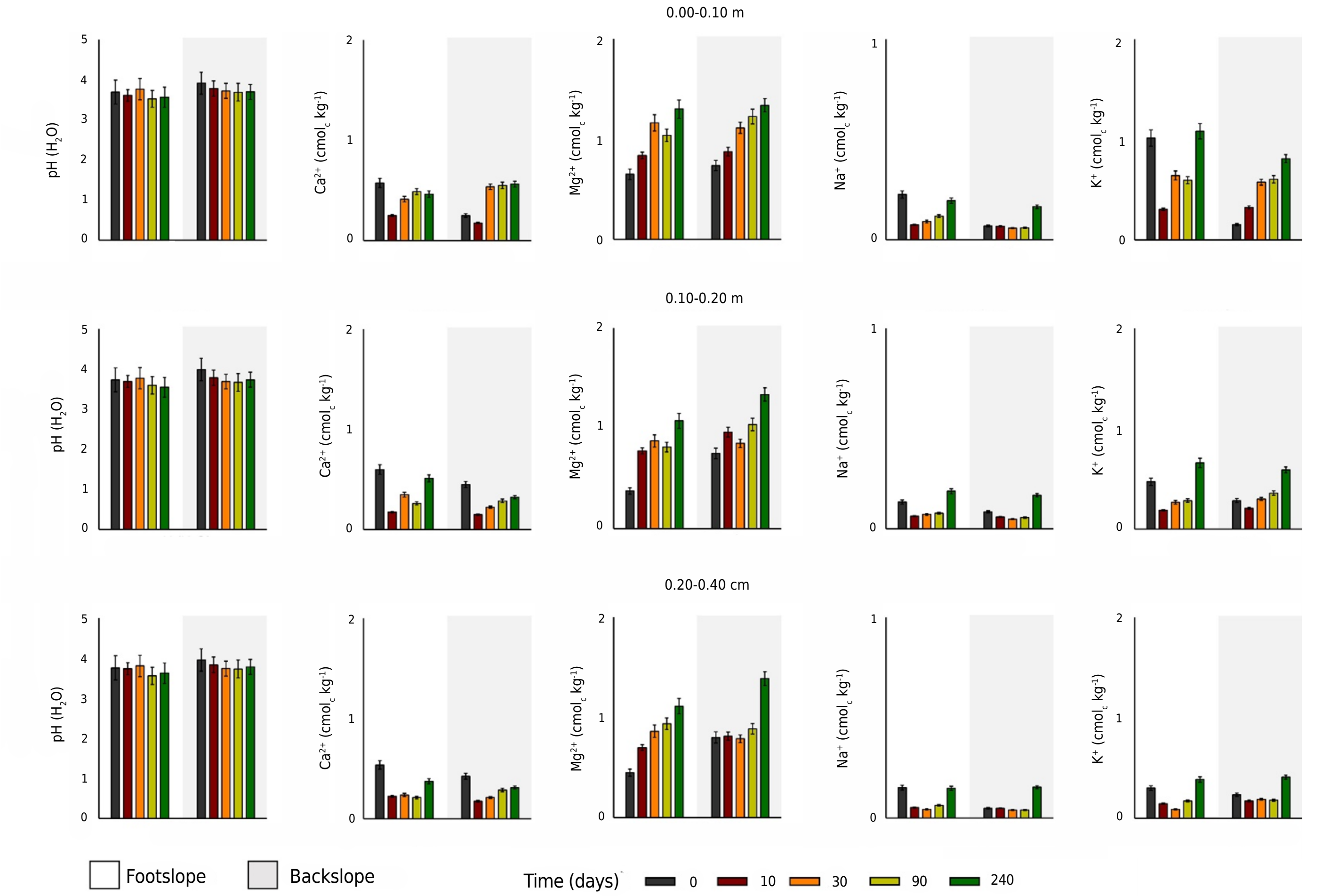

Figure 3. Mean and standard deviation (SD) for pH and soil nutrients, before and at 10, 30, 90 and 240 days after the prescribed fire in footslope and backslope area in the Itatiaia National Park (RJ, Brazil).

In general, for the sum of bases (SB), the same pattern was verified in the backslope and footslope area (Figure 4), with a mean of 1.83±0.42 (footslope, before PF) and 1.43±0.15 $cmol_c$ kg^{-1} (backslope, before PF), decreasing to 1.26±0.14 (footslope, 10 DAPF) and 1.34±0.09 $cmol_c$ kg^{-1} (backslope, 10 DAPF), then increasing until the end of the evaluated period, with a mean of 2.50±0.36 (footslope, 240 DAPF) and 2.52±0.24 $cmol_c$ kg^{-1} (backslope, 240 DAPF). In the footslope area, for potential acidity, there was a reduction until 30 DAPF, followed by an increase until 240 DAPF, with a mean of 23.0±0.95 $cmol_c$ kg^{-1} (before PF), decreasing to 14.5±1.77 $cmol_c$ kg^{-1} (30 DAPF), reaching the highest value at 240 DAPF (H+Al = 44.0±2.89 $cmol_c$ kg^{-1}). Conversely, base saturation increased in this part of the landscape, with a mean of 8.2±1.9 % (before PF), increasing to 11.2±2.8 % (30 DAPF), then decreased until 240 DAPF (SB = 5.5±1.2 %). In the backslope area, H+Al increased over time, with a mean ranging from 11.8±0.75 $cmol_c$ kg^{-1} (before PF) to 39.6±2.38 $cmol_c$ kg^{-1} (240 DAPF), and the V% decreased immediately after the fire, from 10.8±1.3 % (before PF) to 6.6±0.5 % (30 DAPF), followed by an increase until 90 days (V= 9.6±2.3 %) and a subsequent reduction at 240 DAPF (V= 6.3±0.9 %).

Regarding Al^{3+} contents, in the footslope, there was a reduction from 3.8±0.3 (before PF) to 3.1±0.2 $cmol_c$ kg^{-1} (between 30 and 90 DAPF), resulting in values similar to the initial ones at 240 DAPF (Al^{3+} = 3.7±0.3 $cmol_c$ kg^{-1}), a 2 % decrease from BPF to 240 DAPF. In the backslope area, Al^{3+} contents increased over time, with a mean ranging from 2.2±0.1 (before PF) to 3.6±0.2 $cmol_c$ kg^{-1} (240 DAPF, 64 % increase from BPF to 240 DAPF. For available phosphorus (P), there was no clearly discernible pattern for available P in the two landscape compartments (footslope and backslope). In the footslope, the mean contents ranged from 4.6±1.5 (10 DAPF) to 7.7±3.0 mg kg^{-1} (240 DAPF), and in the backslope, between 3.4±0.5 (10 days) and 7.6±2.0 mg kg^{-1} (before PF) (Figure 4).

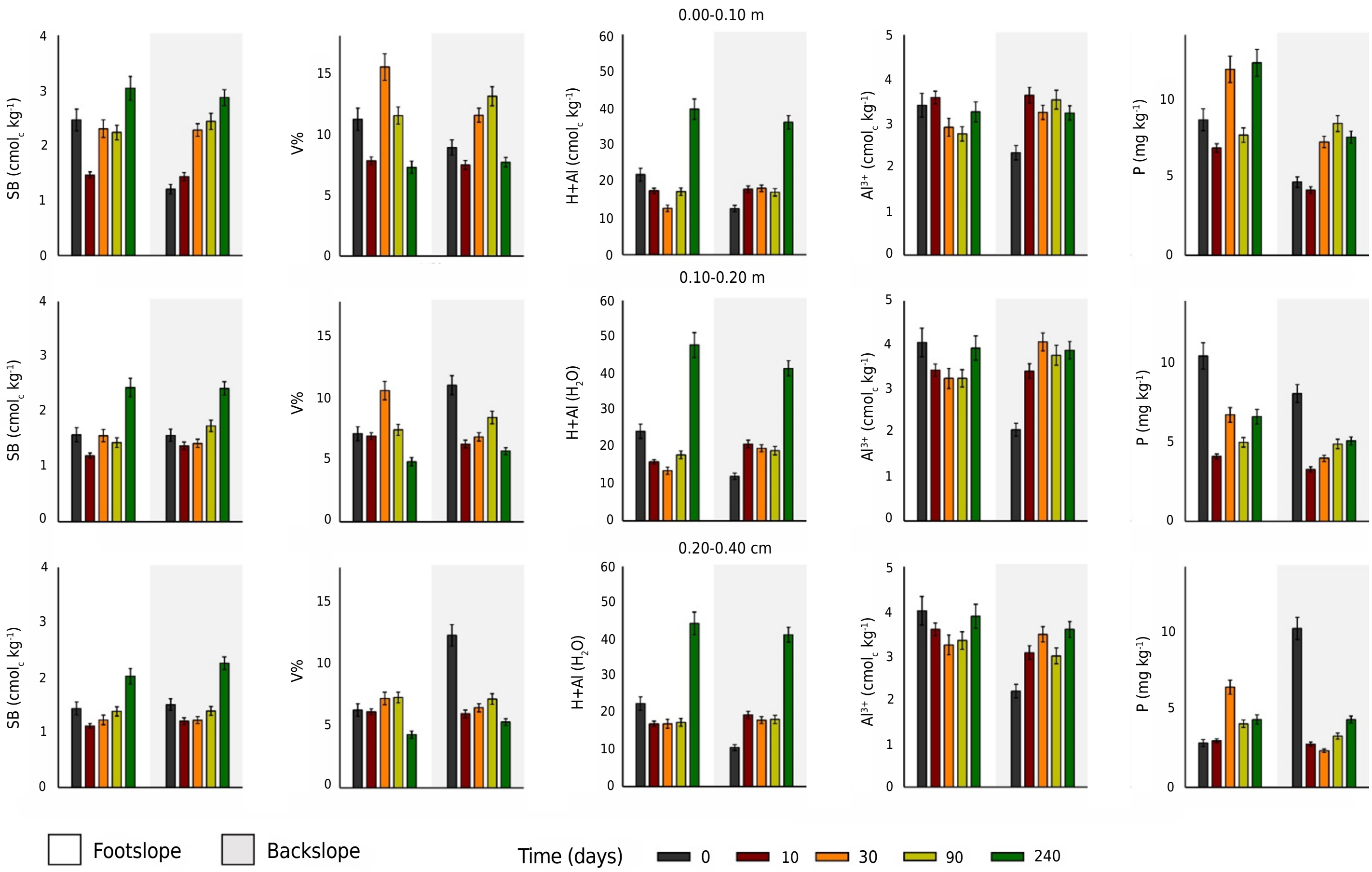

Figure 4. Mean and standard deviation (SD) for sum of bases (SB), base saturation (V%), potential acidity (H+Al), aluminum (Al^{3+}) and available phosphorus (P), before and at 10, 30, 90 and 240 days after the prescribed fire in the footslope and backslope area in the Itatiaia National Park (RJ, Brazil).

CHN and labile organic carbon (LOC)

Total C, H, N, and LOC contents showed a distinct pattern over time between landscape positions (Figure 5). In the footslope area, the same pattern was observed for C, H and N, with reduction immediately after the prescribed fire, with mean decreasing from C of 229±27 g kg^{-1}, H of 38.6±3.1 g kg^{-1} and N of 12.7±1.7 g kg^{-1} (before PF) to 166±12, 32.3±1.9 and 8.5±0.8 g kg^{-1} (10 DAPF), respectively. From 10 days, C, H and N contents increased at 240 DAPF (C = 220±16 g kg^{-1}, H = 37.4±1.9 g kg^{-1} and N = 12.9±1.4 g kg^{-1}). The variation (BPF to 240 DAPF) in percentage value was respectively -4, -3 and +2 %. Similar patterns were also observed in the backslope area for these elements, increasing until 30 DAPF, with means of C = 157±5 g kg^{-1}, H = 29.1±0.6 g kg^{-1} and N = 7.9±0.4 g kg^{-1} (before PF), increasing to C = 205±17 g kg^{-1}, H = 36.8±1.6 g kg^{-1} and N = 10.8±0.8 g kg^{-1} (30 DAPF), and decreasing until 240 DAPF (C = 178±19 g kg^{-1}, H = 32.0±2.1 g kg^{-1}, N = 9.7±1.1 g kg^{-1}). The variation (BPF to 240 DAPF) in percentage value was respectively +15, +10, and +23 %.

For the C:N ratio, there was no clearly discernible pattern in the two landscape positions, with a mean of 17.6±0.7 in the footslope area and 18.6±0.5 in the backslope area. However, at 240 DAPF, the ratio remained lower than that observed before the fire for the two landscape positions. For the labile organic carbon (LOC) content, the same pattern of variation over time was verified in the two landscape positions. Before the prescribed fire, the mean of LOC were 3.4±0.3 (footslope) and 3.2±0.1 g kg^{-1} (backslope), oscillating until 90 DAPF and decreasing at 240 DAPF (LOC = 2.4 ± 0.3 g kg^{-1} in the footslope; LOC = 2.0±0.2 g kg^{-1} in the backslope). The decrease (BPF to 240 DAPF) in percentage was 29 (footslope) and 38 % (backslope) (Figure 5).

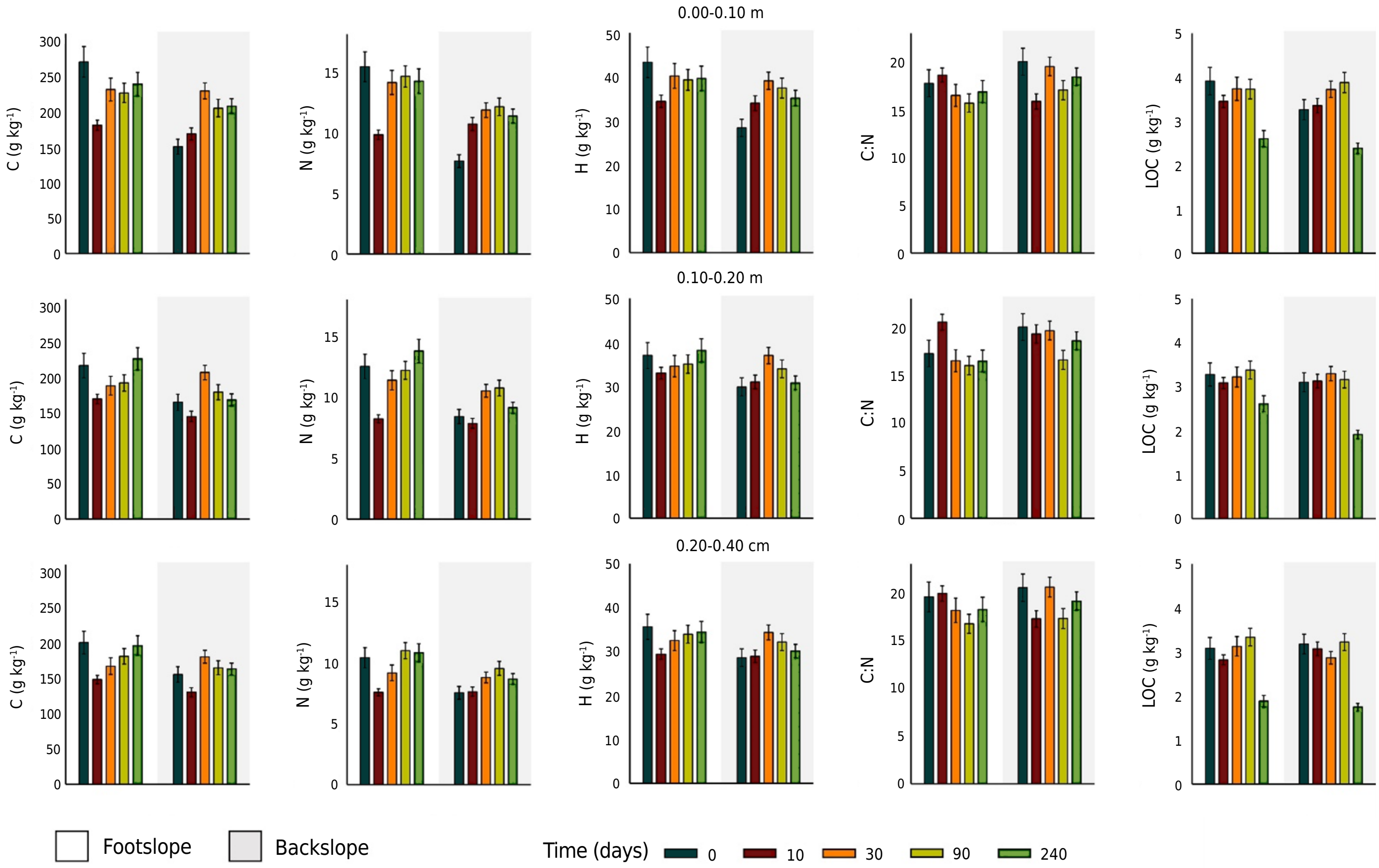

Figure 5. Mean and standard deviation (SD) for C, N, H, C:N ratio and labile organic carbon (LOC) before and at 10, 30, 90 and 240 days after the prescribed fire in backslope and footslope area in the Itatiaia National Park (RJ, Brazil).

Chemical fractions of soil organic carbon

For the carbon in the humic fractions (humin, fulvic acid, and humic acid), different patterns were found between the different landscape compartments (Figure 6). In the footslope area, C-Hum decreased immediately after the prescribed fire, with a mean decreasing from 195±28 (before PF) to 113±19 g kg^{-1} (10 DAPF), and then increased until 240 days (C-Hum = 194±33 g kg^{-1}), without variation in the percentage value from BPF to 240 DAPF. In the backslope area, there was a trend of increase over time (23 % from BFP to 240 DAPF), with mean between 116±13 g kg^{-1} (before PF) and 142±11 g kg^{-1} (240 DAPF). The C-AF also showed a reduction after the pre-scribed fire in the footslope and backslope area, with a mean before PF of 14.4±3.0 (footslope) and 14.3±0.7 g kg^{-1} (backslope), decreasing at 10 DAPF to 10.8±06 (footslope) and 10.8±0.4 g kg^{-1} (backslope). After that, there was a trend of increase over time, reaching at 240 DAPF the mean of C-AF = 15.3±2.0 (footslope) and C-AF = 14.1±0.9 g kg^{-1} (backslope), the variation (BPF to 240 DAPF) of percentage value was +6.5 (footslope), and -1 % (backslope). For C-AH, only the footslope area showed reduction after the prescribed fire, with a mean ranging from 46.6±0.7 (before PF) to 37.2±0.6 g kg^{-1} (10 DAPF), and then increasing until 240 DAPF (C-AH = 43.9±1.3 g kg^{-1}), with a decrease of 6 % (from BPF to 240 DAPF). In the backslope area, the C-AH increased until 90 DAPF, from 33.7±1.2 (before PF) to 41.3±2.0 g kg^{-1} (90 DAPF), and then decreasing until 240 DAPF (C-AH = 37.5±0.4 g kg^{-1}), an increase of 11 % (from BPF to 240 DAPF).

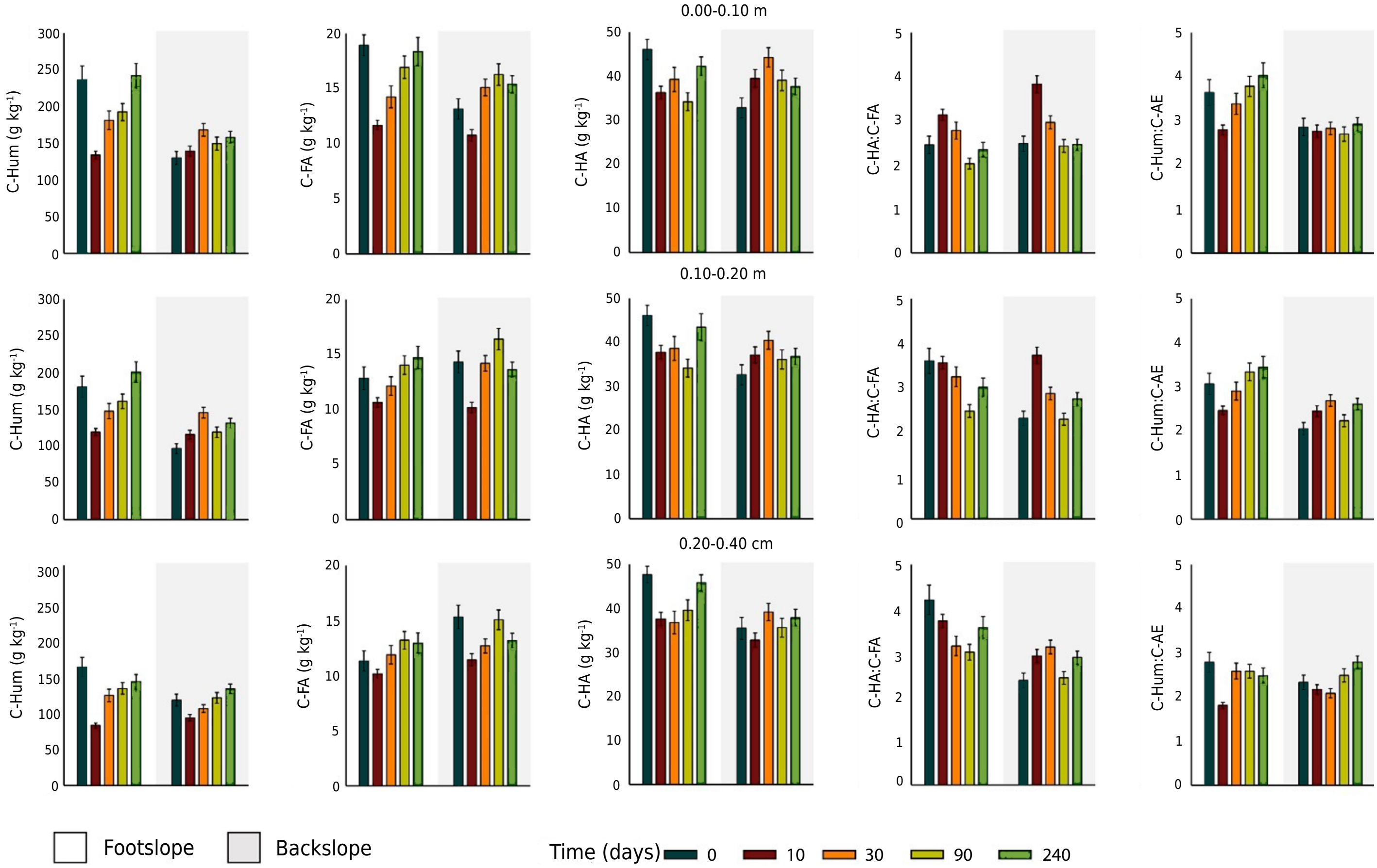

Figure 6. Mean and standard deviation (SD) for carbon in humic fractions, before and at 10, 30, 90 and 240 days after the prescribed fire in footslope and backslope area in the Itatiaia National Park (RJ, Brazil). C-Hum: carbon in humin fraction; C-FA: carbon in fulvic acids; C-HA: carbon in humic acids; AE: alkaline extract (C-FA+C-HA).

Ratios between the humic fractions (C-HA:C-FA and C-Hum:C-AE) used to interpret the data obtained from the chemical fractionation of organic carbon showed different patterns in the footslope and backslope areas. In the footslope, the C-HA:C-FA ratio tended to decrease until 90 DAPF, increasing after 240 DAPF, with mean of 3.4±0.6 (before PF), 2.5±0.3 (90 DAPF) and 3.0±0.4 (240 DAPF). On the other hand, the C-Hum:C-AE ratio in the footslope decreased immediately after the fire and then increased until 240 DAPF, with means of 3.2±0.3 (before PF), 2.4±0.4 (10 DAPF) and 3.3±0.6 (240 DAPF). In the backslope, the C-HA:C-FA ratio increased after fire, between 10 and 30 DAPF, and then decreased between 90 and 240 DAPF, with mean of 2.4±0.1 (before PF), 3.5±0.4 (10 DAPF) and 2.7±0.2 (240 DAPF). For the C-Hum:C-AE ratio, there was no clearly discernible pattern in the backslope, with a mean between 2.4±0.3 (before PF) and 2.8±0.1 (240 DAPF) (Figure 6).

Principal Component Analysis (PCA)

The PCA considering all soil properties showed a clear difference between the landscape positions (Figures 7 and 8), indicating that the effects of fire on the soil were different in the footslope and backslope areas. On the footslope, the principal component 1 (PC1) explained 53.9 % of the total variance, and the principal component 2 (PC2) explained 21.2 %. The PC1 and PC2 together, explained 75.1 % of the variance in the original data (Figure 7). The positive axis of PC1 is defined by the following properties: C, N, H, C-Hum, C-FA, C-Hum:C-AE, and SB; whereas the negative axis is defined by the C:N ratio, C-HA:C-FA, pH, and Al^{3+}. In the case of PC2, the positive axis is mainly represented by Al^{3+}, H+Al, and C-HA, whereas the negative axis is mainly represented by V%, Mg and LOC. Two groups were clearly identified, separating the sampling times: 1) before PF and 240 days after PF; and 2) 10, 30, and 90 days after PF. These results indicate that 240 days after the prescribed fire, the soil properties in the footslope are similar to the soil properties before the fire, demonstrating the high resilience of this area.

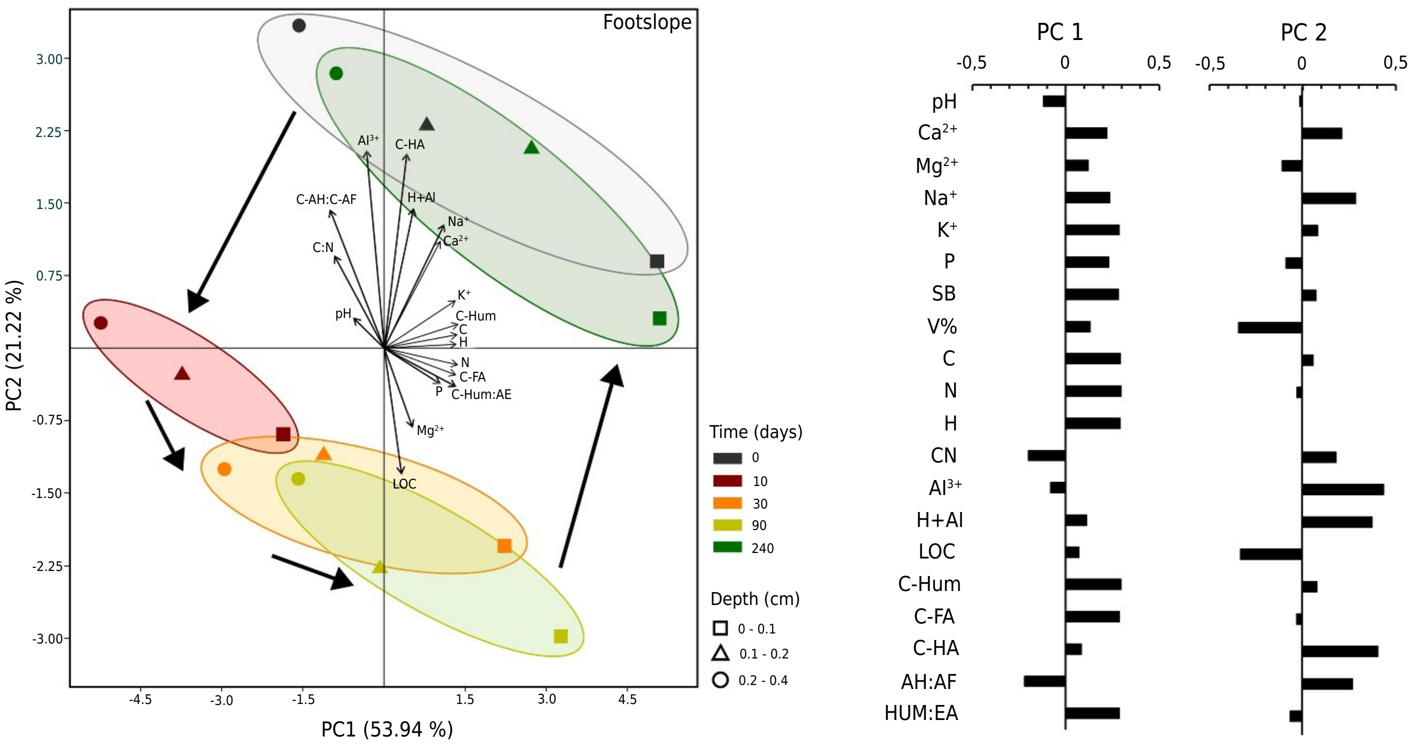

Figure 7. Principal component analysis in samples collected in the footslope area before and at 10, 30, 90, 240 days after the prescribed fire in the Itatiaia National Park (RJ, Brazil). Arrows indicate the chronological sequence.

In the backslope area, the principal component 1 (PC1) explained 41.1 % of the total variance, and the principal component 2 (PC2) explained 20.6 %. Together, they explain 61.7 % of the variance in the original data (Figure 8). The positive axis of PC1 is defined by the properties SB, C, N, H, C-Hum, and K, whereas the negative axis is defined by the pH and C:N ratio. In PC2, the positive axis is mainly represented by V%, P, LOC, C-FA, Ca^{2+}, and pH, whereas the negative axis is mainly represented by H+Al, Al^{3+}, C-HA:C-FA, Na^{+}, and Mg^{2+}. There was no clear pattern of distribution/grouping of the evaluation times, but it was possible to observe that the soil layers before the fire differed from the others on the negative axis of PC1 and the positive axis of PC2. Conversely, the soil layers at 240 days showed positive values for PC1 and negative for PC2. This indicates that 240 days after the fire, the properties of the soil in the backslope area were in contrast with those observed before the fire. In summary, the results of the PCA indicate that the effects of fire on soil are different in different landscape compartments (backslope and footslope). These results are important for the management of prescribed fires in high-elevation grasslands (*Campos de Altitude*).

DISCUSSION

For the two landscape compartments, small variations in pH were observed over time, with a slight reduction at 240 DAPF. This result is contrary to that observed in the literature. Many authors have reported an increase in pH after prescribed fires due to OH losses, SOM oxidation, and the release of cations in the ashes (Switzer et al., 2012; Muqaddas et al.,2016; Alcañiz et al., 2018). However, there are studies in which the pH remained unchanged after controlled burning (Lavoie et al., 2010; Switzer et al., 2012; Meira-Castro et al., 2014).

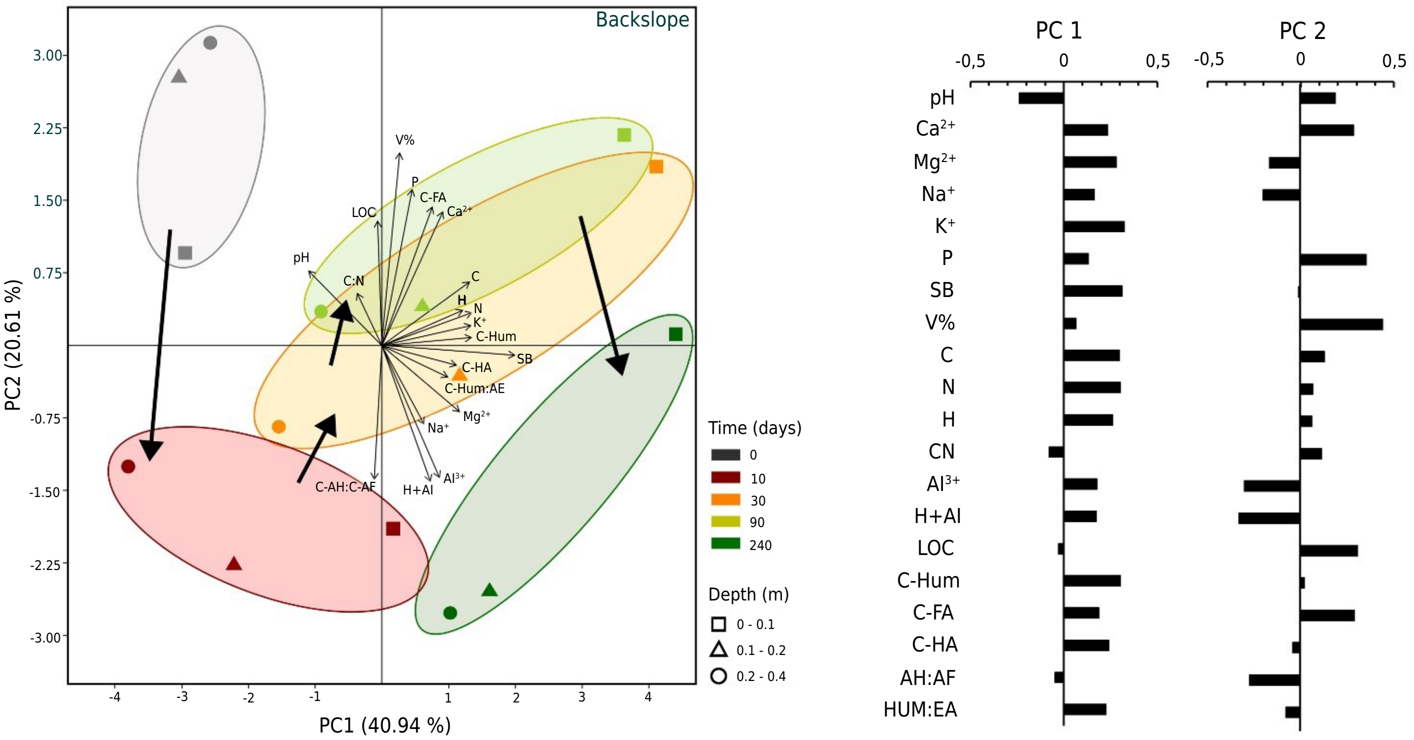

Figure 8. Principal component analysis in samples collected in the backslope area before and at 10, 30, 90, 240 days after the prescribed fire in the Itatiaia National Park (RJ, Brazil). Arrows indicate the chronological sequence.

The reduction in Ca^{2+}, Na^{+} and K^{+} availability 10 days after the prescribed fire, observed in both slope positions, resulted in lower pH, SB, and V% (Figures 4 and 5). This reduction probably resulted from changes in humified organic matter due to the action of fire, as indicated by the lower C contents in the humic fractions (C-Hum, C-FA, and C-HA) (Figure 7). In a study on the characterization of organic matter in soils under high-elevation grasslands in the state of Minas Gerais, Benites et al. (2001) reported the effect of fire on the transformation of humic substances, with the loss of oxygenated groups, dehydration, and condensation. With the reduction of the functional groups of humic substances, basic cations such as Ca^{2+}, Na^{+} and K^{+} can be displaced and leached from the system. However, after 30 days, the Ca^{2+} (in both the slope area and layers) and K^{+} (in both areas on the surface layer) increased, probably because of the effect of the ashes produced by vegetation burning. It is already known in the literature that the prescribed fire alters the distribution and amount of nutrients in the soil (Alcañiz et al., 2018). Several studies have reported an increase in the concentrations of available cations immediately after the prescribed fire due to the release of ash from organic matter and its incorporation into the soil (Shakesby, 2011; Alcañiz et al., 2016, 2018).

Concentrations of cations observed in this study are also related to the contribution of alkaline rocks (nepheline syenite) in the crystalline basement of this region, whose mineralogical composition commonly results in soils with $Mg^{2+} > Ca^{2+}$ (Soares et al., 2016; Silva Neto et al., 2018). Among the alkaline rocks of the Itatiaia complex, nepheline syenites have mafic minerals, such as pyroxenes, amphiboles, and biotite, and the accessory minerals are magnetite, ilmenite, titanite, apatite, and zircon at lower frequencies (Enrich et al., 2005). This may explain the differentiated pattern observed for Mg^{2+}, which increased at all depths analyzed after the prescribed fire until the end of the evaluation period (240 days). The increase in Mg^{2+} availability was also reflected by the increase in SB after the fire.

High potential acidity (H+Al) results from the high concentrations of H^+ due to the high organic matter content (Pereira et al., 2005). In soils with an organic constitution, most of the acidity results from the content of H^+ derived from organic acids and hydrolysis of other compounds, unlike what occurs in mineral soils, where this acidity is due to the hydrolysis of Al^{3+} ions (Ebeling et al., 2008; Silva et al., 2008). In both areas (footslope and backslope), a sharp increase in this parameter was observed at 240 DAPF, which may be due to the effect of seasonality. The increase in the frequency and intensity of rainfall in the study area between September and November (Figure 3) favors the humification process, as can be observed by the increasing trend in the C-Hum, C-FA, and C-HA. Higher moisture/hydromorphism conditions lead to slow decomposition of the plant material and permanence of humic substances that are distributed along the profile (Silva, 2009; Scheer et al., 2011). Higher C-Hum:C-AE ratio (C-Humin:C-Alkaline Extract) corroborates this interpretation, indicating the predominance of the Hum fraction. In addition, in a study evaluating seasonal changes in acidic peatlands of the Atlantic Forest in southern Brazil, Etto et al. (2014) pointed out that rainfall can also influence microbial diversity due to increased groundwater level and alteration of soil redox state, as oxygen plays an essential role in driving changes in the structure and composition of the microbial community (Song et al., 2008).

As for the variations in Al^{3+} content, different patterns were observed in the two slope positions. In the footslope area, there was a reduction trend after the prescribed fire, followed by an increase at 240 DAPF (Figure 5). This reduction may be due to the effect of the ash after the fire, which can reduce the Al^{3+} content in the soil. The chemical composition of ash can neutralize soil acidity due to the high levels of calcium and magnesium oxides, hydroxides, and carbonates, acting as soil corrective and fertilizer (Demeyer et al., 2001; Park et al., 2005; Shi et al., 2017). In a study conducted by Fonseca et al. (2017), in Montesinho Natural Park, a plateau area in Northeastern Portugal, the results for Al^{3+} and exchangeable acidity were similar and decreased during the experimental period. Regarding the variations in Al^{3+} in the backslope, there is a trend of increase in the content of this element over time, in parallel with the reduction in pH, probably due to the release of Al complexed by organic matter (OM) after the fire. Organic matter can complex Al^{3+} and reduce its negative effects on plants (Salet, 1998; Ebeling et al., 2008). Because of its high OM content, soils can complex Al^{3+} in their carboxylic and phenolic radicals, thus reducing the effect of Al^{3+} toxicity on plants (Valladares et al., 2008). Another significant effect of the rainy season on soil properties after a prescribed fire was related to labile organic carbon (LOC) content. A sharp reduction in the LOC was observed at 240 DAPF in both landscape compartments (footslope and backslope). In a study conducted by Muqaddas et al. (2016) in a tall high forest area in Southeast Queensland, the LOC contents were lower in the two yearly burning areas compared to the four yearly burning areas and, according to the authors, this reduction in the two yearly burning areas was equal to 48 % compared to the unburned area. According to Arocena e Opio (2003), the reduction in the labile compartment of C and N may be partially due to the loss of the biome of the forest/litter and soil C and N during the fire.

Various forms of carbon, including hydrocarbons and particulate fractions of SOM, are produced in an ecosystem after the passage of fire, as well as thermal changes in previous forms of C already existing in the ecosystem (González-Pérez et al., 2004). More recalcitrant structures (derived from carbohydrates, lipids, alkylated macromolecules, and peptides), formed after the action of fire, were observed in a study conducted by Vergnoux et al. (2011) in natural ecosystem areas and simulations with soil in the laboratory. According to the authors, some of these newly formed structures, which are initially not humified, may become extractable as the humic fraction.

It is important to highlight that the comparison of the studies cited in the present study should be done with caution, owing to the different soil thicknesses analyzed in each case, as well as the different environments in each study. It is also important to note that it is not possible to generalize the effects of prescribed fire on soil chemical properties and organic matter because many of the variations are associated with intensity, frequency, slope in the landscape, soil moisture, soil type, and degree of combustion of the material in the aerial part (Knicker, 2007; Muqaddas et al., 2016).

For the two slope positions, the results also showed an inversely proportional relationship between the available P and the Al^{3+}, which was also shown in the PCA (Figures 7 and 8). This pattern can be explained by both P adsorption by Al^{3+} complexes and organic matter in the carboxyl groups of peat (Bloom, 1981; Bedrock et al., 1997) and the precipitation of amorphous Al hydroxyphosphate (Bloom, 1981; Sanyal and De Datta, 1991; Giesler et al., 2002). Some studies also indicate that there may be a contribution of the ashes from the burned vegetation, which promotes an increase in phosphorus content in the surface layer after burning. In addition, the phosphorus content tends to increase in the soil due to the mineralization of the organic forms of which this element is part (Úbeda et al., 2005; Pereira et al., 2012; Fonseca et al., 2017). On the other hand, the study conducted by Alcañiz et al. (2016) (in the coastal mountains of Catalonia, Spain) reports an increase in P content after the fire, but a year later, the content were lower than those recorded before the fire.

The impacts of fire on the total C, H, and N contents were different in the two slope positions. Although higher contents of these elements were observed at the end of the evaluation period (240 days) in both cases, the footslope area seems to be more resilient to the effects of fire. After the reduction at 10 days post-fire, the contents of C, H, and N increased linearly until 240 days post-fire. The soil-landscape relationship may explain this result – besides being a slope section with the addition of materials from the higher parts (sediments, organic matter, water, etc.), in the footslope area, the soils are strongly influenced by the presence of high groundwater level (hydromorphic environment with poor drainage) (Soares et al., 2016; Silva Neto et al., 2018). In this area, soils in the footslope position, Typic Haplosaprists, are formed under hydromorphic conditions, which reduce the decomposition of organic matter to the detriment of its transformation under anaerobic conditions (Silva et al., 2013; Weissert and Disney, 2013; Bispo et al., 2015; Silva Neto et al., 2019, 2020). In addition, they form as a result of a decrease in decomposition rates at low temperatures, while maintaining a constant supply of organic matter (Benites et al., 2007; Silva et al., 2009; Benavides e Vitt, 2014; Cooper et al., 2015).

Several studies have reported losses of C and N in soils of organic constitution due to the effect of fire (Turetsky et al., 2011, 2015; Brown et al., 2015) attributed mainly to volatilization. However, in environments such as the high-elevation grasslands of the INP, where peat horizons show significant variations in thickness and distribution, the effect of combustion during fires is spatially variable. In addition, low-intensity fires, as in the prescribed fire, are commonly of low severity because they are used only to reduce the accumulation of fuel biomass and are applied under specific weather conditions to avoid high severity. In most cases, the soil changes produced by this type of fire are only transient.

These results indicate that the slope position controls the changes in the chemical properties of the soil after a prescribed fire in the high-elevation grasslands of the INP. As demonstrated by PCA, despite the variations at 240 DAPF, the chemical properties of the soil in the footslope area were similar to those observed before the prescribed fire. This result is of great relevance for fire management in the INP, as it indicates greater system resilience in this part of the landscape. On the other hand, in the backslope area, at the end of the evaluation period (240 days), the results showed antagonistic properties to those observed before the fire, probably due to pedological and hydro geomorphological differences. These factors are interdependent and can increase or mitigate the effects of fires. At this position, the soils are shallow, less thick, and better drained than those from the footslope. However, with a larger slope, they are more susceptible to erosive processes, and rock outcrops are common. Further studies are needed, especially to determine the medium- and long-term effects of different landscape positions and the use of this management tool more effectively.

CONCLUSIONS

Slope position controls the effects of the prescribed fire on the soil. In the backslope position, the fire produced negative effects in the medium term and could induce soil degradation, and the system had greater resilience to the effects of fire, which was indicated by the recovery of soil chemical properties. Until 240 days after the fire, its effects are still present in the soil, especially in backslope areas, which are more susceptible to degradation by fire and, for this reason, need more time to restore the conditions observed prior to the fire.

This study contributes to assessing the suitability of controlled burning of vegetation for managing risks of fire in mountainous regions, such as the high-elevation grasslands. The results in the time period greater than 240 days, showed that under the conditions of the study, and in the two areas (footslope and backslope), periodic prescribed burns can positively impact the conservation of this ecosystem. This ecological benefit overcomes the chemical changes that are generated.

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