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Soil Biological, Chemical, and Physical Properties After a Wildfire Event in a Eucalyptus Forest in the Pampa Biome

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ABSTRACT: Wildfire events cause considerable environmental disturbance but few studies have examined changes in soil properties due to fire. This study aimed to assess the effect of a wildfire event on chemical, physical, and biological properties of the soil in a eucalyptus forest in the Pampa biome. Part of a seven-year-old eucalyptus forest was affected by a wildfire event that lasted for two days. Soil and plant litter sampling was performed in three areas: in the forest that was not affected by the fire, in the forest affected by it, and in an adjacent natural pasture area (the original vegetation). Seven samples were collected from the 0.00-0.05 and 0.05-0.20 m layers of each plot for biological analysis, and three samples were collected for chemical and physical analyses. Disturbed soil samples were collected in order to determine pH, organic matter, acidity, and nutrient content. Undisturbed samples were collected to determine soil microporosity, macroporosity, total porosity, and density. Soil macrofauna was assessed through the Tropical Soil Biology and Fertility method, and biological activity was tested through substrate consumption in the bait-lamina test. The fire increased soil pH values, CEC, and base saturation, as well as K, Ca, and Mg content; it decreased potential acidity and P content in the soil. Soil physical properties were not altered by the wildfire. The total abundance of macrofauna and of annelids, arachnids, coleoptera, and isoptera decreased due to the wildfire, resulting in lower soil diversity. Hymenoptera abundance increased because of the fire event. The feeding activity of organisms in the soil surface layer decreased due to the fire. The wildfire in the eucalyptus forest in the Pampa biome altered soil chemical and biological properties.

Keywords: fire, environmental disturbance, soil quality, soil diversity.

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INTRODUCTION

Natural environmental disturbances occur in ecosystems and are essential factors in ecosystem dynamics (Gongalsky et al., 2012). Wildfires are one of the main sources of disturbance (Alves and Nógrega, 2011; Verble-Pearson and Yanoviak, 2014; Zaitsev et al., 2016) and they can alter soil physical (Mataix-Solera et al., 2011), chemical (Redin et al., 2011), and biological properties (Myers and Harms, 2011; Gongalsky and Persson, 2013).

Wildfires are a high concern in Brazilian forest activity because planted forests cover approximately 7.8 million hectares (Ibá, 2016). Cultivated areas are divided into forest massifs that measure dozens of hectares; this makes wildfires particularly dangerous. Moreover, adoption of integrated agricultural systems has been strongly encouraged in recent decades, for example, integrated crop-livestock-forestry systems. As a result, the number of fire events has increased considerably, as well as the extension of the areas burned (Alves and Nógrega, 2011).

The extent of environmental disturbances caused by these fires varies depending on the climate, the stand in the forest, the presence of combustible materials, and soil properties (Ojeda et al., 2010; Lehmann et al., 2011). However, few studies describe the effects of fire on soil chemical, physical, and biological properties in Brazil, especially in the Pampa biome, which currently has approximately 1 million hectares of planted forests (Azevedo and Fialho, 2015).

The burning of vegetation and plant litter alters the soil surface layer and some nutrient dynamics since it catalyzes a fast and intense mineralization process (Rheinheimer et al., 2003; Boerner et al., 2009). Increased N, P, K^+, Ca^{2+}, and Mg^{2+} contents are often found in the soil after fire events, since ash has high contents of these nutrients (Rheinheimer et al., 2003; Redin et al., 2011). A significant rise in soil pH (Boerner et al., 2009; Hylander et al., 2011) and even changes in soil mineralogy are other fire effects (Orrutéa et al., 2012).

Burning of forest areas can cause changes in soil physical properties (Mataix-Solera et al., 2011; Verma and Jayakumar, 2012; Thomaz et al., 2014). Forest fires increase soil hydrophobicity through the formation of a water repellent layer, which decrease soil-water affinity and increased water and soil losses (Keesstra et al., 2017; Vogelmann et al., 2017). Wildfire exposes the surface of minerals, alters the aggregates stability (Redin et al., 2011), increases density, and alters soil texture (Stoof et al., 2010). Burning (temperature >300 °C) may increase clay and silt content which can be explained by the physical weathering of sand-sized particles in silt and clay particles. However, other authors show that burning in forest areas did not cause large changes in soil physical properties (Spera et al., 2000; Boerner et al., 2009; Thomaz et al., 2014).

Wildfires can reduce soil fauna abundance and richness in the short term (Verble-Pearson and Yanoviak, 2014) due to the immediate death of many organisms from the direct effects of fire (Gongalsky et al., 2016). Longer term reduction also comes from the indirect effects of destruction of vegetation, plant litter, and surface and sub-surface organic matter in the soil, as well as from changes in temperature and moisture conditions, among other factors (Thomaz et al., 2014; Shaw et al., 2016).

The recovery of organism communities in the soil after the fire event is slow and it depends on burning intensity, among other factors (Malmström, 2006; Gongalsky et al., 2012). The time needed to recover the abundance and richness of these species after low-intensity fires in mixed forests in the United States can be approximately one year (Verble-Pearson and Yanoviak, 2014), but recovery can require up to ten years when the fire is intense, as in the case of pine forests in Sweden (Malmström, 2006). Moreover, it has been shown that after wildfires, the communities of soil organisms form a food chain structure that is drastically different from the one observed before the fire (Cairney and Bastias, 2007; Gongalsky et al., 2012).

Forest fires appear to alter several soil properties, and there is a lack of scientific information on the subject, especially for the Pampa biome. Thus, this study aimed to assess the effect of wildfire on soil chemical, physical, and biological properties in a eucalyptus forest in the Pampa biome.

MATERIALS AND METHODS

Study site characterization

The study was carried out in the municipality of São Gabriel (30° 25′ 49.74″ S and 54° 22′ 5.86″ W), in the Pampa Biome, in the state of Rio Grande do Sul (RS), Brazil. The climate is Cfa, according to the Köppen classification system; it has a sub-tropical humid type climate, with hot summers and mean annual temperature of 18.5 °C (Moreno, 1961). Rainfall throughout the period studied (January to April 2012) was 133 mm (Figure 1), which was 66 % lower than the normal mean rainfall (Inmet, 1992). The soil is classified as an *Argissolo Bruno-Acinzentado* (Santos et al., 2013) or Typic Hapludalf (Soil Survey Staff, 2014), and the natural vegetation is typical of the Pampa biome. The main plant species in the area were *Saccharum angustifolium, Aristida laevis, Eryngium pandanifolium*, and *Paspalum* ssp. This natural pastureland is used for extensive bovine and ovine raising on a slightly rolling topography.

In 2005, 20 hectares of *Eucalyptus dunnii* were established in this natural pastureland; the eucalyptus seedlings were planted at a spacing of 2 × 2 m. A fire of unknown cause in 2012 lasted two days. It affected plant litter, tree branches, and tree canopy in four hectares, since the flames did not cross roads and firebreaks (Figure 2). The natural pasture used in the study covers 5 hectares; it is adjacent to the eucalyptus forest and was not affected by the fire.

Soil chemical and physical properties

Evaluations were performed in the following three areas two months after the wildfire event: in the eucalyptus forest that was not affected by the wildfire (EF); in the eucalyptus forest affected by the wildfire (AWF); and in the natural pasture adjacent to the forest (NP).

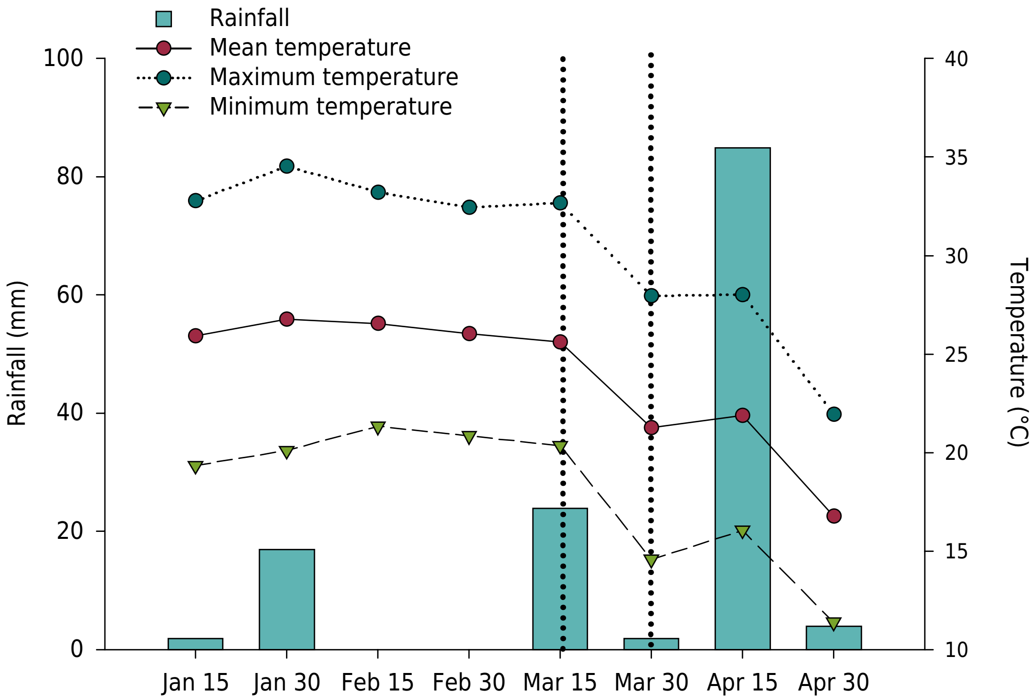

Figure 1. Accumulated rainfall and the mean, maximum, and minimum air temperature in 15-day intervals throughout the months of the study in São Gabriel, RS, Brazil. The time-period between dotted lines corresponds to sampling days.

Figure 2. Overview of the eucalyptus forest, of the burnt area (AWF), and of the unburnt area (EF) in São Gabriel, RS, Brazil.

Four plant litter samples (50 × 50 m) were collected from each area, and dry matter was determined after 72 h at 65 °C in a forced-air circulation laboratory oven. Three soil samples from the 0.00-0.05 and 0.05-0.20 m layers were collected from each area at 20 m from each other and from the edge of the area. The disturbed soil samples were used to determine: pH in soil water suspension (1:1), clay content in densimeter, organic matter content by Walkley-Black method, available P extracted with Mehlich-1 and determined in spectrophotometer (660 nm), available K extracted with Mehlich-1 and determined in flame photometer, contents of Ca^{2+} and Mg^{2+} extracted by EDTA and determined by atomic absorption spectrophotometry; S extracted by $Ca_3(PO_4)_2$ and determined in spectrophotometer (440 nm), potential acidity estimated by H+Al and the cation exchanging capacity (CEC) at pH 7.

Undisturbed samples were collected (with the aid of volumetric rings) and used for soil physical analysis. Soil density was determined according to Claessen (1997). Samples were saturated through capillarity and weighed to determine total porosity (Tp), and macro- (Mac) and microporosity (Mic). Moisture at equilibrium stress -0.006 MPa was obtained on a tension table (Reinert and Reichert, 2006).

Sampling fauna in the soil

Soil fauna was sampled along with the soil collected to check chemical and physical properties. Macrofauna was assessed through the Tropical Soil Biology and Fertility (TSBF) method (Anderson and Ingram, 1993) by collection in seven blocks from each area (0.25 × 0.25 × 0.20 m). The sites were 10 m distant from each other and 20 m from the edge, for a total of 21 samples. The soil blocks were collected manually. The organisms were identified at the order level with the aid of a stereoscopic microscope.

The bait-lamina method was used to assess the activity of the soil organisms (Torne, 1990). This method consists of using an apparatus composed of plastic slides (120 × 6 × 1 mm) with 16 holes of 1.5 mm diameter, spaced 5 mm from each other (Torne, 1990). These holes were filled with the substrate to be consumed by the soil organisms. The substrate was composed of a homogeneous mixture of powdered cellulose (70 %), wheat flour (27 %), activated charcoal (3 %), and water (Kratz, 1998). The holes in the bait lamina were filled manually; after drying at room temperature, the procedure was repeated in order to completely fill the holes with the substrate (Podgaiski et al., 2011). In each area, 4 sites of 1 m^2 were demarcated in which 16 slides were inserted in the soil. Thirty slides were placed in the natural pasture at each site, since 14 slides were used for monitoring consumption. The slides were left in the field for 50 days, which was the time necessary for 60 % of the substrate in the natural pasture to be consumed in at least one replication. The slides were carefully collected and stored in hermetically sealed plastic bags and taken to the laboratory. The slides were assessed as unconsumed (score 0 %), partially consumed (score 50 %), and completely consumed (score 100 %); the assessment procedure was performed with the aid of lighting and a magnifying glass.

Data analysis

The number of individuals of macrofauna in the soil in all treatments was transformed ($x^{0.5}$) for purposes of data normalization. The soil chemical [pH(H_2O), CEC, V%, H+Al, clay, OM, P, K, S, Ca^{2+}, and Mg^{2+}], physical (soil density, total porosity, macro- and microporosity), and biological properties (macrofauna and soil activity) were subjected to analysis of variance (Anova). The means were compared by the Scott-Knott test ($p<0.05$) when they were significant in the F test ($p<0.05$). The Simpson (Is), Shannon (H), Margalef (DMg), and Pielou (J) diversity indexes of the macrofauna in the soil were calculated in Past® software. The properties were subjected to principal component analysis (PCA) in Statsoft Statistica 7.0 software.

RESULTS AND DISCUSSION

The amount of dry matter in the plant litter of the NP, EF, and AWF areas was 1.39, 16.83, and 7.61 Mg ha^{-1}, respectively, showing that the wildfire reduced plant litter dry matter in the forest by approximately 50 %. These values are close to those found by Freitas et al. (2013), Viera et al. (2014), and Ribeiro and Soares (1998) in studies conducted in a natural pasture, in eucalyptus monocultures, and in a monoculture of burnt eucalyptus. The dry matter values in NP were lower than in the EF and AWF areas due to the high grassing pressure on them.

The fire event altered many chemical properties, mainly in the surface layer, but also in the sub-surface layer (Table 1). Cation exchange capacity, pH(H_2O), base saturation, organic matter, and K, Ca^{2+}, and Mg^{2+} content in the soil surface layer exhibited increased values (all of them at $p<0.001$) in the forest affected by the fire. These properties improved 63, 25, 31, 23, 187, 117, and 93 %, respectively, in comparison to the forest not affected by the fire; and they improved 60, 33, 37, 43, 360, 126, and 71 % in comparison to the properties in the NP area, respectively. In contrast, potential acidity and phosphorus content in AWF decreased 64 and 30 % in comparison to EF ($p<0.001$). Comparison to NP showed 68 % reduction in potential acidity; however, there was no change in P content. According to Bodí et al. (2014), large amounts of ash increase the pH(H_2O) values and the content of some nutrients, thus reducing soil acidity.

The wildfire increased the organic matter content in the soil surface layer (Table 1); this same outcome was recorded by Ginzburg and Steinberger (2012), likely due to deposition of carbonized plant residues on the soil (González-Pérez et al., 2004). Phosphorus content decreased in the surface layer and increased in the sub-surface layer (0.05-0.20 m). It is likely that the organic-P fraction in the plant, microbial, and fauna biomass in the soil was mineralized by the fire (Rheinheimer et al., 2003; Silva et al., 2006; Ando et al., 2014). Phosphorus leaching may have occurred because the soil had low clay content (Ceretta et al., 2010; Centeno et al., 2017), and the sampling procedure was conducted two months after the fire. Moreover, there was 43-mm accumulated rainfall in this time interval (Figure 1). Another aspect that may have increased P availability in the sub-surface is the high pH(H_2O), which was a consequence of ash leaching, as well as of ash products.

The fire did not affect soil physical properties; however, these properties were influenced by different soil uses (Table 1). The highest microporosity values were recorded for NP in the 0.00-0.05 m layer; whereas the highest macroporosity was observed in EF.

Table 1. Soil chemical and physical properties under natural pasture (NP), eucalyptus forest (EF), and eucalyptus forest after wildfire (AWF) in São Gabriel, RS, Brazil

Property[1]	NP		EF		AWF		CV
	0.00-0.05 m	0.05-0.20 m	0.00-0.05 m	0.05-0.20 m	0.00-0.05 m	0.05-0.20 m	
							%
pH(H_2O)	5.2 c[2]	5.3 c	5.5 b	5.1 c	6.9 a	5.6 b	2.51
Clay (g kg^{-1})	150.0 a	150.0 a	120.0 b	140.0 a	80.0 b	190.0 a	16.9
OM (g kg^{-1})	30.0 c	24.0 b	35.0 c	14.0 d	43.0 a	15.0 d	15.87
P (mg dm^{-3})	3.7 c	3.0 d	5.3 a	2.2 e	3.7 c	4.5 b	7.91
K (mg dm^{-3})	60.0 b	44.0 b	96.0 b	60.0 b	276.0 a	72.0 b	14.97
Ca^{2+} ($cmol_c$ dm^{-3})	7.6 b	9.2 b	7.9 b	3.4 c	17.2 a	5.7 c	15.07
Mg^{2+} ($cmol_c$ dm^{-3})	1.7 b	1.8 b	1.5 b	1.2 b	2.9 a	1.5 b	13.33
S (mg dm^{-3})	22.0 a	16.6 b	12.2 b	7.7 c	10.6 b	10.3 b	9.75
CEC ($cmol_c$ dm^{-3})	13.9 c	16.6 b	13.6 c	8.7 e	22.2 a	10.4 d	4.67
V (%)	68.4 b	67.1 b	71.2 b	54.8 c	93.8 a	70.6 b	2.78
H+Al ($cmol_c$ dm^{-3})	4.4 b	5.5 a	3.9 b	3.9 b	1.4 c	3.1 b	13.13
Ds (Mg m^{-3})	1.36 b	1.54 a	1.33 b	1.48 a	1.37 b	1.55 a	3.88
Total Porosity (m^3 m^{-3})	0.43 a	0.36 a	0.40 a	0.32 a	0.40 a	0.32 a	13.28
Macroporosity (m^3m^{-3})	0.08 b	0.07 b	0.13 a	0.11 a	0.09 b	0.08 b	18.12
Microporosity (m^3 m^{-3})	0.37 a	0.29 b	0.29 b	0.22 d	0.31 b	0.23 c	6.46

[1] pH(H_2O) (soil:water ratio of 1:1); clay content (densimeter); organic matter (Walkley-Black); P and K (Mehlich-1); Ca^{2+} and Mg^{2+} (EDTA), S [$Ca_3(PO_4)_2$]; soil density (Ds, volumetric rings); total porosity, macro, and microporosity determined by weight difference after capillary saturation. H+Al = potential acidity; V% = base saturation. [2] Means followed by the same letter in the line are not significantly different based on the Scott-Knott test ($p<0.01$).

Suzuki et al. (2012) found similar results in a study assessing the effect of land use change, from pasture to eucalyptus, on physical and moisture properties of the soil in the Pampa biome. Areas covered with eucalyptus forest had higher macroporosity due to root development and decomposition in the deeper layers, to organic matter input, to exclusion of grazing, and to the action of soil organisms, which were influenced by the large amount of dry matter on the soil surface.

The wildfire reduced the total abundance of organisms in the soil by 31 % (Table 2). The relative frequency of the groups assessed decreased an average of 82 % due to the fire event. This reduction was significant ($p<0.01$) for arachnids, coleoptera, and isoptera, among others, and was not significant for annelids ($p = 0.078$) and diptera ($p = 0.079$). These results corroborate those of Silva et al. (2011), who also observed a reduced total number of organisms, including arachnids and coleoptera, fifteen days after a fire event in a eucalyptus forest in the municipality of Santa Maria, Rio Grande do Sul, Brazil. Hymenoptera (ants) recorded higher relative frequency; they accounted for 71.44 % of the total of organisms identified and were the only ones whose frequency increased in the burnt area ($p<0.01$). These organisms are recognized as indicators of environmental disturbances in the soil (Silva et al., 2011), and they have high mobility, which facilitates their dispersion to areas altered by the fire (Cordeiro et al., 2004).

The groups of annelids, arachnids, coleoptera, and isoptera showed low frequency in AWF (Table 2) because they are all very susceptible to changes in habitat (Gongalsky et al., 2012). Most plant litter disappeared due to the wildfire, and many soil chemical properties, as well as soil temperature and humidity conditions, were altered by this. This process probably resulted in reduced communities of these organisms (Collins, 1969; Traoré and Lepage, 2008; Oliveira Filho et al., 2014). The lowest soil diversity was observed in the AWF area, and this result was confirmed by the higher Simpson index and the lower Shannon, Margalef, and Pielou indexes (Table 2). This behavior can be explained by the lower total abundance, the lower abundance of annelids, arachnids, coleoptera, and isoptera and the prevalence of hymenoptera in the area affected by the fire. These results show that the ecosystem services performed by these organisms are temporarily compromised in the burnt area, which compromises the stability, the resilience, and even the sustainability of the forest (Zaitsev et al., 2016).

The mean feeding activity of organisms in the soil was 34, 30, and 34 % for NP, EF, and AWF, respectively (Figure 3). Feeding activity in the current study is quite close to that observed by Musso et al. (2014) in two different seasons in burnt and unburnt areas covered by native grasses and by invasive plant species in the Brazilian *Cerrado.* The effects of different uses of soil and of fire on the soil organisms activity were significant in the soil surface (up to the 0.02 m depth) (Figure 3). The large accumulation of plant residue in EF resulted in higher biological activity in surface soil. In contrast, the large amount of ash on the surface and the changes in soil chemical properties in AWF inhibited biological activity at the surface. The low relative frequency of annelids and isoptera partially explains the low feeding activity of soil organisms living in deeper layers. According to Hamel et al. (2007), the low frequency of earthworms may explain the low feeding activity of soil fauna assessed through the bait-lamina method, especially in deeper layers.

Table 2. Relative frequency of macrofauna in the soil, total abundance, and the diversity indexes of the soil under natural pasture (NP), eucalyptus forest (EF), and eucalyptus forest after wildfire (AWF), in São Gabriel, RS, Brazil

Groups	Relative Frequency (%)		
	NP	EF	AWF
Annelidae	1.16 a[1]	3.11 a	0.75 a
Arachnida	3.24 b	7.34 a	0.90 b
Coleoptera	10.48 b	17.17 a	4.78 c
Diptera	0.13 a	3.06 a	0.30 a
Hymenoptera	64.48 b	58.27 c	91.59 a
Isoptera	18.76 a	4.98 b	0.35 b
Others[2]	1.24 b	6.09 a	1.33 b
		Diversity indexes	
Abundance (ind m^{-2}) (19.3)[3]	3,086 a	2,190 a	1,493 a
Simpson (23.3)	0.61 b	0.30 c	0.89 a
Shannon (32.2)	0.77 b	1.40 a	0.25 c
Margalef (31.6)	0.96 b	1.55 a	0.49 c
Pielou (35.8)	0.49 b	0.85 a	0.18 c

[1] Means followed by the same lowercase letter in the line are not significantly different based on the Scott-Knott test ($p < 0.01$). [2] The groups of Blattodea (cockroaches), Quilopoda (centipedes), Diplopoda (millepedes), Isopoda (termites), and Orthoptera (crickets and grasshoppers) were grouped in "Others", due to the small number of individuals collected. [3] Coefficient of variation expressed in percentage (CV%).

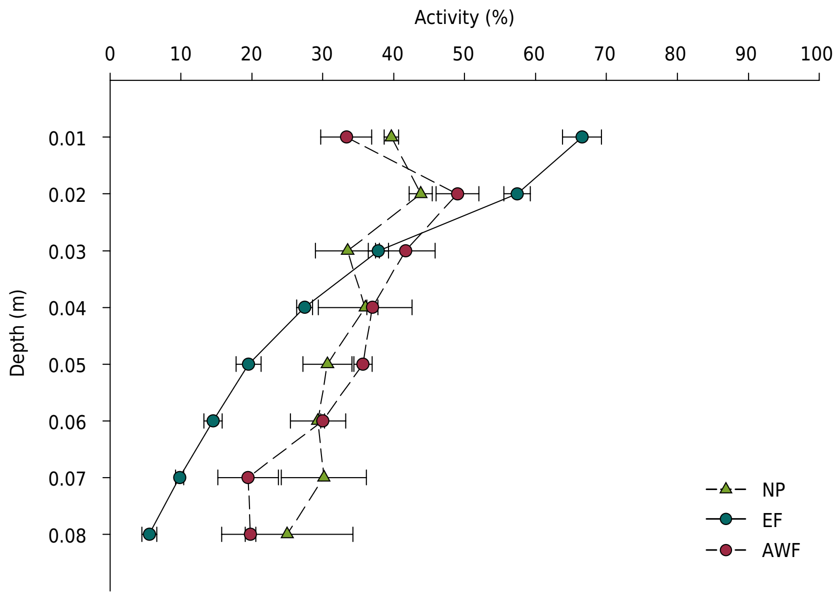

Figure 3. Feeding activity of organisms in the soil at different depths under natural pasture (NP), in the eucalyptus forest (EF), and in the eucalyptus forest after wildfire (AWF), in São Gabriel, RS, Brazil. The dots represent the mean values and the horizontal bars correspond to the standard deviation.

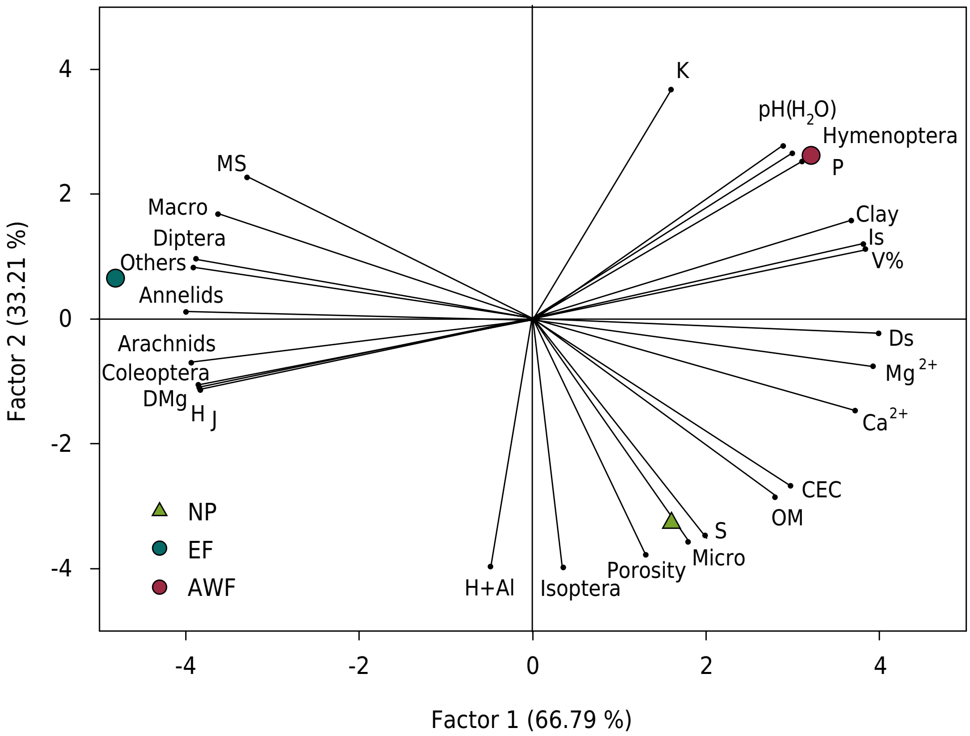

Figure 4. Principal Component Analysis (PCA) between the natural pasture (NP), the eucalyptus forest (EF), and the eucalyptus forest after wildfire (AWF), and the soil physical, chemical, and biological properties in São Gabriel, RS, Brazil. Is = Simpson index; H = Shannon index; J = Pielou index; Macro = macropososity; Micro = microporosity; Porosity = total porosity; Ds = soil bulk density; OM = organic matter content; V% = base saturation; H+Al = potential acidity.

Principal component analysis showed that the large amount of dry matter on the soil surface in EF was related to annelids, arachnids, coleoptera, diptera, and other groups (Figure 4). The incidence of these organisms in EF resulted in higher biological diversity and in a larger number of macropores. The diversity of soil fauna organisms collaborates to the genesis of soil macropores, which favors to greater water infiltration, soil aeration, and root development (Barros et al., 2001). The fire event increased soil pH, the contents of most nutrients, CEC, and base saturation. These properties were positively associated with the prevalence of organisms belonging to the group of hymenoptera (Figure 4). The presence of isoptera was associated with S content (resulting from OM), with the amount of micropores, as well as with total porosity, organic matter, and CEC (Figure 4). According to Holt and Legage (2000), isoptera positively influence organic residue decomposition, nutrient cycling and soil porosity.

The wildfire in the eucalyptus forest led to chemical and biological changes in the soil; however, the soil physical properties did not change. The effect of fire on the chemical properties can be explained by the large amount of ash on the soil surface after plant litter, branch, and leaf burning. Soil macrofauna uses plant litter as a habitat; so, the wildfire reduced its abundance and diversity. In contrast, the hymenoptera population increased in the burnt area; it is a bioindicator of environmental impacts. The feeding activity of the soil organisms was altered by the fire event.

CONCLUSIONS

The wildfire in a seven-year-old eucalyptus forest in the Pampa biome altered the soil chemical and biological properties; however, the soil physical properties did not change.

The wildfire increased pH(H_2O) values, CEC, base saturation, and K, Ca^{2+}, and Mg^{2+} content. It also reduced potential acidity and the P content in the soil surface layer.

The wildfire reduced the total abundance of macrofauna in the soil and the abundance of annelids, arachnids, coleoptera, and isoptera, which resulted in lower soil diversity. Moreover, the feeding activity of organisms in the soil surface layer was also reduced by the fire event.

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