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Edaphic fauna and soil properties under different managements in areas impacted by natural disaster in a mountainous region

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ABSTRACT: Soil invertebrate fauna plays a major role in several environmental processes, and its absence can negatively impact ecosystem health. This study aimed to assess the recovery of epigeal and edaphic invertebrate faunal communities following an environmental disaster, with landslides, mudflow, and river floods, in sites under different management systems, the effects of cover crops on invertebrate fauna, and their relationship with soil physical and chemical properties in the mountainous region of Rio de Janeiro State, Brazil. The following sites were evaluated: CF, a site under conventional farming without any record of natural hazard events; LS, a site impacted by an intense landslide event that left the area buried by mudflow; RO1, a site affected by river overflow and treated with NPK fertilizer and poultry litter; RO2, a site affected by river overflow and subjected to liming and heavy fertilization with NPK; and RO3, a site affected by a less intense river overflow and subjected to fertilization with poultry litter and NPK fertilizer. At each site, epigeal and edaphic fauna were sampled using pitfall traps and a monolith sampler, respectively. Physical (soil temperature, moisture, aggregate stability, and density) and chemical (pH in water, Ca^{2+}, Mg^{2+}, Al^{3+}, K^{+}, P, cation-exchange capacity, and total organic carbon) properties were determined in the 0.00-0.05 and 0.00-0.10 m layers. The predominant epigeal faunal groups were Entomobryomorpha, Poduromorpha, Diptera, and Coleoptera; and the predominant edaphic faunal groups, Coleoptera and Oligochaeta. There was a positive correlation between Coleoptera larvae, Hymenoptera, and species richness with total organic carbon. Coleoptera larvae were positively associated with biogenic aggregate stability, whereas Coleoptera was positively associated with physicogenic aggregate stability. Oligochaeta showed a positive correlation with soil moisture. Cover crops favored the development of epigeal and edaphic faunal groups that enhance soil properties through organic matter fragmentation and decomposition, and structural engineering. The strong correlation between soil chemical, physical, and biological properties demonstrate the importance of monitoring these components to assess the recovery of disaster-affected areas.

Keywords: bioindicator, cover crop, soil conservation.

INTRODUCTION

Natural hazards are commonly unexpected and uncontrollable. The most frequent weather-related events are landslides, floods, and storms (Guha-Sapir, 2018). These phenomena have a large impact on agricultural production, which is highly dependent on climate, and result in significant crop losses (Ribeiro, 2016). In January 2011, an environmental disaster triggered by heavy rainfall (182.8 mm in 2 h) resulted in the destruction of extensive areas in Nova Friburgo, a municipality located in the mountainous region of Rio de Janeiro State, Brazil. Landslides, mudflow, and river floods affected more than 60 % of the area planted with vegetable crops (Seapec RJ, 2011; Rossi et al., 2015). The same region experienced a less severe flood event in 2015. Thus, to recover the production capacity of depleted soils due to climate tragedy, Nova Friburgo farmers implemented practices to restore soil quality, such as cover cropping (Assis et al., 2012; Antonio et al., 2019).

Cover crops have been proposed as an alternative to increase soil cover and C inputs (Poeplau and Don, 2015; Duval et al., 2016; Lima et al., 2020) and to improve soil physical quality (Recio-Vázquez et al., 2014). For example, black oats (*Avena strigosa* Schreb.) can add as much as 3.0-4.0 Mg ha^{-1} of dry matter to the soil (Ziech et al., 2015) hence contributing to soil protection and appear to be economic (e.g., low seed cost and high availability). However, their biomass contains a higher C:N ratio compared to that of legumes (Snapp et al., 2005; Chu et al., 2017). On the other hand, legumes like common vetch (*Vicia sativa*) are an alternative source of nitrogen, commonly used as a cover crop in winter (Aita et al., 2001; Cargnelutti Filho et al., 2020). Intercropping of black oats with vetch results in a high residue production and hinders spontaneous plants growth (Forte et al., 2018). Moreover, they are also beneficial to other soil aspects, such as the maintenance of edaphic fauna, allowing greater balance in the soil's functioning (Scoriza et al., 2016; Balin et al., 2017). Thus, because soil invertebrates also contribute to nutrient cycling, they can be effectively influenced by the quantity and quality of plant material in the soil (Tripathi et al., 2010). Additionally, because of the several roles for soil functioning and sensitivity to management, especially at the soil-litter interface, soil fauna has been used as an indicator of soil quality (Lima et al., 2010; Silva et al., 2016; Pereira et al., 2017).

To better understand the effects of management practices in areas affected by natural disasters (landslides, mudflow, and river floods), we assessed soil fauna abundance and diversity together with traditional measures of soil fertility (i.e., physicochemical properties) across areas affected by the natural disasters of 2011 and 2015 in the mountainous region of Rio de Janeiro. In this context, this study aimed to (i) investigate the characteristics of epigeal and edaphic fauna communities in cultivated sites affected by the 2011 and 2015 natural disasters, (ii) analyze the complex relationships between epigeal and edaphic fauna and soil physical and chemical properties, and (iii) assess the effectiveness of management practices and cover crops using soil quality indicators.

MATERIALS AND METHODS

Description of study sites

This study was conducted in a vegetable production area, namely the Rio Grande Farm, located in the Barracão dos Mendes watershed, in Nova Friburgo municiaplity, a mountainous region of Rio de Janeiro State, Brazil. The region is characterized by soils with low pedogenic development, such as *Cambissolo Háplico* - Inceptisol, associated with more developed soils, such as *Argissolo Vermelho Amarelo* - Ultisol (Rossi et al., 2015). The climate is humid subtropical (Cfa in the Köppen–Geiger climate classification system). The region is naturally prone to landslides. The few remnants of the Atlantic Forest in the area play a crucial role in collecting and distributing rainwater in the watersheds. Samples were collected from five sites in the first half of November 2016. Study sites and their characteristics are presented in table 1.

Table 1. Description of study sites in the Rio Grande Farm region, Nova Friburgo, Rio de Janeiro, Brazil

Study site	Coordinates	Description
CF	22° 17' 15" S 42° 39' 36.6" W	Site under conventional farming without any history of natural hazard events. Fallow has been practiced since 2011. At the time of sampling, the entire area was covered by grasses.
LS	22° 17' 11.9" S 42° 39' 33.8" W	The site was highly impacted by an intense landslide event that left the area buried by mudflow in 2011. In 2013, after a mud cleanup operation, the soil was limed, fertilized with poultry litter and NPK fertilizer, and pre-cropped with black oat (*Avena strigosa*) and common vetch (*Vicia sativa*). In 2015, the site was cropped with black oat, tomato, and *Brassica*. In 2016, the site was pre-cropped with vetch and cropped with *Brassica*.
RO1	22° 17' 9.1" S 42° 39' 32.3" W	The site was impacted by a continuous 2-month flood and extensive sand deposition resulting from a river overflow event in 2011. After this period, the soil was treated with poultry litter and NPK fertilizer and cropped under a no-till system using black oat as a cover crop. After another overflow in 2015, the same fertilization treatment was applied, followed by pre-cropping with black oat and cropping with *Brassica* and tomato. Tomato was planted in 2016.
RO2	22° 17' 7.3" S 42° 39' 30.9" W	The same river overflow event that impacted RO1 also impacted the area RO2. After the conclusion of the disaster, the soil was limed and cropped with celery (*Apium graveolens*) and chard (*Beta vulgaris* var. *cicla*) under intensive fertilization with poultry litter, NPK fertilizer, and potassium thermophosphate (Yoorin). The site was left fallow after the 2015 overflow and was so at the time of sample collection.
RO3	22° 17' 6.5" S 42° 39' 30.3" W	The site was impacted by the same river overflow event as RO1 but flooded to a lesser extent. Soils have a gley horizon (locally known as *tabatinga*). The 2015 river overflow had a reduced impact. The site was subsequently fertilized with poultry litter and NPK fertilizer and planted with broccoli in 2016.

Sampling of epigeal and edaphic fauna

Four sampling points were selected at the edges of each site (0.20 ha) and one in the center. Epigeal invertebrates, which inhabit the soil–litter interface, were sampled with pitfall traps (Moldenke et al., 1994) consisting of plastic pots (0.10 m diameter and 0.10 m height) filled with 300 mL of 4 % formaldehyde. A total of five traps were installed at each site. After seven days, the traps were removed (Aquino et al., 2006). In the laboratory, sampled individuals were removed from the formaldehyde solution and stored in 70 % alcohol.

Identification of epigeal invertebrates was performed under a binocular loupe with 80× magnification. Individuals were classified into classes and orders according to Gallo et al. (2002) and Pereira et al. (2018). After identification, the total number of epigeal individuals was counted and calculated by dividing the number of individuals captured by the number of traps and collection days (ind trap^{-1} day^{-1}). Results are presented as mean and standard error.

Edaphic faunal organisms were sampled by the method of the Tropical Soil Biology and Fertility Program of UNESCO (Anderson and Ingram, 1993), as described by Aquino (2001) and Korasaki et al. (2013). Five soil monoliths with dimensions of 0.25 × 0.25 × 0.10 m were collected from each site. The organisms were manually separated and stored in 70 % alcohol. After identification, the edaphic fauna total abundance (density) was obtained by dividing the total number of individuals by the sampled area (ind m^{-2}). Results are presented as mean and standard error. Epigeal faunal individuals were classified into ten taxonomic groups and edaphic faunal individuals into eight taxonomic groups. Groups of epigeal and edaphic organisms with low representativeness (<2 % of total ind.) were combined into a category named "Others."

Analysis of soil chemical and physical properties

Five disturbed soil samples were collected from each site at the layers of 0.00-0.05 and 0.00-0.10 m for moisture and temperature analyses. Five undisturbed soil samples were collected in the 0.00-0.10 m layer to analyze soil density (Donagemma et al., 2011), aggregation, and chemical properties. The aggregates that were retained in the sieves' range between 8.0 and 9.7 mm were classified according to the formation pathways. The aggregates were examined and separated manually using a binocular lens, according to the definitions of Bullock et al. (1985) into physicogenic (angular-shaped) and biogenic (round-shaped by macrofaunal, individuals, and/or with signs of root activity). Aggregate stability was assessed by the wet method, using wet sieving technique, composed of a set of sieves with mesh diameters of 2.0, 1.0, 0.50, 0.25, and 0.105 mm for 15 min on the Yooder apparatus. The mean weight diameter of physicogenic (MWDphy) and biogenic (MWDbio) aggregates were calculated according to Donagemma et al. (2011). Soil pH in water, Ca^{2+}, Mg^{2+}, Al^{3+}, K^{+}, P, and cation-exchange capacity (CEC) were determined according to Donagemma et al. (2011). The total organic carbon (TOC) was determined according to Yeomans and Bremner (1988). The results of the analyses are presented in table 2.

Statistical analyses

The diversity, evenness, and richness of epigeal and soil faunal communities were determined. The Shannon diversity index was calculated using the equation $H = -Sp_i \log p_i$, in which $p_i = n_i/N$, and n_i is the density of group i; and N is the sum of densities of all groups. Pielou evenness index was determined as $e = H/\log R$, in which R is the species richness or the

Table 2. Microclimate, chemical, and physical properties of 0.00-0.05 and 0.05-0.10 m soil layers from the sites under different management systems five years after a natural disaster

Parameter	Site				
	CF	LS	RO1	RO2	RO3
			0.00-0.05 m layer		
pH(H_2O)	6.17	6.70	5.99	6.48	6.17
TOC (g kg^{-1})	19.66	19.73	22.33	21.00	26.51
Available P (mg kg^{-1})	22.2	142.0	210.0	95.1	164.0
CEC ($cmol_c$ kg^{-1})	11.4	24.8	23.2	16.4	17.8
Moisture (%)	14.2	11.4	19.8	14.4	20.9
Temperature (°C)	21.8	24.4	22.8	23.5	24.5
			0.00-0.10 m layer		
pH(H_2O)	6.2	6.8	5.9	6.4	6.1
TOC (g kg^{-1})	19.42	19.54	22.16	21.00	24.76
Available P (mg kg^{-1})	25.8	174.0	199.0	95.2	122.0
CEC ($cmol_c$ kg^{-1})	11.4	22.3	22.3	16.2	17.3
Bulk density (Mg m^{-3})	0.05	0.04	0.06	0.09	0.12
MWDphy (mm)	4.63	3.69	3.60	4.12	4.62
MWDbio (mm)	4.37	3.47	4.22	4.15	4.38

CF: conventional farming site not impacted; LS: affected by landslide and mudflow; RO1: river overflow and treated with NPK fertilizer and poultry litter; RO2: river overflow and subjected to liming and heavy fertilization with NPK fertilizer; RO3: less intense river overflow and subjected to fertilization with poultry litter and NPK fertilizer.

number of taxonomic groups (Odum, 1986). For richness and the total number of individuals, the normality of errors was evaluated using the Shapiro-Wilk test and the homogeneity of variances using Bartlett's test. Given that normality and homoscedasticity assumptions were not met, means were compared by the nonparametric Kruskal–Wallis test using R statistical software version 3.5.0 (R Development Core Team, 2019).

Chemical (0.00-0.05 m layer) and physical and chemical (0.00-0.10 m layer) soil properties were subjected to analysis of variance and compared by Tukey's test, as normality and homoscedasticity assumptions were met. Principal component analysis (PCA) and between-class PCA were performed to investigate the relationship between variables of a dataset and multivariate differences between study sites. This approach involves the use of permutation tests (Monte Carlo test) to compare observed test statistics with random permutation of data. In addition, co-inertia analysis was used to assess covariance and general similarity in data structure between two datasets (chemical properties of 0.00-0.05 m soil layer and epigeal fauna; physical and chemical properties of 0.00-0.10 m soil layer and soil fauna). Multivariate analyses were performed using the ade4 package of the R software (Dray et al., 2007; R Development Core Team, 2019).

RESULTS

Faunal activity, total abundance, and diversity indices

The faunal activity was higher in CF and RO3 (Figure 1a) than in the others. Species richness was higher in RO2 and CF, followed by RO3 and LS (Figure 1b). The highest

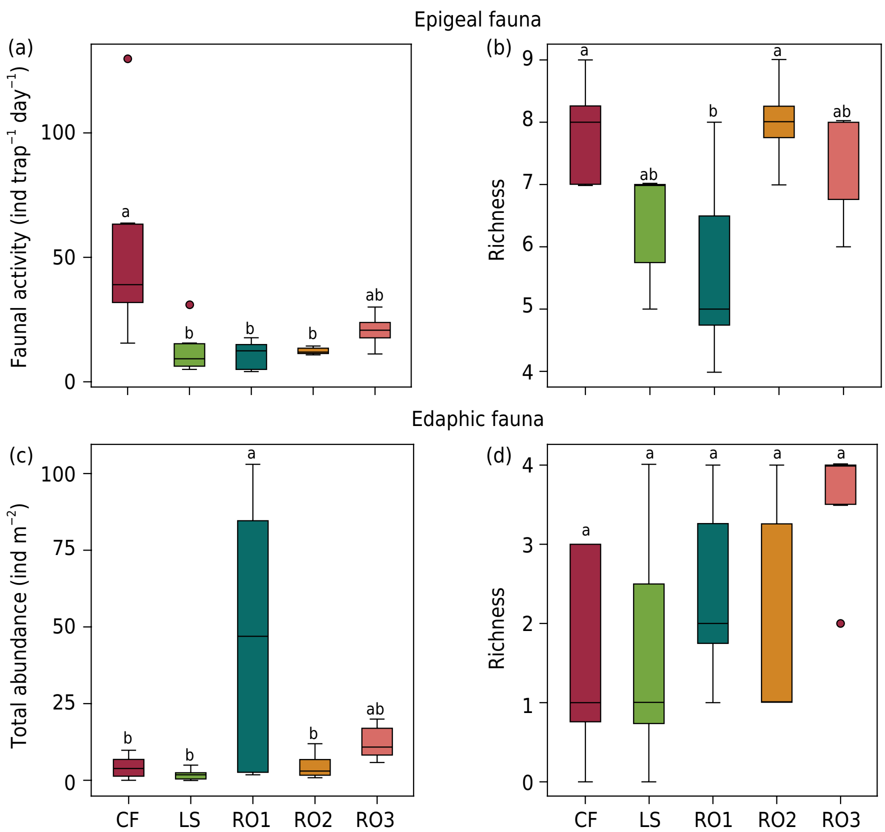

Figure 1. Activity (a) and species richness of epigeal fauna (b) and total abundance (c) and species richness of edaphic fauna (d) in cropping sites under different management systems five years after a natural disaster. Different letters above error bars denote significant differences by the Kruskal–Wallis test ($p<0.05$). CF: conventional farming site not impacted; LS: affected by landslide and mudflow; RO1: river overflow and treated with NPK fertilizer and poultry litter; RO2: river overflow and subjected to liming and heavy fertilization with NPK fertilizer; RO3: less intense river overflow and subjected to fertilization with poultry litter and NPK fertilizer.

total abundance was found under RO1 and RO3 (Figure 1c), whereas species richness did not differ among sites (Figure 1d).

The activity of Entomobryomorpha and Poduromorpha, which belong to the subclass Collembola, differed between sites. The Entomobryomorpha activity was higher in CF, whereas Poduromorpha activity was higher in CF and RO3 than in the others. Coleoptera larvae were most active in RO2. The epigeal fauna group classified as Others (Heteroptera, Hymenoptera, Isopoda, Isoptera, Auchenorrhyncha, Chilopoda, Lepidoptera, Oligochaeta, Lepidoptera pupae, and Thysanoptera) was higher in LS and RO3 than in the others. The diversity of epigeal fauna, as measured by the Shannon diversity index, was higher than 2.5 in CF, RO1, RO2, and RO3, and the Pielou evenness index was above 0.70 in RO1, RO2, and RO3 (Table 3).

The total abundance also differed between sites. The Coleoptera and Coleoptera larvae abundances were highest in RO3 and lowest in LS. The group Oligochaeta was more abundant in RO1. No differences were observed between sites in the density of other edaphic faunal groups (Auchenorrhyncha, Blattodea, Diptera, Gastropoda, Heteroptera, Diptera larvae, Lepidoptera larvae, and Lepidoptera). Conventional

Table 3. Epigeal faunal activity (ind trap^{-1} day^{-1}) and ecological indices in sites under different management systems five years after a natural disaster

Epigeal fauna	Site					*p*-value
	CF	LS	RO1	RO2	RO3	
	ind trap^{-1} day^{-1}					
Acari	0.94^{a}	0.97^{a}	1.91^{a}	0.23^{a}	4.00^{a}	
	1.13	*0.89*	*1.04*	*0.24*	*3.84*	
Araneae	0.89^{a}	0.37^{a}	0.20^{a}	0.51^{a}	0.29^{a}	
	0.83	*0.34*	*0.16*	*0.21*	*0.28*	
Coleoptera	1.83^{a}	1.91^{a}	2.57^{a}	2.49^{a}	2.11^{a}	
	0.87	*1.13*	*2.08*	*0.72*	*1.33*	
Diptera	1.66^{a}	0.54^{a}	1.60^{a}	0.69^{a}	0.83^{a}	
	0.54	*0.37*	*1.20*	*0.34*	*0.52*	
Entomobryomorpha	32.4^{a}	4.43^{b}	2.17^{b}	3.77^{b}	2.66^{b}	0.005
	31.0	*1.55*	*1.44*	*1.96*	*9.24*	
Formicidae	0.6^{a}	0.86^{a}	1.83^{a}	0.54^{a}	0.34^{a}	
	0.34	*0.59*	*1.47*	*0.28*	*0.31*	
Hymenoptera	0.11^{a}	0.06^{a}	0.06^{a}	0.06^{a}	0.03^{a}	
	0.12	*0.05*	*0.07*	*0.08*	*0.06*	
Coleoptera larvae	0.02^{b}	0.00^{b}	0.08^{b}	1.80^{a}	0.74^{ab}	<0.001
	0.01	*0*	*0.12*	*1.09*	*0.71*	
Poduromorpha	14.00^{a}	3.23^{b}	0.00^{b}	2.03^{b}	9.17^{a}	0.004
	8.98	3.00	0.00	1.23	2.17	
Other	0.26^{b}	1.17^{a}	0.09^{b}	0.80^{b}	1.40^{a}	0.032
	0.15	*1.07*	*0.10*	*0.59*	*1.36*	
Shannon diversity index	2.63	1.63	2.71	2.54	2.92	
Pielou evenness index	0.63	0.41	0.73	0.76	0.75	

Means within rows followed by the same letter are not significantly different by the Kruskal–Wallis test. Numbers in italics below each mean are the standard error of the mean. CF: conventional farming site not impacted; LS: affected by landslide and mudflow; RO1: river overflow and treated with NPK fertilizer and poultry litter; RO2: river overflow and subjected to liming and heavy fertilization with NPK fertilizer; RO3: less intense river overflow and subjected to fertilization with poultry litter and NPK fertilizer.

Table 4. Edaphic faunal abundance (ind m^{-2}) and ecological indices in sites under different management systems five years after a natural disaster

Edaphic fauna	Site					p-value
	CF	LS	RO1	RO2	RO3	
	ind m^{-2}					
Araneae	6.4[a]	3.2[a]	0.00[a]	12.8[a]	0.00[a]	
	3.92	3.20	*0.00*	*0.82*	*0.00*	
Chilopoda	0.00[a]	3.2[a]	6.4[a]	16.0[a]	19.2[a]	
	0.00	*0.14*	3.92	16.0	15.51	
Coleoptera	48[ab]	6.4[b]	22.4[ab]	35.2[ab]	83.2[a]	0.031
	22.05	*3.92*	*11.97*	*19.86*	*13.76*	
Formicidae	3.2[a]	6.4[a]	0.00[a]	0.00[a]	3.2[a]	
	3.20	*3.92*	*0.00*	*0.00*	*3.20*	
Hymenoptera	3.2[a]	0.00[a]	0.00[a]	3.2[a]	22.4[a]	
	3.20	*0.00*	*0.00*	*3.20*	*18.66*	
Coleoptera larvae	0.00[b]	0.00[b]	12.8[ab]	0.20[ab]	22.4[a]	0.017
	0.00	0.00	5.99	0.14	8.16	
Oligochaeta	0[b]	6.4[b]	697.6[a]	3.2[b]	41.6[b]	0.011
	0	*3.92*	306.79	3.20	18.66	
Other	9.6[a]	6.4[a]	6.4[a]	0.00[a]	6.4[a]	
	3.80	*3.49*	*3.49*	*0.00*	*3.49*	
Shannon diversity index	2.32	1.70	2.52	0.47	2.02	
Pielou evenness index	0.77	0.61	0.98	0.18	0.78	

Means within rows followed by the same letter are not significantly different by the Kruskal-Wallis test. Numbers in italics below each mean are the standard error of the mean. CF: conventional farming site not impacted; LS: affected by landslide and mudflow; RO1: river overflow and treated with NPK fertilizer and poultry litter; RO2: river overflow and subjected to liming and heavy fertilization with NPK fertilizer; RO3: less intense river overflow and subjected to fertilization with poultry litter and NPK fertilizer.

farming and RO1 showed higher values for the Shannon and Pielou indexes compared to the other areas (Table 4).

Soil physical and chemical properties and soil fauna

PCA of chemical properties of 0.00–0.05 m soil layer explained 40.21 % (PC1) and 28.01 % (PC2) of the variance in the dataset, with a simulated *p*-value of 0.001 using Monte Carlo methods (Figure 2a). Moisture, TOC, P, and CEC were strongly associated with RO1 and RO3, whereas temperature and pH were associated with LS (Figure 2a). In the PCA of chemical and physical properties of the 0.00-0.10 m soil layer, PC1 explained 31.78 % and PC2 26.75 % of the variance in the dataset, with simulated $p = 0.001$ by the Monte Carlo test (Figure 2b). Total organic carbon, bulk density, moisture, MWDphy, MWDbio, CEC, and P were associated with RO1, RO2, and RO3, and temperature and pH were associated with LS.

Co-inertia analysis showed a significant covariance between the two datasets (Figures 3 and 4). The covariance between the soil chemical properties of the layer 0.00-0.05 m and epigeal faunal groups ($p = 0.021$, RV coefficient = 31.7 %) indicated that Coleoptera larvae, Hymenoptera, and species richness were positively associated with TOC and that Formicidae was positively associated with CEC, P, and moisture. Most groups, especially Collembola, were negatively associated with temperature (Figure 3).

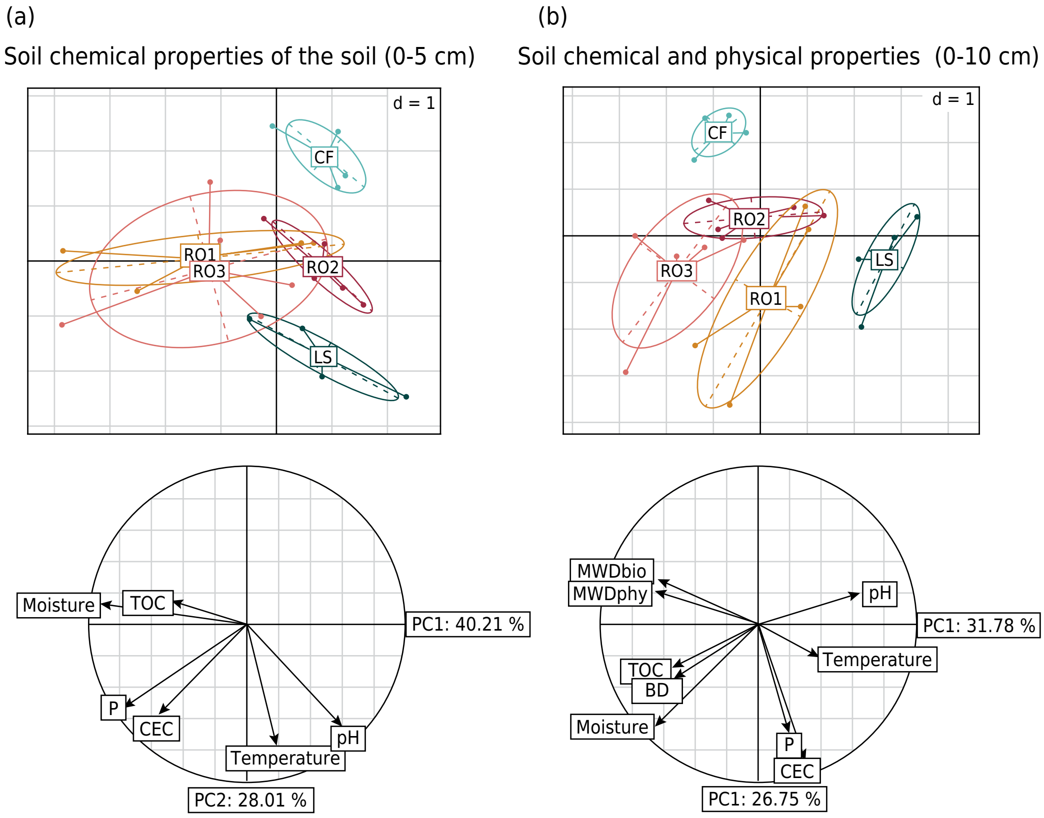

Figure 2. Factorial maps and variable correlation circles obtained by between-class analysis of soil chemical properties in the 0.00–0.05 m soil layer (a) and soil physical and chemical properties in the 0.00–0.10 m soil layer (b) of cultivated sites impacted by natural disasters. CF: conventional farming site not impacted; LS: affected by landslide and mudflow; RO1: river overflow and treated with NPK fertilizer and poultry litter; RO2: river overflow and subjected to liming and heavy fertilization with NPK fertilizer; RO3: less intense river overflow and subjected to fertilization with poultry litter and NPK fertilizer; TOC: total organic carbon; P: phosphorus; CEC: cation-exchange capacity; BD: bulk density; MWDphy: mean weight diameter of physicogenic aggregates; MWDbio: mean weight diameter of biogenic aggregates.

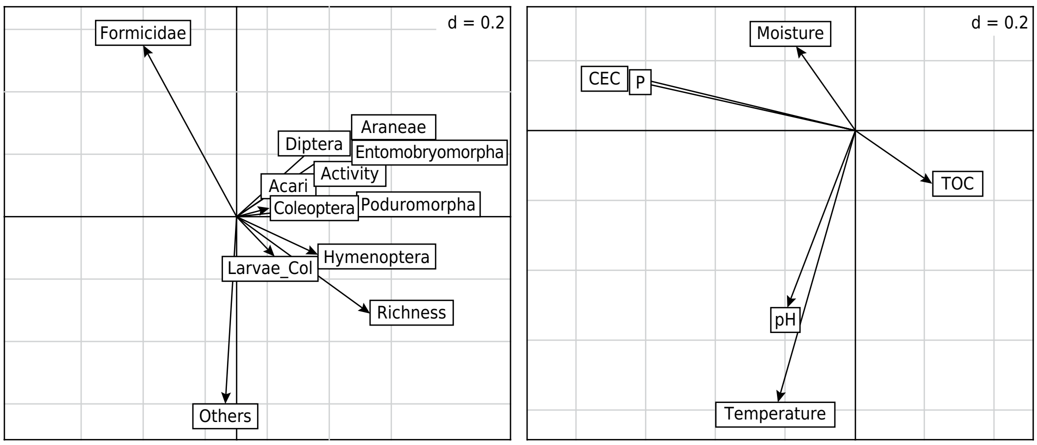

Figure 3. Co-inertia analysis of the relationship between epigeal fauna (a) and soil chemical properties (b) in the 0.00-0.05 m soil layer. RV coefficient = 31.70 %, $p<0.021$ (Monte Carlo permutation test). TOC: total organic carbon; P: phosphorus; CEC: cation-exchange capacity.

The covariance between physical and chemical properties of the 0.00-0.10 m soil layer and soil fauna ($p = 0.001$, RV coefficient = 41.78 %) indicated a positive association of Coleoptera larvae with MWDbio, species richness with TOC, Chilopoda with bulk density, and Coleoptera with MWDphy. Earthworms and total abundance (represented mainly by earthworms) correlated positively with CEC, P, and soil moisture and negatively with temperature (Figure 4).

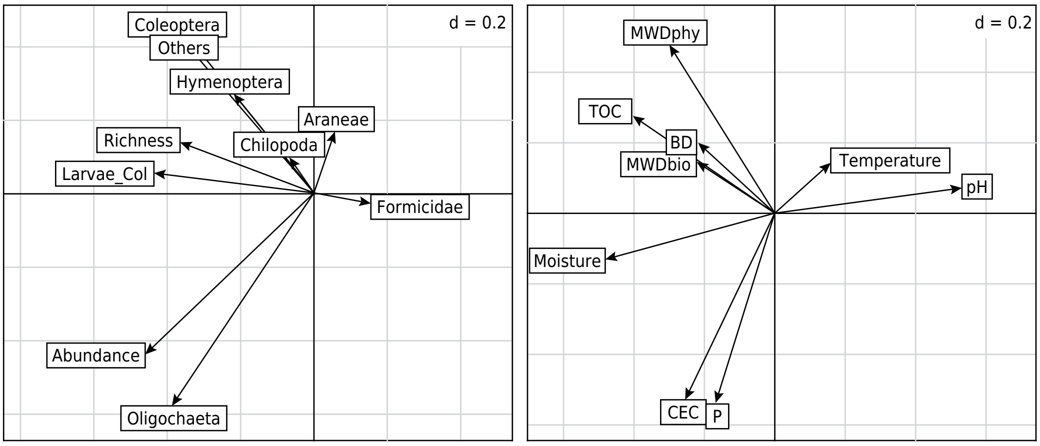

Figure 4. Co-inertia analysis of the relationship between (a) soil fauna and (b) soil physical and chemical properties in the 0.00-0.10 m soil layer. RV coefficient = 41.78 %, p<0.001 (Monte Carlo permutation test). TOC: total organic carbon; P: phosphorus; CEC: cation-exchange capacity; BD: bulk density; MWDphy: mean weight diameter of physicogenic aggregates; MWDbio: mean weight diameter of biogenic aggregates.

DISCUSSION

Response of the soil fauna community to soil management systems

Differences in epigeal fauna community were evident between the CF, LS, RO1, RO2, and RO3 plots. We suggest that the history of fallow in CF led to greater availability of ecological niches and the consequent restoration of food chains, resulting in higher activity and richness of the epigeal fauna related to the others. Even though the fallow period has been shorter in RO2, the vegetation cover is composed of several spontaneous plants, which possibly contributed to the fauna groups richness. Usually, soils with greater plant diversity (spontaneous plants in RO2) are expected to have a higher diversity and abundance of soil fauna groups since they allow for higher numbers of microhabitats and, therefore, increase niche differentiation between groups (Santonja et al., 2017). In RO3, the high epigeal faunal activity may be due to the lower intensity of environmental impact and practices such as fertilization with chicken litter and NPK for the cultivation of broccoli (main crop). These practices associated with the diversity of spontaneous herbaceous plants that grew together with the main crop probably increased the soil cover and, consequently, stimulated the development of the epigeal fauna.

The most representative group of epigeal fauna of all sites was Collembola. Meantime, we could infer that the higher activity of this group in CF and RO3 (Table 3) was associated with fallowing and low-intensity agricultural land use, which possibly provided better conditions in terms of soil cover. The Collembola group is very sensitive to the effects of soil management practices, temperature, and moisture (Oliveira Filho and Baretta, 2016; Daghighi et al., 2017; Rousseau et al., 2019). Application of high poultry litter-based organic fertilizer doses in the soil can increase the toxic effects on Collembola (Baretta et al., 2021). Another study showed that fertilization with pig slurry stimulates the population of Collembola in comparison to the poultry litter (Silva et al., 2019).

Another group that occurred in all sites was Coleoptera, and Coleoptera larvae were most active in RO3 and RO2; this result is probably related to the fertilization with poultry litter and NPK. Soil with high P, K, and organic matter contents favors individuals of this order (Wink, 2005). Organic compost produced with chicken, cow, or swine manure mixed with fibrous plant material favored the edaphic macrofauna, mainly Coleoptera (Santos et al., 2018). This order tended to be more abundant in conserved environments with the greatest ecological balance; it may be that this group is more sensitive to disturbance and thus a good indicator of environmental restoration (Work et al., 2008; Teixeira et al., 2009).

The epigeal faunal diversity verified in CF can be attributed to the high occurrence of Entomobryomorpha and Poduromorpha to the detriment of that of other groups (Table 3). The Pielou evenness index revealed that areas affected by river overflow (RO1, RO2, and RO3) had favorable soil conditions (promoted by poultry litter and NPK fertilization) for the balanced development of epigeal faunal groups. It is important to emphasize that the management of organic fertilizer (poultry litter) must be carried out carefully, considering the size of the area and the amount of fertilizer. Ecotoxicological studies have shown that high doses of poultry litter can be highly toxic to Collembola (Maccari et al., 2020; Baretta et al., 2021). On the other hand, when used in conjunction with other management practices (NPK fertilization and cover crops), it can favor the soil invertebrate community.

The high diversity and abundance (largely determined by earthworms) of edaphic fauna founded in RO1 (Figure 1c; Table 4) reflect the sustainability of the management practices adopt in this area. The site was fertilized with poultry litter and NPK and pre-cropped with single black oats. This indicates that soil fauna most likely ingests coarse organic matter such as crop residues with high C/N ratios. Soil fauna first fractures the litter, thereby increasing the surface area available to microbes (Lavelle et al., 1997). Through litter decomposition by microbes, the availability of nutrients increases (Belovsky and Slade, 2000). Some authors showed that cover crops with high C:N ratio have slow decomposition rate, which increased soil moisture and earthworm abundance (Roarty et al., 2017; Euteneuer et al., 2020). The effect of black oats as a cover crop on macrofauna density and diversity following an environmental disaster in the same region of the present study was studied by Lima et al. (2016). The authors found that intercropping black oat favored the occurrence of soil engineers, such as Oligochaeta and Isoptera, like that observed in this study. Highly diverse ecosystems tend to recover faster from changes and are more capable of restoring the balance in nutrient cycling and energy flow (Aquino and Correia, 2005).

Interaction between soil fauna and physical and chemical properties

The improvement of physical and chemical properties at both layers were associated with the areas that suffered the least impact (RO1, RO2, and RO3) compared to LS (area with the greatest magnitude of impact) (Figures 4a and 4b). In addition, the use of cover crops and fertilization was possibly the main factor that differentiated it from the reference area (CF), promoting improvement in the physical and chemical properties of these areas. More importantly, these properties showed high correlations with epigeal and edaphic fauna (Figures 3 and 4). These connections suggest that management aimed at modifying one of these components is likely to have had unintended cascading effects throughout the system. In this context, soil fertility management (e.g., poultry litter, fertilizers, lime, or cover crops) is likely to affect crop growth and soil physicochemical properties and have direct and indirect impacts on the composition of non-target soil fauna communities (de Valença et al., 2017). Understanding such interactions is critical for developing land use management strategies that support long-term soil productivity, biodiversity, and other soil ecosystem services.

The linkages between fauna and soil physical and chemical properties identified in this study corroborate previous studies (Lima et al., 2010; Birkhofer et al., 2012; Baretta et al., 2014; Pompeo et al., 2016; Kraft et al., 2019). The strongest co-inertia result was found for associations between soil chemical and physical properties and epigeal and edaphic fauna. Soil properties impact soil invertebrate communities (Oliveira et al., 2018) and, according to Lavelle et al. (1997), the soil fauna (ecosystem engineers in particular) can affect soil chemical and physical properties. In our study, a positive association was observed (Figure 4) between Coleoptera larvae, Hymenoptera, species richness, and TOC. This can be attributed to the importance of organic matter to the survival, diversity and activity of soil organisms. High TOC contents stimulate the activity of individuals responsible for the decomposition and humification of soil organic matter, contributing to nutrient availability (Negassa and Sileshi, 2018). The negative correlation between temperature and epigeal fauna is explained by the preference of most epigeal organisms for more thermally stable environments (Figure 3). Temperature and moisture content are the main factors influencing metabolic regulation in soil organisms (Pompeo et al., 2016). The entire food web is favored when soil moisture and temperature conditions remain stable (Rosa et al., 2015).

The soil fauna community is known to influence the formation and stability of biogenic aggregates (Ferreira et al., 2020; Lima et al., 2020). In this study, Coleoptera larvae were positively associated with MWDbio, whereas Coleoptera was associated with MWDphy (Figure 4). Although some families of Coleoptera are agricultural pests, particularly in the larval stages, they can help improve soil fertility and physical properties (Correia and Oliveira, 2005). The Coleoptera have important ecological functions, such as the decomposition of organic matter (Nichols et al., 2008) and construction of tunnels, which increase soil aeration (Bang et al., 2005). Because of these organisms' positive contribution to agricultural ecosystems, it is recommended to adopt sustainable practices that promote Coleoptera diversity.

The Oligochaeta (earthworms) were positively associated with moisture, phosphorus (P), and cation-exchange capacity (CEC) (Figure 4). Earthworms are considered excellent indicators of agro-ecosystem quality because they respond to different types of land use and management (Paoletti, 1999; Lavelle et al., 2006), being related to environmental conditions such as soil fertility and being susceptible to habitat disturbance and contamination (Brown and Domínguez, 2010). This illustrates the potential complexity of the interactions between soil fauna organisms and the physical and chemical properties of the soil, as well as the importance of the significant covariation observed in this study between soil fauna and the main parameters of soil quality.

CONCLUSIONS

The presence of important taxonomic groups of epigeal and edaphic fauna in the areas affected by natural disasters points to the restoration of the resilience of soil food webs.

The positive correlations among richness of the edaphic fauna, fauna groups, and physical-chemical properties reveal that the joint evaluation of these indicators of soil health constitutes a robust tool to provide a more complete diagnosis of the recovery of soil quality, under different management practices.

The management with organic fertilization combined with cover crops (black oats) favors the epigeal and edaphic fauna considering the ecological indexes and the greatest abundance of earthworms.

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