**Soil arthropod community responses to restoration in areas impacted by iron mining tailings deposition after Fundão dam failure**

Letícia Gonçalves Ribeiro1, Aline Oliveira Silva1, Kátia Augusta Vaz1, Jessé Valentim dos Santos1, Cássio Alencar Nunes2, Marco Aurélio Carbone Carneiro1\*

1Universidade Federal de Lavras, Escola de Ciências Agrárias, Departamento de Ciência do Solo - Lavras, Minas Gerais, Brazil, 37200‑900.

2Universidade Federal de Lavras, Instituto de Ciências Naturais, Departamento de Ecologia e Conservação - Lavras, Minas Gerais, Brazil, 37200‑900.

**Corresponding author:** [marcocarbone@ufla.br](mailto:marcocarbone@ufla.br)

**Abstract:** In 2015, the failure of the Fundão dam in Mariana, Brazil released ~43 million m³ of iron mining tailings into the environment. Despite restoration initiatives in the following years, few studies – and most focused on revegetation – have evaluated the effectiveness of restoration process in areas impacted by the disaster. We aimed to evaluate the responses of arthropod community in areas impacted by iron mining tailings deposition from Fundão dam that are in restoration process. We defined sampling units in the riparian zone of the Gualaxo do Norte River, that is under restoration, and in a native not impacted riparian zone. We collected soil arthropods using pitfall traps and sampled environmental variables in the same sites. We used to generalize least squares models (GLS) to test if the restored areas already presented values of arthropod diversity and functional group abundance similar to the reference area and to test which environmental variables are influencing arthropod diversity. We also tested how large are the differences of arthropod community composition between the study areas and used the index of indicator species (IndVal) to verify which species could be used as indicator of reference or restoration areas. The diversity of arthropods and the functional groups of detritivores and omnivores were higher in the native riparian zone. Understory density, soil density, organic matter content and microbial biomass carbon were the environmental variables that significantly explained the diversity and species composition of arthropods. We show that restoration areas still have different soil arthropod diversity values and community composition when compared to reference areas. Evaluating the response of arthropod community to the restoration process and long-term monitoring are essential to achieve a satisfactory result in this process and achieve a self-sustaining ecosystem.

**Keywords:** Fundão dam; Soil fauna; Macrofauna; Revegetation.

**Graphical abstract:**

Diagrama

Descrição gerada automaticamente

**Soil arthropod community responses to restoration in areas impacted by iron mining tailings deposition** **after Fundão dam failure**

**1. Introduction**

The failure of the Fundão dam, which occurred in November 2015 in the municipality of Mariana in southeastern Brazil, is considered the biggest tailings dam failure in the world in the last 100 years and the biggest environmental disaster in Brazil (Islam; Murakami, 2021). The Fundão dam released 43 million cubic meters of iron mining tailings into the environment, and most of this tailing was deposited along the riparian zone of the Gualaxo do Norte River that is located downstream of the Fundão dam (Carmo et al., 2017; Silva et al., 2021). The Gualaxo do Norte River is part of the Rio Doce Basin, which, in turn, has 98% of its territory inserted in the Atlantic Forest biome, a hotspot of global biodiversity that is highly threatened by human activities (Myers et al., 2000; Garcia et al., 2017).

The mud wave and tailings deposition in the riparian zones of affected rivers caused severe environmental damage, including the suppression of vegetation (Omachi et al., 2018), changes in chemical composition of water, and an increase in turbidity that led to high fish mortality (Fernandes et al., 2016; Gomes et al., 2018). In addition, the tailings deposition caused changes in soil physical, chemical, and biological attributes of soil, such as an increase in soil density and pH (Segura et al., 2016), a decrease in soil organic matter content and available nutrients (Silva et al., 2016) and a reduction in soil microbial biomass and activity (Batista et al., 2022).

Following the environmental and socioeconomic damages caused by the Fundão dam failure, a Transaction and Conduct Adjustment Agreement (TTAC) was signed among the involved parties to restore and compensate for the consequent impacts in Rio Doce Basin (TTAC, 2016). The TTAC established an emergency and temporary revegetation program using grass and leguminous species for four years, followed by six years of maintenance. Additionally, as a compensatory measure, the TTAC demanded the restoration of 40,000 hectares of permanent preservation areas (APP) within ten years. Of these, 10,000 hectares were designated for the planting of native species, while the rest would be restored through facilitating natural regeneration. Despite over six years having passed since the restoration process began, the few studies designed to understand the effectiveness of this process focused on the revegetation of the areas (Campanharo et al., 2021; Martins et al., 2021; Cordeiro et al., 2022). Hence, there is still a gap in our understanding of how other ecosystem components, such as edaphic fauna, have responded to the restoration process.

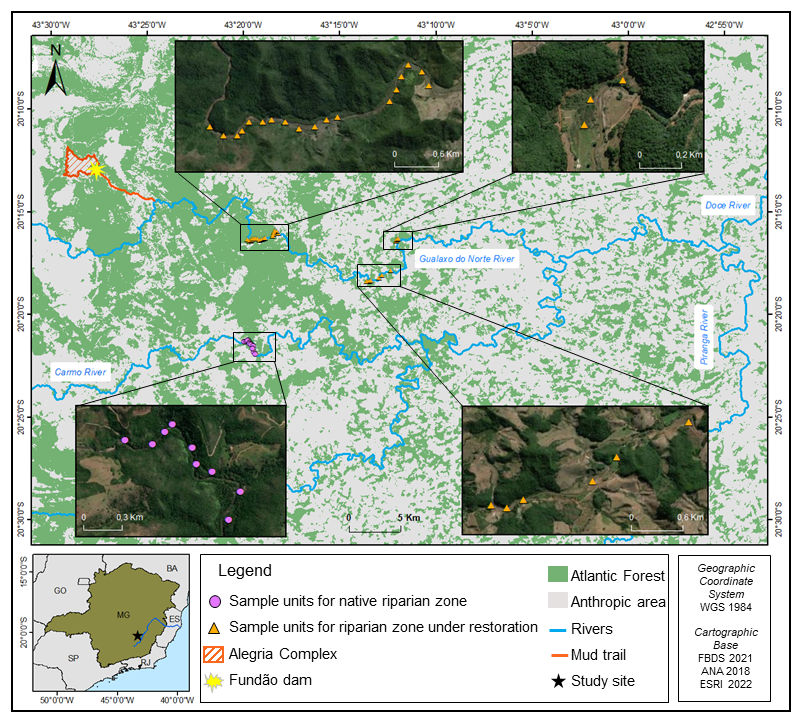
Soil arthropods are useful bioindicators for assessing the progress of ecological succession in restoration areas (Borges et al., 2021). These organisms possess several morphological and ecological characteristics making them particularly effective as bioindicators. Their small size makes them sensitive to local conditions, and their short generation times and high morphological variability enable them to produce rapid and quantifiable responses in a short period of time (Kremem et al., 1993; Hoye et al., 2018). These organisms are also simple to sample in large numbers, making them ideal for studies that compare species richness and abundance in areas with different environmental conditions (Gonçalves et al., 2020). Arthropod communities tend to reflect the successional stage of vegetation, as vegetation provides resources and conditions for their survival and development (Kenyeres, 2020; Arenhardt et al., 2021). In addition, these organisms occupy different roles in the food web and can be classified into functional groups according to their feeding habits, such as herbivores, detritivores, omnivores, and predators (Wong et al., 2019). Arthropods also perform different functions in the ecosystem, such as decomposition and translocation of organic matter, soil structuring, biological control, and secondary seed dispersal (Menta and Remelli, 2020).

Evaluating the recolonization of the arthropod community can provide valuable insights into the effectiveness of restoration process (Nakamura et al., 2003; Pais and Varanda, 2010). Therefore, the present study aimed to assess the response of the arthropod community to restoration process in the riparian zone of the Gualaxo do Norte River. To measure arthropod community response, we examined four variables: composition (1), indicator species (2), diversity (3), and abundance of functional groups (4) in the riparian zone under restoration (RZUR) along the Gualaxo do Norte River, and for purposes of comparison we used a native riparian zone (NRZ) as reference. In addition, we assessed environmental variables such as soil attributes (physical, chemical, and microbiological), diversity and dry biomass of litter, and vegetation (understory density) to explain the richness and composition of arthropod communities. Given the environmental conditions imposed by tailings deposition and emergency vegetation implanted in the riparian zone of the Gualaxo do Norte River, we present the following hypotheses: (1) The composition of the arthropod community in zone under restoration will still differ from that of native zone due to the remaining differences in the vegetation of the two regions. These differences are promoted using grass and leguminous species during the revegetation process. Also, the iron mining tailings deposition changed the soil conditions, making it difficult to reestablish native vegetation. (2) Following the differences in the arthropod community composition, we expect distinct indicators species for each zone. Specifically, in zones under restoration, we expect that the indicator species are adapted to disturbance due to the tailings deposition on the soil or that they can be species associated with grass and leguminous plants. (3) We expect that arthropod diversity will be lower in zone under restoration due to the tailings deposition and early vegetation with grass and leguminous species. These plants can provide fewer resources and refuges than in a native forest environment. (4) Among all functional groups, we expect herbivores to be more abundant in the zone under restoration since the grass and leguminous species can present a more palatable and attractive composition for this functional group compared with a native forest in a more advanced stage of succession.

**2. Material and methods**

*2.1. Study area*

The study was conducted in the municipality of Mariana, in the state of Minas Gerais, southeastern Brazil. The region is part of Atlantic Forest biome, being originally characterized as Seasonal Semideciduous Forest (Figure 1) (IBAMA, 2015). The region has an average annual temperature of 19 C° and an average annual rainfall of 1375 mm (Alvares et al., 2023), with dry season occurring between April and September and rainy season between October and March, with more precipitation in December and January. The collections occur at the end of the dry season, in September 2021, almost six years after the Fundão dam collapsed (in November 2015).

**Figure 1:** Map with the location of the municipality of Mariana, Brazil, and the sample units in the riparian zone under restoration (RZUR) of the Gualaxo do Norte River and in the native riparian zone (NZR) of the Carmo River.

*2.2 Sample design*

We defined twenty-seven sampling units in the riparian zone under restoration (RZUR) along the Gualaxo do Norte River (Figure 1). The sampling units' location was defined based on a previous field recognition, which considered the accessibility and access authorization of areas. The Gualaxo do Norte riparian zone has been in the process of restoration since January 2016 and was initially re-vegetated with exotic fast-growing species of grasses and legumes, such as crotalaria (*Crotalaria ololeuc*a), perennial soybean (*Neonotonia wightii*) and pigeon pea (*Cajanus cajan*). In addition, these areas were fenced to facilitate the natural regeneration of vegetation and secure the growth of some spontaneous species, such as assa-peixe (*Vernonia sp.*) (TTAC, 2016; Cordeiro et al., 2022). During the period of the study, the vegetation was dominated by grasses and spontaneous species such as mimosa (*Mimosa sp.*) and “assa-peixe” (*Vernonia sp.*), and still presents characteristics of primary vegetation (Figure S3) (Cordeiro et al., 2022).

For comparison purposes, one area of Carmo River riparian zone (also a tributary of the Doce River), which was not impacted by the tailings, was used as a reference due to its proximity to the Gualaxo do Norte River and their similar original soil conditions (Figure 1). We established nine sampling units in the native riparian zone (NRZ) – reference area due to the short extension of the riparian zone covered with native vegetation and steep relief. At least 200 m of distance was adopted between each sampling unit in the riparian zone of the Gualaxo do Norte and Carmo rivers to ensure sampling independence.

*2.2.1 Arthropods sampling*

We used pitfall traps composed of 750 ml plastic containers that were filled with 300 ml of a mixture composed of water, salt, and detergent to sample arthropods (Hohbein et al., 2018). In each sampling unit, three pitfalls were installed and disposed of in a triangle, with a distance of 1 m between each edge, forming a single sample that remained in the field for 48 hours. This sampling design increases the number of captures and minimizes the consequences of eventual trap losses (Braga et al., 2013). The collected arthropods presented in each sampling unit were stored in an identified Falcon tube with 70% alcohol for transportation to the laboratory for triage and identification.

*2.2.2 Triage and identification of arthropods*

The collected arthropods underwent a sorting process, separating only arthropods with a 2-20 mm wide body size. Subsequently, they were separated into orders and identified at the family and genus levels when possible. Then, they were further separated into morphospecies based on the morphological differences between individuals of the same taxon. Araneae was identified according to the taxonomic key proposed by Brescovit et al. (2002). Acari was identified based on the taxonomic key elaborated by Krantz (1978), and only free-living individuals were considered VAGUE. Formicidae was identified according to the taxonomic key proposed by Baccaro et al. (2015). The rest of the arthropods were identified according to the taxonomic keys proposed by Rafael et al. (2012). Arthropods were classified according to the predominant feeding habit of each family or genus into predators, herbivores, detritivores, and omnivores classes (Keneyeres, 2020; Wong et al., 2019). The only exception was Formicidae, which have specific functional groups.

*2.2.3 Sampling of environmental variables*

At each sampling unit, a simple soil sample was collected in the 0-10 cm depth layer with a straight shovel for physical, chemical, and microbiological analysis of the soil. Samples were stored in plastic bags and placed in a cooler. To measure soil density, an undisturbed soil sample was taken from each sampling unit and collected through a volumetric aluminum ring (2.5 cm high x 6.3 cm in diameter) with an Uhland sampler (Teixeira et al., 2007). Rings containing soil samples were stored wrapped in plastic film to ensure the integrity of samples. A wooden quadrant (25 x 25 cm) was used for collecting a litter sample in the middle of each sample unit (Scoriza et al., 2017). Litter samples were stored in brown paper bags to avoid material deterioration due to water loss. All samples were collected after the pitfalls traps were removed to avoid disturbances in soil that could compromise the collection of arthropods.

The understory density was used as a variable related to vegetation since the riparian zone of the Gualaxo do Norte River does not present a canopy formation. An adaptation of the methodology proposed by Marsden (2002) was made, which consists of photographing vegetation with a black background. A black fabric measuring 1x1 m supported by a wooden stick was used to compose the background, which was extended at ground level and 4.5 meters away from the photographer. At each sampling point, four photographs were taken corresponding to north, south, east, and west directions around a triplicate of pitfalls. The photos were recorded before installing pitfalls.

*2.3. Analysis of environmental variables*

For the microbiological analysis of soil, carbon of microbial biomass was quantified using fumigation-extraction method (Vance et al., 1987) and microbial effort of the soil was determined using the CO2 capture method using NaOH (Alef, 1995). In the physical analysis of soil, the density was measured through the dry soil mass of each sample divided by the volume of cylinder used in the collection (Teixeira et al., 2007). For texture, the fraction of sand (2.0–0.02 mm), silt (0.02–0.002 mm), and clay (>0.002 mm) were determined (Bouyoucos, 1962). In chemical analysis pH was determined in deionized water (1:2,5 v/v) (Teixeira et al., 2017). Fe and Mn contents were determined with the Mehlich-1 extractor solution (Mehlich, 1953) and quantified by optical emission spectrometry with inductively coupled plasma. The organic matter content was determined by oxidation with potassium dichromate (Walkley and Black, 1934), and N content was determined by the Kjeldahl digestion method after extraction with KCl (Bremner, 1960). Litter was dried in a stoven with forced air circulation at a temperature between 50 and 75°C until reaching constant dry weight (Scoriza et al., 2017). After obtaining dry mass, litter was weighed and then separated into the following fractions: leaves, branches, bark, flowers, and fruits, and material in an advanced stage of decomposition was classified as “others”. Each litter fraction was weighed separately, making it possible to calculate the InvSimpson diversity index (InvD) (Queiroz et al., 2021). The photographs of understory were analyzed and processed using the free software Image J, which determines the percentage of area covered by vegetation through the analysis of white and black pixels (Rasband, 2006). For each sampling unit average of the four registered photographs was taken to obtain the mean percentage of understory coverage. The mean values obtained in the analysis of all above mentioned environmental variables can be found in Table S1 in the supplementary material.

*2.4. Statistical analyzes*

Statistical analyzes were performed using the R software (R Development Core Team, 2020). First, a Pearson correlation analysis was performed to verify collinearity between sampled environmental variables (Figure S1). Variables that showed a strong correlation (> 0.7) were disregarded in statistical analysis to avoid inducing a type II error, which reduces statistical significance of correlated variables (Benesty et al., 2009). After correlation analysis, sand and clay content were not used in statistical analyses.

To verify differences in overall arthropod community composition between riparian zone under restoration (RZUR) and native riparian zone (NRZ), a non-metric multidimensional scaling analysis (NMDS) was performed with the *Vegan* package. We used the Bray-Curtis distance metric, which considers each species abundance (Oksanen et al., 2019). To verify differences in ant community composition an NMDS was also carried out, but using Jaccard distance metric that considers presence and absence of each species (Real and Vargas, 1996). Subsequently, a PERMANOVA was performed to provide statistical rigor to the clusters formed in the NMDS for overall arthropods and ants. The *envifit* function was used to verify whether formed clusters in the NMDS showed a pattern associated with environmental variables and which of them significantly explained species composition.

To determine occurrence of possible indicator species of overall arthropods and ants in the zone under restoration and native zone, indicator species analysis (IndVal) (Dufrêne and Legendre, 1997) was used with the *labdsv* package (Roberts, 2019). IndVal combines measures of specificity degree species, that is, whether a given species is found in only one habitat, and fidelity, which is the frequency species occurrence in a given habitat.

To verify overall arthropod and Formicidae diversity and test the differences between zone under restoration and native zone, we used a rarefaction and extrapolation method with the *iNext* package (Hsieh et al., 2016), to estimate the species richness for each sampling unit using the Hill Numbers approach (Chao and Jost, 2012). We performed the rarefaction and extrapolation separately for overall arthropods without Formicidae and for Formicidae and estimated only species richness for Formicidae due to the difficulty of using individuals for social insects. To estimate species richness, we used the maximum number of individuals found in a sampling unit (42 for arthropods and 451 for Formicidae). Simply counting species in a sample may underestimate true species richness, which may not be detected in the sample. Hence, an asymptotic approach via estimation of species richness and a non-asymptotic approach via rarefaction and extrapolation can infer species richness and make fair comparisons between various assemblages based on unequal sampling efforts and incomplete samples that miss many species (Chao and Chiu, 2014).

Models with generalized least squares (GLS) and ANOVA were used to verify if estimated diversity (species richness and diversity indices0 and the abundance within each functional group differed between zone under restoration and native zone through the *lme4* package (Bates, 2014). The GLS is an extension of linear model and is used when there is heteroscedasticity in the data, that is, when standard error variance is not constant (Cleasby and Nakagawa, 2011). The GLS was also used to verify the response of estimated richness of overall arthropods and ants as a function of environmental variables (Mazerolle, 2020). The assumptions of each model were verified through visual inspection of the plot of residuals for normality and homogeneity of variance (Odum et al., 1962).

**3. Results**

*3.2 Indicator species value (IndVal)*

For overall arthropods (except Formicidae), 11 indicator species were detected in the native zone (p <0.05) (Table 1). They belong to the orders Isopoda, Orthoptera, Coleoptera, and Araneae. IndVal did not detect any indicator species for the zone under restoration. For the Formicidae, four indicator species were found for the zone under restoration and six indicator species for the native zone (Table 1).

**Table 1:** Indicator species (IndVal) of overall arthropods and of the Formicidae for the native riparian zone of the Carmo River and the riparian zone under restoration of the Gualaxo do Norte River.

|  |  |  |  |
| --- | --- | --- | --- |
| **Species** | **Habitat** | **IndVal** | ***p-value*** |
| **Overall Arthropods** |  |  |  |
| *Paragryllidae* sp.1(Orthoptera) | NRZ | 0.96 | 0.001 |
| *Sthaphylinidae* sp.1(Coleoptera) | NRZ | 0.91 | 0.001 |
| *Phalangopsidade* sp.1(Orthoptera) | NRZ | 0.76 | 0.001 |
| *Isopoda* sp.1 | NRZ | 0.64 | 0.001 |
| *Agyneta* sp.1(Araneae) | NRZ | 0.44 | 0.002 |
| *Theridiidae* sp.1(Araneae) | NRZ | 0.39 | 0.019 |
| *Tenedos* sp.1 (Araneae) | NRZ | 0.33 | 0.014 |
| *Sthaphylinidae* sp.2(Coleoptera) | NRZ | 0.33 | 0.014 |
| *Coleosoma floridana* (Araneae) | NRZ | 0.3 | 0.023 |
| *Ctenidae* sp.3(Araneae) | NRZ | 0.22 | 0.045 |
| *Linyphiidae* sp.1(Araneae) | NRZ | 0.22 | 0.046 |
| **Family Formicidae** |  |  |  |
| *Solenopsis* | RZUR | 0.78 | 0.009 |
| *Brachymyrmex* sp.2 | RZUR | 0.69 | 0.009 |
| *Oxyepoecus* sp.3 | RZUR | 0.55 | 0.008 |
| *Oxyepoecus* sp.2 | RZUR | 0.51 | 0.019 |
| *Pheidole* sp.1 | NRZ | 0.74 | 0.001 |
| *Brachymyrmex* sp.1 | NRZ | 0.65 | 0.001 |
| *Diponera* sp.1 | NRZ | 0.64 | 0.001 |
| *Gnamptogenys* | NRZ | 0.54 | 0.001 |
| *Oxyepoecus* sp.1 | NRZ | 0.53 | 0.002 |
| *Simopelta* sp.1 | NRZ | 0.33 | 0.009 |

Native riparian zone of the Carmo River (NRZ); Riparian zone under restoration of the Gualaxo do Norte River (RZUR); Indicator value (IndVal). p-value means the probability as a result of the permutation test. The table only presents the significant values (p<0.05) according to the IndVal result.

*3.3 Diversity of arthropods*

The estimated species richness (q0) of arthropods (without Formicidae) were higher in the native zone when compared to the zone under restoration (Figure 3A and Figures S2). The estimated species richness of Formicidae presented similar values for the native zone and the zone under restoration (Figure 3B).

Gráfico, Gráfico de caixa estreita

Descrição gerada automaticamente

**Figure 3:** Estimated species richness (q0) of arthropods (except Formicidae) (A) and for Formicidae (B).

*3.4 Functional groups of arthropods*

The abundance of detritivores (Figure 4A) and omnivores (Figure 4C) was higher in the native zone when compared to the zone under restoration (p<0.05), while the abundance of predators (Figure 4D) and herbivores (Figure 4B) showed no significant difference between the zone under restoration and the native zone (all data shown in Table S3).

Gráfico, Gráfico de caixa estreita

Descrição gerada automaticamente

**Figure 4:** Abundance of functional groups of detritivores (A), herbivores (B), omnivores (C) and predators (D) present in the native riparian zone (NRZ) of the Carmo River and in the riparian zone under restoration (RZUR) in the Gualaxo do Norte River.

*3.5 Effect of environmental variables on arthropod diversity*

For the overall arthropod diversity, microbial biomass carbon, understory density, and soil organic matter content were the environmental variables that best explained the variation in estimated species richness of arthropod species (Table 2). None of the environmental variables explained the variation in the estimated species richness of ants (Formicidae), and the null model was selected as the best one (Table 2).

**Table 2:** Model selection based on the lowest AICc for estimated richness.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Response variables** | **Explanatory variables** | **K** | **AICc** | **DeltaAIC** | **w** |
| Estimated richness of arthropods | UV + MBC + OM | 5 | 311.53 | 0 | 51 |
| Estimated richness of arthropods | UV + MBC | 4 | 312.47 | 0.93 | 0.32 |
| Estimated richness of arthropods | Global model | 14 | 314.16 | 2.63 | 0.14 |
| Estimated richness of arthropods | Null model | 2 | 316.7 | 5.16 | 0.04 |
| Estimated richness of ants | Null model | 2 | 198.11 | 0 | 1 |
| Estimated richness of ants | Global model | 14 | 249.28 | 51.17 | 0 |

Microbial carbon biomass (MBC); Organic matter (OM); Understory vegetation (UV); Number of model parameters (K); Akaike Information Criterion for Small Samples (AICc); Difference in AIC score between the best model and the model being compared (DeltaAIC); Model weight (w).

*3.4 Community composition analysis*

For overall arthropods, the NMDS presented a stress of 0.12 and showed a clear visual separation in the composition of the arthropod community between the native zone and the zone under restoration (Figure 4A), which was confirmed by the PERMANOVA (p<0.05 and R²=0.13). The environmental variables that significantly explained the composition of overall arthropod species were soil bulk density (p<0.05 and R²=0.22) and understory density (p<0.05 and R²=0.33) (Figure 4A and Table S3). The understory density was higher in the native zone, and the soil density was higher in the zone under restoration. The two vectors formed an obtuse angle indicating that these two variables are negatively correlated. For Formicidae NMDS presented stress of 0.21 and showed significantly different communities between NRZ and RZUR according to PERMANOVA (p<0.05 and R²=0.60) (Figure 4B). Soil density (p<0.05 and R²=0.56) and understory density were also the environmental variables that significantly explained the ant species composition (Figure 4B and Table S4).

Gráfico, Gráfico de radar

Descrição gerada automaticamente

**Figure 4:** Non-metric multidimensional scaling (NMDS) representing the ordering of environmental variables with the structure of the overall arthropod community (A) and for Formicidae (B) in the native riparian zone (NRZ) of the Carmo River and in the riparian zone under restoration (RZUR) of the North Gualaxo River. Legend: The black arrows represent the ordering of environmental variables, the purple arrows with a triangle point represent the ordering of the arthropod community of the native riparian zone of the Carmo River and the orange arrows with a round tip refer to the riparian zone undergoing river restoration Gualaxo do Norte River. Microbial respiration (MR), Microbial biomass carbon (MBC), Organic matter (OM), Litter diversity measure by Inverse Simpson Index (Litter InvD).

**4. Discussion**

*41 Community composition analysis*

The composition of overall arthropod community and ants was different between the native zone (NZR) and zone under restoration (RZUR). When secondary colonization occurs after a major disturbance, it is common to detect significant variations in the composition of the arthropod community (Frouz et al., 2008). Changes in habitat can cause native species to be replaced by species tolerant to disturbances or invasives, modifying species composition (Zettler et al., 2004; Ribeiro-Neto et al., 2016).

Soil density and understory density were environmental variables that determined overall arthropods and ants composition between the native zone and the zone under restoration. Tailings deposition in the areas affected by Fundão dam promote an increase in soil density, a fact associated with mineralogical composition of tailings, which is rich in quartz and iron oxides, and size of its particles, which have a silty and sandy texture, disfavoring the formation and stabilization of wastes aggregates (Silva et al., 2021; Santos et al., 2019). Changes in soil density can, directly and indirectly, influence arthropod community. The pores present in the soil are a direct channel for the movement of edaphic arthropods, especially those with larger body sizes. Thus, reduction in soil porosity caused by increase in soil density can act as a limiting factor for movement and dispersion of these organisms in zone under restoration (Pressler et al., 2018). In addition, high soil density can hinder development of vegetation, which grows under stress conditions and presents morphological and physiological changes that can compromise the development of the plants (Table 1S) (Fernandes et al., 2015; Segura et al., 2016). In NMDS, our results demonstrated this negative relationship between higher soil density and understory vegetation since they are represented by contrary ordinations. The understory vegetation was higher in native zone, a common characteristic of the areas with native forests or in an advanced stage of ecological succession (Wali, 1999). Vegetation is considered one of the main factors that determine the structure and composition of arthropod community, as it is a physical habitat for most species, in addition to being a primary source of resources (Lewinsohn et al., 2005). So, in the zone under restoration, higher soil density can act as a limiting factor for arthropods movement and dispersion and also is a limiting factor for vegetation development, resulting in lower understory vegetation and consequently less available resources for the arthropod community.

*4.2 Indicator species value*

IndVal pointed out overall arthropod species that were indicative only in the native zone, belonging to Orthoptera, Araneae, Coleoptera, and Isopoda. This method combines the degree of specificity of a determined species for an ecological status and its fidelity within the status, which is measured through its percentage of occurrence (Dufrêne and Legendre, 1997). Therefore, absence of indicator species in the zone under restoration may be evidence of low specificity of species found in this region.

We found that species with highest indicator value of the native zone belongs to Paragryllidae (Orthoptera). Orthoptera is a central element in food chain, as they represent first-order consumers and are a source of food for other taxa, such as birds (Odum et al., 1962 Kok and Louw, 2000). In general, aspects of environment that tend to interfere with Orthoptera occurrence are vegetation structure and climatic conditions, such as humidity (Weyer et al., 2012; Humbert et al., 2021). The second species with highest indicator value in the native zone belongs to Staphylinidae (Coleoptera). Staphylinids are predatory beetles and are common in natural and altered systems, but species composition tends to be determined by aspects such as vegetation, litter nutritional quality, and N content in the soil (Bohac, 1999; Stašiov et al., 2021). So, the presence of Orthoptera and Staphylinidae as indicator species of the native area can point out that the native area presents more available resources and ideal conditions for different groups of arthropods community.

For Formicidae four indicator species were recorded for zone under restoration and six species for the native zone. A species of *Solenopsis* had the highest indicator value for riparian zone under restoration, and a species of *Pheidole* had the highest indicator value for native zone. The genera *Solenopsis* and *Pheidole* correspond to foraging ants that build nests in soil and are abundant and widely distributed (Grahan et al., 2004; Pacheco et al., 2013). In addition, both genera contribute to secondary seed dispersal and maintenance of soil structure through nest building (Sanabria et al., 2014). The occurrence of *Solenopsis* and *Pheidole* as indicator species in zone under restoration and native zone, respectively, may demonstrate a certain degree of similarity in terms of the ecological function performed by ants between the two regions.

*4.3 Diversity of arthropods*

The overall arthropod richness was higher in the native zone. Native areas or advanced stages of ecological succession tend to develop more diverse vegetation that supplies the formation of more complex habitats that can support different niches, contributing to higher species richness (Stein et al., 2014). In contrast, the zone under restoration showed a greater dominance of species. This fact may be related to a more homogeneous vegetation of the zone under restoration, which is composed principally of grass and leguminous species, which may result in dominance of species adapted to this specific type of resource (Randlkofe et al., 2010).

Richness and diversity of Formicidae were higher in the zone under restoration. Areas in the initial stage of restoration may show an increase in ant species richness due to the initial input of resources, but over the years, richness tends to stabilize (Majer, 1996). In addition, areas in early stages of restoration may favor more generalist ant groups, such as genera *Solenopsis* and *Atta* (Myrmicinae), which were recorded in great abundance in the zone under restoration (Zettler et al., 2004). Ants can bring benefits and problems to restoration process in the zone under restoration. On one hand, ants can contribute to decreasing soil density and increasing water infiltration by building nests (Nkem et al., 2000). Furthermore, ants can incorporate organic matter and contribute to soil fertility through their foraging habit (Cammeraat et al., 2008). On other hand, leaf-cutting ants are potential causes of damage to development of seeds and plants in the early stages of development (Vasconcelos and Cherrett, et al., 1997; Montoya-Lerma et al., 2012). Leaf-cutting ants belong to genera *Atta* and *Acromyrmex* (Myrmicinae), and both were recorded in greater abundance in the zone under restoration (Table S1). Plants grown in soils with a higher concentration of iron mining tailings from the Fundão dam failure were more likely to be attacked by leaf-cutting ants of the *Acromyrmex subterraneus* species (Nascimento et al., 2021). The physiological response of plants to stress caused by the physical and chemical properties of tailings acts as an attraction for these ants. Given this, seedlings implanted in areas with a high concentration of tailings may have more difficulties in growing, reducing their chance of survival and effectiveness of restoration process.

*4.4 Functional groups of arthropods*

Regarding functional groups of arthropods (except Formicidae), detritivores and omnivores were significantly more abundant in the native zone. Variations in resource availability can modify the structure of arthropod community so that absence of a resource can led to a decrease in abundance of respective functional group (Lessard et al., 2011). The lower abundance of omnivores may impair the resilience of the food chain in zone under restoration. Since omnivores can mitigate effects of declines in predators, herbivores, and detritivores populations, they can contribute to the stability of the food chain (Fagan, 1997). The lower abundance of detritivores may impair nutrient cycling in zone under restoration. They fragment organic matter into smaller pieces, facilitating colonization and decomposition by fungi and bacteria that carry out the mineralization process of nutrients (Barrios, 2007). So, lower abundance of detritivore arthropods can be implied in reducing the nutrient cycling process in the zone under restoration.

Functional groups tend to reestablish faster than species composition (Cole et al., 2016). However, it is necessary to seek the re-establishment of all aspects of the biota since each species acts in a specific niche of the soil trophic chain and in environmental functions that result in a functional, self-sustaining, and resilient ecosystem. For example, ants dominance in the zone under restoration can be controlled through trophic relationships such as predation and competition, exerting a natural control of population (Dunn et al., 2007).

4.5 *Effect of environmental variables on arthropod diversity*

Understory vegetation density, microbial biomass carbon, and soil organic matter content were the explanatory environmental variables for estimated arthropod richness. Considering ecosystem functioning, these three variables are related to each other. Microbial community is responsible for carrying out decomposition and mineralization of soil organic matter, releasing nutrients in forms assimilable by plants and other organisms, and contributing to nutrition and development of community that lives in the soil (Prasad et al., 2021). Furthermore, in terms of energy flow through the soil trophic chain, microbial biomass is a source of food resources for certain microarthropods, such as springtails, which are prey to larger body-size arthropods (Moore et al., 1988). Therefore, microbial biomass, soil organic matter content, and vegetation had been negatively affected by the deposition of Fundão dam tailings and are environmental variables that are involved in providing resources and creating habitats for the arthropod community, enhancing its richness and diversity (Potapov et al., 2017; Batista et al., 2022; Cordeiro et al., 2022). So, the effects of the tailings deposition in these attributes can be reflected in the arthropods community.

*4.6 The restoration process*

As the ecological succession of vegetation occurs, an improvement in environmental conditions is expect, and composition of arthropods in zone under restoration tend to be more similar to the native areas used as reference (Meloni and Varanda, 2015). However, despite showing an improvement compared to the initially degraded areas, there is a tendency that areas in the restoration process do not return to the same biodiversity as the reference (Atkinson et al., 2022). This occurs because even with restoration process, these areas may still be influenced by the initial disturbance and other environmental factors. In view of this, it is possible that due to the presence of tailings in the environment, the ecosystem does not resemble original natural conditions, but that it starts to develop different attributes that support a distinct community (Fernandes et al., 2016; Hossner et al., 1992).

It is important emphasize that the final goal of restoration process in areas affected by Fundão dam mining tailings is not clear in TTAC (2016) and other available documents. What we know is that according to TTAC, the deadline for planting native vegetation ends in 2026. Emergency vegetation, composed of leguminous and grass species, still predominates in the region (Cordeiro et al., 2022). The use of exotic plant species contributes to promoting arthropod communities with distinct attributes between the zone under restoration versus the native zone. Therefore, planting of native species combined with other technics such as artificial shelters or perches to attract seed-dispersing fauna, the installation of vegetation islands by the transposition of topsoil, seeds, or branches, can favor the re-establishment of the arthropod community and mitigate these differences (Rodrigues et al., 2009; Vogel et al., 2015). According to Cordeiro et al. (2021), the planting of woody native species in the areas affected by Fundão tailings was unsuccessful due to the higher contents of amine and sodium in the soil that are produced during the mining process. The use of remediation strategies, such as organic matter amendment, sediment scraping, phytoremediation with tolerant woody species, and using herbaceous species with mycorrhizal inoculation, is already being tested in the soils affected by Fundão tailings and has demonstrated promising results (Gomes et al., 2021; Zanchi et al., 2021). These remediation strategies can promote soil health and facilitate future revegetation strategies with native species. Even in an initial phase of restoration, studies like this are important to understand how the components of the ecosystem behave in the face of the restoration process and to seek alternatives that can stimulate functional and taxonomic diversity to ensure the effectiveness of this process. In addition, monitoring of these areas is essential since it is an unprecedented environmental disaster, and little is known about long-term impacts on ecosystem (Carmo et al., 2017; Herrick et al., 2006).

**5. Conclusion**

The arthropod community was a good bioindicator for pointing out that the riparian zone under restoration after the iron mining tailings deposition of the Fundão dam rupture presents large and significant differences of arthropod community composition than those found in a native riparian zone. The differences between the community composition of arthropods in the native zone and in the zone under restoration were related to soil bulk density and understory vegetation density. The indicator species for the zone under restoration was only individuals for Formicidae (*Solenopsis*) being evidence of the low specificity of ants species found in this zone. Also, the zone under restoration has a lower richness of arthropods and a lower abundance of functional groups of omnivores and detritivores. The environmental variables that explain arthropod richness were microbial biomass carbon, understory vegetation density, and soil organic matter. All these variables are impacted by the tailings deposition in the soil and can act to limit the re-establishment of soil arthropods community. The restoration process focusing on soil health can improve the environmental conditions related to soil and vegetation in the riparian zone of the Gualaxo do Norte River and, consequently, the return of the arthropod community. Therefore, assessing the response of the arthropod community and other organisms in the face of the restoration process and long-term monitoring is essential to achieve a satisfactory result and a self-sustaining ecosystem.

**Acknowledgment**

We thank the Coordination for the Improvement of Higher Education Personnel (CAPES), the National Council for Scientific and Technological Development (CNPq), and the Minas Gerais State Research Foundation (FAPEMIG-APQ-01661-16) for the financial support and scholarships granted to the authors. We also thank Mateus de Melo Dias for the help in the map elaboration, Antonio Domigos Brescovit for the help to identify the spiders, and Júlio Neil Cassa Louzada for permitting the use of Laboratório de Ecologia e Conservação de Invertebrados (LECIN) for the arthropods triage and identification process.

**Funding**

This research was financed by grants from the Minas Gerais State Research Foundation (FAPEMIG), National Council for Scientific and Technological Development (CNPq), and Coordination for the Improvement of Higher Education Personnel (CAPES).

**Availability of data and material Statements**

The authors declare that data supporting the findings of this study are available within the article and its supplementary information files.

**Author Contributions Statement**

The experiment was mainly planned and designed by LGR and MACC, and all authors were involved in the designing of the study; LGR: conceptualization, methodology, investigation, data analysis, writing (original draft preparation); AOS: collecting all the data, methodology, writing (review and editing); KAV: collecting all the data, methodology, writing (review and editing); ESSF: collecting all the data, methodology, writing (review and editing); JVS: collecting all the data, methodology, writing (review and editing); ESSF: collecting all the data, methodology, writing (review and editing); CAN: conceptualization, methodology, supervision, writing (review and editing); MACC: conceptualization, methodology, investigation, analysis of the data, project administration, supervision, writing (review and editing). All authors have read and agreed to the published version of the manuscript.

**Conflict of Interest Statement**

The authors declare that they have no conflict of interest.

**Competing interests Statement**

The authors declare that they have no competing interests.

**References**

Alef, K. (1995). Field methods. In: Alef, K., Nannipieri, P. (Eds*.), Methods in Applied Soil Microbiology and Biochemistry*., Academic Press (pp. 463-490), London.

Alvares, C. A., Stape, J. L., Sentelhas, P. C., Gonçalves, J. L. M., Sparovek, G. (2013). Köppen’s climate classification map for Brazil. *Meteorologische Zeitschrift*, 22, 711-728. <https://doi.org/10.1127/0941-2948/2013/0507>

Arenhardt, T. C. P., Vitorino, M. D., Martins, S. V. (2021). Insecta and Collembola as bioindicators of ecological restoration in the Ombrophilous Dense Forest in Southern Brazil. *Floresta e Ambiente*, 28. <https://doi.org/10.1590/2179-8087-FLORAM-2021-0008>

Atkinson, J., Brudvig, L. A., Mallen‐Cooper, M., Nakagawa, S., Moles, A. T., Bonser, S. P. (2022). Terrestrial ecosystem restoration increases biodiversity and reduces its variability, but not to reference levels: A global meta‐analysis. *Ecology Letters,* 25(7), 1725-1737. <https://doi.org/10.1111/ele.14025>

Baccaro, F. B., Feitosa, R. M., Fernández, F., Fernandes, I. O., Izzo, T. J., Souza, J. D., Solar, R. (2015). Guia para os gêneros de formigas do Brasil. Manaus: Editora INPA,  pp. *388*. <https://doi.org/10.5281/zenodo.32912>

Barrios, E. (2007). Soil biota, ecosystem services and land productivity. *Ecological economics*, 64(2), 269-285. <https://doi.org/10.1016/j.ecolecon.2007.03.004>

Bates, D. (2014). Penalized least squares versus generalized least squares representations of linear mixed models. R package version, 1-1. <http://cran.nexr.com/web/packages/lme4/vignettes/PLSvGLS.pdf>

Batista, E. R., Franco, A. J., Silva, A. P. V., Silva, J. A. G. F., Tavares, D. S., Souza, J. K., Silva, A. O., Barbosa, M. V., Santos, J. V., Carneiro, M. A. (2022). Organic substrate availability and enzyme activity affect microbial-controlled carbon dynamics in areas disturbed by a mining dam failure. *Applied Soil Ecology* 169, 104169. <https://doi.org/10.1016/j.apsoil.2021.104169>

Benesty, J., Chen, J., Huang, Y., Cohen, I. (2009). *Pearson correlation coefficient*. In: Cohen, I., Huang, Y., Chen, J., Benesty, J. (Eds.), Noise reduction in speech processing. Springer Berlin Heidelberg. <https://doi.org/10.1007/978-3-642-00296-0_5>

Bohac, J. (1999). Staphylinid beetles as bioindicators. *Agriculture, ecosystems & environment*, *74*, 357-372. <https://doi.org/10.1016/S0167-8809(99)00043-2>

Borges, F. L. G., da Rosa Oliveira, M., de Almeida, T. C., Majer, J. D., Garcia, L. C., (2021). Terrestrial invertebrates as bioindicators in restoration ecology: A global bibliometric survey. *Ecological Indicators*, 125, 107458. <https://doi.org/10.1016/j.ecolind.2021.107458>

Bouyoucos, G. J. (1962). Hydrometer method improved for making particle size analyses of soils. *Agronomy Journal,* 54, 464-465. <https://doi.org/10.2134/agronj1962.00021962005400050028x>

Braga, R. F., Korasaki, V., Andresen, E., Louzada, J. (2013). Dung beetle community and functions along a habitat-disturbance gradient in the Amazon: a rapid assessment of ecological functions associated to biodiversity. *PLoS One*, 8(2), e57786. <https://doi.org/10.1371/journal.pone.0057786>

Bremner, J. M. (1960). Determination of nitrogen in soil by the Kjeldahlmethod*. Journal of Agricultural Science*,55, 11–33. <https://doi.org/10.1017/S0021859600021572>.

Brescovit, A. D. Araneae. (2002). In: Flórez-Daza, E. (Ed.), *Amazonian Arachnida and Myriapoda*. Pensoft, (pp. 303-344), Sofia.

Campanharo, Í. F., Martins, S. V., Villa, P. M., Kruschewsky G. C., Dias, A. A., Nabeta, F. H. (2021). Effects of forest restoration techniques on community diversity and aboveground biomass on area affected by mining tailings in Mariana, Southeastern Brazil*. Research in Ecology*, 2 (4). <https://pdfs.semanticscholar.org/151b/4cc4577b6473f3826d8dd8cc0a7650be50bf.pdf>

Carmo, F. F., Kamiro, L. H., Junior, R. T., Campos, I. C., Carmo, F. F., Silvino, G., Castro, K. J., Mauro, M. L., Rodrigues, N. U., Miranda, M. P., Pinto, C. E. (2017). Fundão tailings dam failures: the environment tragedy of the largest technological disaster of Brazilian mining in global context. *Perspectives in ecology and conservation*, 15(3), 145-151. <https://doi.org/10.1016/j.pecon.2017.06.002>

Chao, A., Jost, L. (2012). Coverage-based rarefaction and extrapolation:standardizing samples by completeness rather than size. *Ecology*, 93, 2533–2547. <https://doi.org/10.1890/11-1952.1>

Cleasby, I. R., Nakagawa, S. (2011). Neglected biological patterns in the residuals. *Behavioral Ecology and Sociobiology*, 65(12), 2361-2372.  <https://doi.org/10.1007/s00265-011-1254-7>

Cole, R. J., Holl, K. D., Zahawai, R. A., Wickey P., Townsend, A. R. (2016). Leaf litter arthropod responses to tropical forest restoration. *Ecology and Evolution*, 6(15), 5158-5168. <https://doi.org/10.1002/ece3.2220>

Cordeiro, J., Gomes, A. R., Santos, C. H. B., Rigobelo, E. C., Baptista, M. B., Moura, P. M., Scotti, M. R. (2022). Rehabilitation of the Doce River Basin after the Fundão dam collapse: What has been done, what can be done and what should be done?. *River Research and Applications*, 38(2), 194-208. <https://doi.org/10.1002/rra.3894>

Dufrêne, M., Legendre, P. (1997). Species assemblages and indicator species: The need for a flexible asymmetrical approach. *Ecological Monographs*, 67, 345-366. https://doi.org/10.1890/0012-9615(1997)067[0345:SAAIST]2.0.CO;2

Dunn, R. R., Parker, C. R., Sanders, N. J. (2007). Temporal patterns of diversity: assessing the biotic and abiotic controls on ant assemblages. *Biological Journal of the Linnean Society*, *91*(2), 191-201. <https://doi.org/10.1111/j.1095-8312.2007.00783.x>

Fagan, W. F. (1997). Omnivory as a stabilizing feature of natural communities. Am. Nat. 150:554–67. <https://doi.org/10.1086/286081>

Fernandes, G. W., Goulart, F. F., Ranieri, B. D., Coelho, M. S., Dales, K., Boesche, N., Bustamante, M., Carvalho, F. A., Carvalho, D. C., Dirzo, R., Fernandes, S., Galetti, P. M., Millian, V. E. G., Mielke, C., Ramirez, J. L., Neves, A., Rogass, C., Ribeiro, S., Soares-Filho, B. (2016). Deep into the mud: ecological and socio-economic impacts of the dam breach in Mariana, Brazil. *Natureza & Conservação*, 14, 35-45. <https://doi.org/10.1016/j.ncon.2016.10.003>

Frouz, J., Prach, K., Pižl, V., Háněl, L., Starý, J., Tajovský, K., Materna, J., Balík, V., Kalcik, J., Rehounková (2008). Interactions between soil development, vegetation and soil fauna during spontaneous succession in post mining sites. *European journal of soil biology*, 44(1), 109-121. <https://doi.org/10.1016/j.ejsobi.2007.09.002>

Gann, G. D., McDonald, T., Walder, B., Aronson, J., Nelson, C. R., Jonson, J., Hallet, J. G., Eisenberg, C., Guariguata, M. R., Liu, J., Hua, F., Echeverría, C., Gonzales, E., Shae, N., Decleer, K., Dixon, K. W. (2019). International principles and standards for the practice of ecological restoration. Restoration *Ecology,* 27 (S1)*.* <https://doi.org/10.1111/rec.13035>

Garcia, L. C., Ribeiro, D. B., Roque, F. O., Quintero, J. M., Laurance, W. F. (2017). Brazil's worst mining disaster: Corporations must be compelled to pay the actual environmental costs. *Ecological Applications* 27, 5-9. <https://doi.org/10.1002/eap.1461>

Gomes, A. R., Antão, A., Santos, A. G., Lacerda, T. J., Medeiros, M. B., Saenz, L. A. I., Alvarenga, S., Santos, C. H., Rigobelo, E., Scotti, M. R. (2021). Rehabilitation of a riparian site contaminated by tailings from the Fundão Dam, Brazil, using different remediation strategies. *Environmental Toxicology and Chemistry*, 40(8), 2359-2373. https://doi.org/10.1002/etc.5075

Gomes, L. C., Chippari-Gomes, A. R., Miranda, T. O., Pereira, T. M., Merçon, J., Davel, V. C., Barbosa, B. V., Pereira, A. C. H., Frossard, A., Ramos, J. P. L. (2018). Genotoxicity effects on Geophagus brasiliensis fish exposed to Doce River water after the environmental disaster in the city of Mariana, MG, Brazil. *Brazilian Journal of Biology,* 79, 659-664. <https://doi.org/10.1590/1519-6984.188086>

Gonçalves, F., Nunes, C., Carlos, C., López, Á., Oliveira, I., Crespí, A., Teixeira, B., Pinto, R., Costa, C. A., Torres, L. (2020). Do soil management practices affect the activity density, diversity, and stability of soil arthropods in vineyards?. *Agriculture, Ecosystems & Environment*, 294, 106863. <https://doi.org/10.1016/j.agee.2020.106863>

Graham, J. H., Hughie, H. H., Jones, S., Wrinn, K., Krzysik, A. J., Duda, J. J., Freeman, D. C., Emlen, J. M., Zak, J. C., Kovacic, D. A., Chamberlin-Graham, C., Balbach., H., (2004). Habitat disturbance and the diversity and abundance of ants (Formicidae) in the Southeastern FallLine Sandhills. *Journal of Insect Science*, 4, 1–15. <https://doi.org/10.1093/jis/4.1.30>

Herrick, J. E., Schuman, G. E., Rango, A. (2006). Monitoring ecological processes for restoration projects. *Journal for Nature Conservation*, 14 (3-4), 161-171. <https://doi.org/10.1016/j.jnc.2006.05.001>

Hohbein, R. R., Conway, C. J. (2018). Pitfall traps: A review of methods for estimating arthropod abundance. *Wildlife Society Bulletin*, 42, 597-606. <https://doi.org/10.1002/wsb.928>

Hossner, L. R., Hons, F. M. (1992). Reclamation of Mine Tailings. In: Lal, R., Stewart, B. A. (Eds.), Soil Restoration. *Advances in Soil Science*, 17. Springer, New York, NY. <https://doi.org/10.1007/978-1-4612-2820-2_10>

Hoye, T. T., Culler, L. E. (2018). Tundra arthropods provide key insights into ecological responses to environmental change. *Polar Biology*, 41(8), 1523-1529. <https://doi.org/10.1007/s00300-018-2370-x>

Hsieh, T. C., Ma, K. H., Chao, A. (2016). iNEXT: an R package for rarefaction and extrapolation of species diversity (Hill numbers*). Methods in Ecology and Evolution*, 7, 1451-1456. <https://doi.org/10.1111/2041-210X.12613>

Humbert, J. Y., Delley, S., Arlettaz, R. (2021). Grassland intensification dramatically impacts grasshoppers: experimental evidence for direct and indirect effects of fertilisation and irrigation. *Agriculture, Ecosystems & Environment*, *314*, 107412. <https://doi.org/10.1016/j.agee.2021.107412>

Instituto Brasileiro do Meio Ambiente e dos Recursos Renováveis- IBAMA (2015). Laudo Técnico Preliminar: Impactos ambientais decorrentes do desastre envolvendo o rompimento da barragem de Fundão, em Mariana, Minas Gerais. Disponível em: http://www.ibama.gov.br/phocadownload/barragemdefundao/laudos/laudo\_tecnico\_preliminar\_Ibama.pdf. Acesso em: 07 jan. 2021.

Islam, K., Murakami, S. (2021). Global-scale impact analysis of mine tailings dam failures: 1915–2020. *Global Environmental Change*, 70, 102361. <https://doi.org/10.1016/j.gloenvcha.2021.102361>

Kenyeres, Z. (2020). Rapid succession of orthopteran assemblages driven by patch size and connectivity. *Rangeland Ecology & Management*, 73(6), 838-846. <https://doi.org/10.1016/j.rama.2020.07.004>

Kok, O. B., Louw, S. V. (2000). Avian and mammalian predators of Orthoptera in semi-arid regions of South Africa. *South African Journal of Wildlife Research,* 30, 122–128. <https://hdl.handle.net/10520/EJC117100>

Kozak, M., Piepho, H. P. (2018). What's normal anyway? Residual plots are more telling than significance tests when checking ANOVA assumptions. *Journal of Agronomy and Crop Science*, 204(1), 86-98.<https://doi.org/10.1111/jac.12220>.

Krantz, G. W. (1978). A manual of acarology. Oregon State University, Corvallis, USA.

Kremem, C., Colwell, R. K., Erwin, T. L., Murphy, D. D., Noss, R. F., Sanjayan, M. A. (1993). Terrestrial arthropod assemblages: their use in conservation planning. *Conservation Biology*, pp. 796-808. <https://www.jstor.org/stable/2386811>

Laurance, W. F., Lovejoy, T. E., Vasconcelos, H. L., Bruna, E. M., Didham, R. K., Stouffer, P. C., Gascon, C., Bierregaard, R. O., Laurance, S. G., Sampaio, E. (2002). Ecosystem decay of Amazonian forest fragments: a 22‐year investigation. *Conservation Biology*, 16(3), 605-618. <https://doi.org/10.1046/j.1523-1739.2002.01025.x>

Lessard, J. P., Sackett, T. E., Reynolds, W. N., Fowler, D. A., Sanders, N. J. (2011). Determinants of the detrital arthropod community structure: the effects of temperature and resources along an environmental gradient. *Oikos, 120*(3), 333-343. <https://doi.org/10.1111/j.1600-0706.2010.18772.x>

Lewinsohn, T. M., Novotny, V., Basset, Y. (2005). Insects on plants: diversity of herbivore assemblages revisited. *Annual Review of Ecology, Evolution, and Systematics*, 597-620. <https://www.jstor.org/stable/30033818>

Machado, G. (2007). What are harvestmen? In: Pinto-da-Rocha, R., Machado, G., Giribet, G. (Eds.), Harvestmen: The Biology of Opiliones. Harvard University Press.

Majer, J. D., Brennan, K. E., Moir, M. L. (2007). Invertebrates and the restoration of a forest ecosystem: 30 years of research following bauxite mining in Western Australia. *Restoration Ecology*, 15, S104-S115. <https://doi.org/10.1111/j.1526-100X.2007.00298.x>

Marsden, S. J., Fielding, A. H., Mead, C., Hussin, M. Z. (2002). A technique for measuring the density and complexity of understorey vegetation in tropical forests. *Forest Ecology and Management*, 165(1-3), 117-123. <https://doi.org/10.1016/S0378-1127(01)00653-3>

Martins, S. V., Villa, P. M., Nabeta, F. H., Silva, L. F., Kruschewsky, G. C., Dias, A. A. (2021). Study on site preparation and restoration techniques for forest restoration in mining tailings of Mariana, Brazil. *Research in Ecology*, 2. <http://dx.doi.org/10.30564/re.v2i4.2610>

Mazerolle, M. J. (2020). Model selection and multimodel inference using the AICcmodavg package. <https://mirror.marwan.ma/cran/web/packages/AICcmodavg/vignettes/AICcmodavg.pdf>

Mehlich, A. (1953). Determination of P, Ca, Mg, K, Na and NH4 by North Carolina Soil Testing Laboratories. Raleigh, University of North Carolina, pp. 195.

Meloni, F., Varanda, E. M. (2015). Litter and soil arthropod colonization in reforested semi‐deciduous seasonal Atlantic forests. *Restoration Ecology*, 23(5), 690-697. <https://doi.org/10.1111/rec.12236>

Menta, C., Remelli, S. (2020). Soil health and arthropods: From complex system to worthwhile investigation. *Insects*, 11(1), 54. <https://doi.org/10.3390/insects11010054>

Meyer, S. T.; Roces, F.; Wirth, R. (2006). Selecting the drought stressed: Effects of plant stress on intraspecific and within-plant herbivory patterns of the Leaf-Cutting Ant *Atta colombica*. *Functional Ecology*, 20(5), 973-981. <https://www.jstor.org/stable/4139334>

Minor A. K., Eichholz M. W., Liechty J. S. (2021). Vegetation richness, diversity, and structure influence arthropod communities of native and restored northern mixed‐prairies. *Restoration Ecology*, 29 (7):e13407. <https://doi.org/10.1111/rec.13407>

Montoya-Lerma, J., Giraldo-Echeverri, C., Armbrecht, I., Farji-Brener, A., Calle, Z. (2012). Leaf-cutting ants revisited: towards rational management and control. *International Journal of Pest Management*, 58(3), 225-247. <https://doi.org/10.1080/09670874.2012.663946>

Moore, J. C., Walter, D. E., Hunt, H. W. (1988). Arthropod regulation of micro-and mesobiota in below-ground detrital food webs*. Annual Review of Entomology*, 33(1), 419-435. <https://doi.org/10.1146/annurev.en.33.010188.002223>

Myers, N., Mittermeier, R., Mittermeier, C., et al. (2000). Biodiversity hotspots for conservation priorities. *Nature*, 403, 853-858. <https://doi.org/10.1038/35002501>

Nakamura, A., Proctor, H., & Catterall, C. P. (2003). Using soil and litter arthropods to assess the state of rainforest restoration. *Ecological Management & Restoration*, *4*, S20-S28. https://doi.org/10.1046/j.1442-8903.4.s.3.x

Odum, E. P., Connell, C. E., Davenport, L. B. (1962). Population energy-flow of 3 primary consumer components of old-field ecosystems. *Ecology*, 43-88. <https://www.jstor.org/stable/1932043>

Oksanen, J., Blanchet, F. G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P. T., O’Hara, R. B., Simpson, G. L., Solymos, P., Stevens, M. H. H., Szoecs, E., Wagner, H. (2019). Vegan: Community Ecology Package. R package version 2.5–4. https:// CRAN.R- proje ct. org/ packa ge= vegan

Omachi, C. Y., Siani, S. M., Chagas, F. M., Mascagni, M. L., Cordeiro, M., Garcia, G. D., Thompson C. C., Siegle, E., Thompson, F. L. (2018). Atlantic Forest loss caused by the world´ s largest tailing dam collapse (Fundão Dam, Mariana, Brazil). *Remote Sensing Applications: Society and Environment*, 12, 30-34. <https://doi.org/10.1016/j.rsase.2018.08.003>

Pacheco, R., Vasconcelos, H. L., Groc, S., Camacho, G. P., Frizzo., T. L. M. (2013). The importance of remnants of natural vegetation for maintaining ant diversity in Brazilian agricultural landscapes. *Biodiversity Conservation*, 22, 983–997. <https://doi.org/10.1007/s10531-013-0463-y>

Pais, M. P., Varanda, E. M. (2010). Arthropod recolonization in the restoration of a semideciduous forest in southeastern Brazil. *Neotropical entomology*, *39*, 198-206. https://doi.org/10.1590/S1519-566X2010000200009

Pedro, L., Perera-Fernández, L. G., López-Gallego, E., Pérez-Marcos, M., Sanchez, J. A. (2020). The effect of cover crops on the biodiversity and abundance of ground-dwelling arthropods in a Mediterranean pear orchard. *Agronomy*, 10(4), 580. <https://doi.org/10.3390/agronomy10040580>

Potapov, A. M., Goncharov, A. A., Semenina, E. E., Korotkevich, A. Y., Tsurikov, S. M., Rozanova, O. L., Anichkin A. E., Zuev, A. G., Samoylova, E. S., Semenyuk I. I., Yevdokimov, I. V., Tiunov, A. V. (2017). Arthropods in the subsoil: Abundance and vertical distribution as related to soil organic matter, microbial biomass and plant roots. *European Journal of Soil Biology*, 82, 88-97. <https://doi.org/10.1016/j.ejsobi.2017.09.001>

Prasad, S., Malav, L. C., Choudhary, J., Kannojiya, S., Kundu, M., Kumar, S., Yadav, A. N. (2021). Soil microbiomes for healthy nutrient recycling. In: Yadav, A. N., Singh, C., Yadav, N. (Eds.), Current trends in microbial biotechnology for sustainable agriculture. pp. 1-21. Springer, Singapore. <https://doi.org/10.1007/978-981-15-6949-4>

Prescott, C. E. (2005). Decomposition and mineralization of nutrients from litter and humus. In: BassiriRad, H. (Ed.), Nutrient acquisition by plants (pp. 15-41). Springer, Berlin, Heidelberg. <https://doi.org/10.1007/3-540-27675-0>

Pressler, Y., Moore, J. C., Cotrufo, M. F. (2018). Belowground community responses to fire: meta‐analysis reveals contrasting responses of soil microorganisms and mesofauna. *Oikos*, 128(3), 309-327. <https://doi.org/10.1111/oik.05738>

Price, P. W., Diniz, I. R., Morais, H. C., Marques, E. S. A. (1995). The abundance of insect herbivore species in the tropics: the high local richness of rare species. *Biotropica*, 27, 468-478. <https://doi.org/10.2307/2388960>

Queiroz, A., Rabello, A. M., Lasmar, C. J., Cuissi, R. G., Canedo-Júnior, E. O., Schmidt, F. A., Ribas, C. R. (2021). Diaspore Removal by Ants Does Not Reflect the Same Patterns of Ant Assemblages in Mining and Rehabilitation Areas. *Neotropical Entomology*, 50, 335-348. <https://doi.org/10.1007/s13744-021-00861-7>

R Development Core Team. (2020). R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. <https://www.R-project.org>

Rafael, J. A., Melo, G. A. R, de Carvalho, C. J. B., Casari, A. S., Constantino, R. (2012). Insetos do Brasil: Diversidade e Taxonomia. Holos Editora, Ribeirão Preto.

Rasband, W. S. (2006). ImageJ. US National Institutes of Health. <http://rsb.info.nih.gov/ij>

Real, R., Vargas, J. M. (1996). The probabilistic basis of Jaccard's index of similarity. *Systematic Biology*, 45(3), 380-385. <https://doi.org/10.2307/2413572>

Ribeiro-Neto, J. D., Arnan, X., Tabarelli, M., Leal, I., R. (2016). Chronic anthropogenic disturbance causes homogenization of plant and ant communities in the Brazilian Caatinga. *Biodiversity Conservation*, 25, 943–956. <https://doi.org/10.1007/s10531-016-1099-5>

Roberts, D. W. (2019). Labdsv: Ordination and multivariate analysis for Ecology. R. package version 2.0-1. [http://cran.r-project.org/package=labdsv](http://cran.r-project.org/package=labdsv" \t "_blank)

Rodrigues, R. R., Lima, R. A., Gandolfi, S., Nave, A. G. (2009). On the restoration of high diversity forests: 30 years of experience in the Brazilian Atlantic Forest. *Biological Conservation*, 142(6), 1242-1251. <https://doi.org/10.1016/j.biocon.2008.12.008>

Sáenz-Romo, M. G., Veas-Bernal, A., Martinez-Garcia, H., Campos-Herrera, R., Ibanez-Pascual, S., Martinez-Villar, E., Pérez-Moreno, I., Marco-Mancebón, V. S. (2019). Ground cover management in a Mediterranean vineyard: Impact on insect abundance and diversity. *Agriculture, Ecosystems & Environment*, 283, 106571. <https://doi.org/10.1016/j.agee.2019.106571>

Sanabria, C., Lavelle, P., Fonte., S. J. (2014). Ants as indicators of soil-based ecosystem service in agroecosystems of the Colombian Llanos. *Applied Soil Ecology*, 84, 24–30. <https://doi.org/10.1016/j.apsoil.2014.07.001>

Santos, O. S. H., Avellar, F. C., Alves, M., Trindade, R. C., Menezes, M. B., Ferreira, M. C., França, G. S., Cordeiro, J., Sobreira, F. G., Yoshida, I. M., Moura, P. M., Baptista, M. B., Scotti, M. R. (2019). Understanding the environmental impact of a mine dam rupture in Brazil: Prospects for remediation. *Journal of Environmental Quality*, 48(2), 439-449. <https://doi.org/10.2134/jeq2018.04.0168>

Schowalter, T. D. (2000). Insect ecology: an ecosystem approach. Academic Press, San Diego, California, 483p. <https://doi.org/10.1086/590579>

Scoriza, R. N., Pereira, M. G., Pereira, G. H. A., Machado, D. L., Silva, E. M. R. (2017). Métodos para coleta e análise de serrapilheira aplicados à ciclagem de nutrientes. Série Técnica Floresta e Ambiente, 2, 1-18. <https://app.periodikos.com.br/article/587fb8330e8825696bb65ffe/pdf/stfloram-2-1.pdf>

Segura, F. R., Nunes, E. A., Paniz, F. P., Paulelli, A. C. C., Rodrigues, G. B., Braga, G. U. L., Filho, W. R. P., Barbosa, F., Cerchiaro, G., Silva, F. F., Batista, B. L. (2016). Potential risks of the residue from Samarco's mine dam burst (Bento Rodrigues, Brazil). *Environmental Pollution*, 218, 813-825. <https://doi.org/10.1016/j.envpol.2016.08.005>

Silva, A. C., Cavalcante., C. D., Fabris, J. D., Júnior, R. F., Barral, U. M., Farnezi, M. M. M., Viana, A. J. S., Ardisson, J. D., Fernandez-Outon, L. E., Lara, L. R. S., Stumpf, H. O., Barbosa, J. B. S., da Silva, L. C. (2016). Características químicas, mineralógicas e físicas do material acumulado em terraços fluviais, originado do fluxo de lama proveniente do rompimento de barragem de rejeitos de mineração de ferro em Bento Rodrigues, Minas Gerais, Brasil. *Revista Espinhaço|* UFVJM, 44-53. <https://doi.org/10.5281/zenodo.3957942>

Southwood, T. R. E., Moran, V. C., Kennedy, C. E. J. (1982). The richness, abundance and biomass of the arthropod communities on trees. *The Journal of Animal Ecology*, 635-649. <https://doi.org/10.2307/3988>

St John, M. G., Bagatto, G., Behan-Pelletier, V., Lindquist, E. E., Shorthouse, J. D., Smith, I. M. (2002). Mite (Acari) colonization of vegetated mine tailings near Sudbury, Ontario, Canada. *Plant and Soil*, 245(2), 295-305. <https://doi.org/10.1023/A:1020453912401>

Stašiov, S., Litavský, J., Majzlan, O., Svitok, M., Fedor, P. (2021). Influence of Selected Environmental Parameters on Rove Beetle (Coleoptera: Staphylinidae) Communities in Central European Floodplain Forests. *Wetlands*, 41, 1-13. <https://doi.org/10.1007/s13157-021-01496-5>

Stein, A., Gerstner, K., Kreft, H. (2014). Environmental heterogeneity as a universal River of species richness across taxa, biomes and spatial scales. *Ecology Letters*, 17(7), 866-880. <https://doi.org/10.1111/ele.12277>

Sun, W., Ji, B., Khoso, S. A., Tang, H., Liu, R., Wang, L., Hu, Y. (2018). An extensive review on restoration technologies for mining tailings. *Environmental Science and Pollution Research*, 25(34), 33911-33925. <https://doi.org/10.1007/s11356-018-3423-y>

Symonds, M. R., Moussalli, A. (2011). A brief guide to model selection, multimodel inference and model averaging in behavioural ecology using Akaike’s information criterion. Behavioral Ecology and Sociobiology, 65(1), 13-21. <https://doi.org/10.1007/s00265-010-1037-6>

Teixeira, P. C., Donagemma, G. K., Fontana, A., Teixeira, W. G. (2017). Manual de métodos de análise de solo. <https://ainfo.cnptia.embrapa.br/digital/bitstream/item/194786/1/Pt-5-Cap-1-Micromorfologia-do-solo.pdf>

Termo de Transação e Ajustamento de Conduta (TTAC) entre União/Estados de MG e ES/Samarco/Vale/BHP. p. 137 (2016). Disponível em: http://www.ibama.gov.br/cif. Acesso em: 15 de mar 2021.

Vance, E. D., Brookes, P. C., Jenkinson, D. S. (1987). An extraction method for measuring soil microbial biomass C. *Soil biology and Biochemistry* 19, 703-707. <https://doi.org/10.1016/0038-0717(87)90052-6>

Vogel, H. F., J. B. Campos, F. C. Bechara. (2015). Early bird assemblages under different subtropical forest restoration strategies in Brazil: Passive, nucleation and high diversity plantation. *Tropical Conservation Science,* 8: 912–939.

Wali, M. K. (1999). Ecological succession and the rehabilitation of disturbed terrestrial ecosystems. *Plant and Soil*, 213(1), 195-220. <https://doi.org/10.1023/A:1004475206351>

Walkley, A., Black, I. (1934). A. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science,* 37, 29-38.

Warton, D.I., Wright, S.T., Wang, Y. (2012). Distance-based multivariate analyses confound location and dispersion effects. *Methods in Ecology and Evolution,* 3: 89–101. <http://hdl.handle.net/10453/112721>

Weyer J., Weinberger J., Hochkirch, A. (2012). Mobility and microhabitat utilization in a flightless wetland grasshopper, *Chorthippus montanus* (Charpentier, 1825). *Journal Insect Conservation*, 16, 379–390. <https://doi.org/10.1007/s10841-011-9423-6>

Wilson, E. O. (1990). Success and dominance in ecosystems: the case of the social insects. Oldendorf/Luhe: Ecology Institute.

Wong, M. K., Guénard, B., Lewis, O. T. (2019). Trait‐based ecology of terrestrial arthropods. *Biological Reviews*, 94(3), 999-1022. <https://doi.org/10.1111/brv.12488>

Yamamoto, T., Nakagoshi, N., Touyama, Y. (2001). Ecological study of pseudoscorpion fauna in the soil organic layer in managed and abandoned secondary forests. *Ecological Research*, 16(3),593-601. <https://doi.org/10.1046/j.1440-1703.2001.00422.x>

Zanchi, C. S., Batista, É. R., Silva, A. O., Barbosa, M. V., Pinto, F. A., dos Santos, J. V., & Carneiro, M. A. C. (2021). Recovering soils affected by iron mining tailing using herbaceous species with mycorrhizal inoculation. *Water, Air, & Soil Pollution, 232,* 1-13. https://doi.org/10.1007/s11270-021-05061-y

Zettler, J. A., Taylor, M. D., Allen, C. R., Spira, T. P. (2004). Consequences of forest clear-cuts for native and nonindigenous ants (Hymenoptera: Formicidae). *Annals of the Entomological Society of America*, 97(3), 513-518. [https://doi.org/10.1603/0013-8746(2004)097[0513:COFCFN]2.0.CO;2](https://doi.org/10.1603/0013-8746(2004)097%5b0513:COFCFN%5d2.0.CO;2)

**Figure Captions**

**Figure 1:** Map with the location of the municipality of Mariana, Brazil, and the sample units in the riparian zone under restoration (RZUR) of the Gualaxo do Norte River and in the native riparian zone (NZR) of the Carmo River.

**Figure 2:** Non-metric multidimensional scaling (NMDS) representing the ordering of environmental variables with the structure of the overall arthropod community (A) and of the Formicidae (B) in the native riparian zone (NRZ) of the Carmo River and in the riparian zone under restoration (RZUR) of the North Gualaxo River. Legend: The black arrows represent the ordering of environmental variables, the purple arrows with a triangle point represent the ordering of the arthropod community of the native riparian zone of the Carmo River and the orange arrows with a round tip refer to the riparian zone undergoing river restoration Gualaxo do Norte River. Microbial respiration (MR), Microbial biomass carbon (MBC), Organic matter (OM), Litter diversity measure by Inverse Simpson Index (Litter InvD).

**Figure 3:** Estimated species richness (q0) of arthropods (without Formicidae) and (A) for Formicidae (B).

**Figure 4:** Abundance of functional groups of detritivores (A), herbivores (B), omnivores (C) and predators (D) present in the native riparian zone (NRZ) of the Carmo River and in the riparian zone under restoration (RZUR) in the Gualaxo do Norte River.