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ORIGINAL PAPER

Ecotoxicological assessment after the world's largest tailing dam collapse (Fundão dam, Mariana, Brazil): effects on oribatid mites

Andressa Cristhy Buch · Klaus Dieter Sautter · Eduardo Duarte Marques · Emmanoel Vieira Silva-Filho

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Abstract Worldwide, environmental tragedies involving mining dam ruptures have become more frequent. As occurred a few years ago in Brazil (on 5 November 2015, in Minas Gerais state) the Fundão Dam rupture released 60 million m^3 of tailings into terrestrial and aquatic ecosystems. Since then, little information on the ecotoxicity of these tailings has been disclosed. In the laboratory, the acute, chronic and bioaccumulation effects of increased Fundão tailing concentrations on oribatid mites (*Scheloribates praeincisus*) were assessed. Additionally, the bioaccumulation of 11 trace metals (Al, As, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb and Zn) and the total density of oribatid mites found in the areas contaminated by the Fundão tailings were determined. The percentages of mite survival and reproductive inhibition were higher than 60% and 80%, respectively, in all contaminated areas with the highest concentration (100% mine tailings). Field studies showed an expressive reduction in the total density of oribatids per m^{-2} (up to 54 times) in the contaminated areas compared with the reference area. Metal accumulations in the field were 5.4 and 3.2 higher (for Ni and Hg, respectively) and up to two times higher (for most metals) than those in the laboratory for 42 days. The mite responses to the Fundão tailings found in this study suggest long-term interference in their biological development. In this sense, we can conclude that the introduction of mine tailings onto soils tended to compromise the functionality of the mites in the ecosystem, which causes imbalances to cascade other organisms of the trophic web.

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A. C. Buch (✉) · E. V. Silva-Filho
Department of Environmental Geochemistry, Fluminense
Federal University, Outeiro São João Baptista, s/n.,
Centro, Niterói, RJ 24020-007, Brazil
e-mail: andressabuch@hotmail.com

K. D. Sautter
University Center Campos de Andrade, R. João
Scuissiato, 01, Santa Quitéria, Curitiba,
PR 81220-090, Brazil

E. D. Marques
CPRM - Geological Survey of Brazil, Av. Brasil, 1731,
Funcionários, Belo Horizonte 30140-002,
MG, Brazil

Graphic abstract

Keywords Bioaccumulation · Mine tailings · Mite density · *Scheloribates praeincisus* · Trace metals · Tropical soil

Introduction

The environmental impacts of mine tailings on terrestrial ecosystems are still poorly elucidated (Figueiredo et al. 2019). These tailings are often enriched in metals and affect the surrounding areas (Agnieszka et al. 2014). They might have a negative overall impact on the environment, causing changes in landscapes and ecosystems, habitat destruction, plant or animal biodiversity losses, land degradation, and soil and water pollution (Gabarrón et al. 2018). The world's greatest environmental tragedies have been associated with mining dam ruptures, such as in Aznalcóllar (Spain), Borsa (Romania) and Arizona (USA), in which adverse effects have been apparent for decades (Macklin et al. 2003; Cabrera et al. 2008; USDA 2017; Cánovas et al. 2019). Ecological and environmental impact assessments of mine tailing deposition on terrestrial ecosystems should not be restricted only to chemical evidence, such as by excessive amounts of one or more metals on soils in comparison with limits established at the national level in compliance with directives. The tailing dispositions in the environments must also be monitored due to toxicity effects to humans, animals and plants, and the potential implications for their development during life should be evaluated (Farmer 2012).

The Fundão dam rupture (in 2015) has been one of the greatest environmental tragedies recorded in recent decades in Brazil (CPRM and ANA 2015a, b; Fernandes et al. 2016). This dam, owned by Samarco Corporation, spilled over 60 million m^3 of iron ore tailings that spread down the Rio Doce River, killing 20 people and affecting biodiversity across hundreds of kilometres of river, riparian lands and Atlantic coast (IBAMA 2017). Due to the Fundão dam rupture, the regional loss of environmental services was assumed to be $\sim$ US\$521 million per year, in addition to its countless socioeconomic consequences (Garcia et al. 2017). Fundão tailings contain high contents of Fe (above 50%), SiO_2 (above 10%) and Al (above 10%) and different concentrations of trace metals such as As, Cr, Cd, Hg and Pb (Gomes et al. 2017; Pires et al. 2003). Their metal composition persists over long periods of time in the environment and may accumulate and pass from one species to the next through the food chain (Fernandes et al. 2016; do Carmo et al. 2017). Furthermore, their physical–chemical properties may make them very hazardous, e.g. by exhibiting more synergistic tendencies than antagonistic tendencies in terrestrial ecosystems, which raises future environmental concerns (Fernandes and Ribeiro 2017; Chibuike and Obiora 2014).

Currently, the toxicity of mine tailings is understudied, and information about their effects on terrestrial fauna is scarce, mainly on microarthropods (Wahl and Maboeta 2012). Edaphic mesofauna organisms such as mites and springtails represent approximately 95% of the microarthropod abundance in soils (Orgiazzi et al. 2016). Oribatid mites are the world's most abundant soil arthropods and inhabit almost all types of land use. In the organic horizons of most soils, they can be found in densities of several hundred thousand individuals per square metre (Zaitsev and Van Straalen 2001). Most species are generalists that feed on decomposing plant debris and fungi, constituting important links in the food web as decomposer organisms (Schneider et al. 2004). They also accelerate the release of elements within ecosystems either directly or indirectly by stimulating the action of soil microbes. Moreover, they significantly contribute to the formation and maintenance of soil structure (Luo et al. 2015). Thus, these organisms provide an early indication of ecosystem health and play an important role in functional ecology and associated ecosystem services (Owojori et al. 2019).

Several studies have reported that oribatid mites have a higher ability to accumulate trace metals than do other soil arthropods (Caruso et al. 2009; Skubala and Zaleski 2012). However, the levels of sensitivity and resistance are quite variable among different species of mites and dependent on a variety of factors, including microhabitat choice, mode of feeding, uptake and elimination kinetics, and biochemical strategies as well as particular morpho-physiological traits of species (Van Straalen et al. 2001; Eeva and Penttinen 2009). With respect to the sensitivity of mite species in ecotoxicological assessments, few studies have been carried out with *S. praeincisus*, most of which were related to the biological aspects or effects of genetically modified plants (Subías 2004; Oliveira et al. 2007). To date, no study of this species has been performed in polluted soils (by mine tailing and/or trace metals). Toxic effects on their behaviour, metabolism and biological development should be further understood, since it is a predominant species in tropical soils (Ferreira et al. 2012; Ermilov and Anichkin 2014). The importance of toxicity testing with indigenous species that typically inhabit soils where contamination occurs or may occur has gained recognition in risk assessment for terrestrial fauna (Kuperman et al. 2009). Different sensitivity levels of mite species to pollutants may be an excellent factor to determine the maximum permissible values of soil pollutants to ensure their quality while ensuring they remain biologically functional.

Despite the worldwide need for studies focused on environmental tragedies involving mine tailings and dams, even four years after the Fundão dam rupture, the impacts of mine tailings on the Rio Doce basin are not properly understood. In this case, the use of an ecotoxicological approach is highly necessary to understand the effects that mine mud has on organisms living and feeding there. In addition, it complements existing information to help protect the structure and functioning of terrestrial ecosystems.

The aim of this study was to assess the toxicity of Fundão tailings to soil oribatid mites. The total density of oribatid mites and the bioaccumulation of trace metals were investigated in situ, and the acute, chronic and accumulation effects were evaluated in ex situ conditions for the pantropical mite *Scheloribates praeincisus*.

Materials and methods

Study areas and sampling collection

The Fundão dam located in Mariana city (Minas Gerais state, Brazil) was situated in a very steep area (20% to 40% slope; most portions were 850–1090 m altitude) (de Souza et al. 2005). This geomorphological characteristic favoured the formation of intense tailing waves in areas with lower slopes (850–38 m altitude) after the dam ruptured (CPRM and ANA 2015a, b).

The study comprises 18 areas of the Rio Doce basin that were directly affected by the Fundão tailings spill along the 679-km stretch, between the Fundão dam and the Atlantic Ocean (Fig. 1). The geographical coordinates of the study areas and their distances from the ruptured areas of Fundão dam are available in Supplementary Material (Table S1). In addition, a

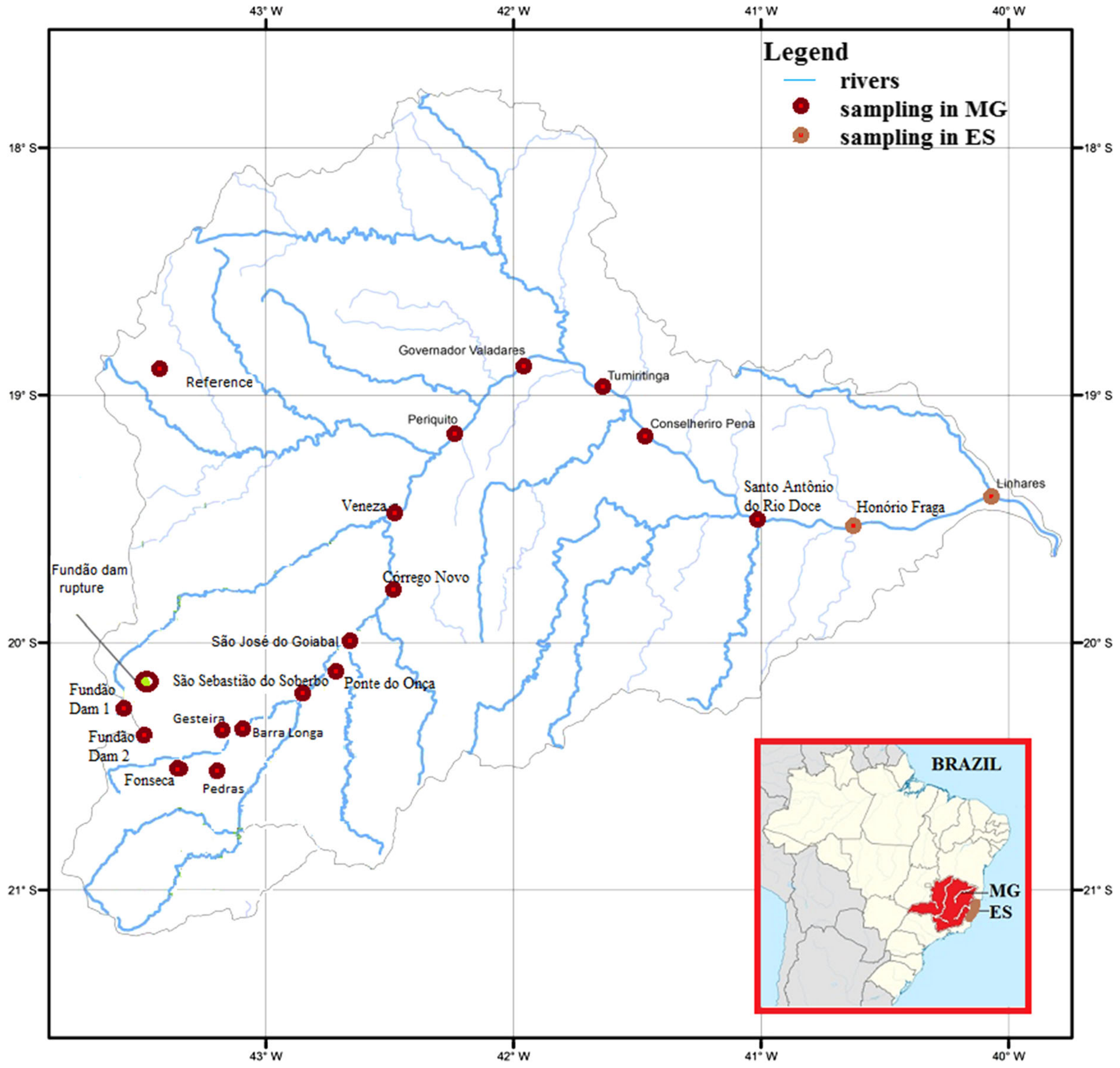


Fig. 1 Study areas affected by the Fundão dam rupture, Minas Gerais and Espírito Santo states, Brazil

reference area (RA) of native forest in Meloso (Conceição do Mato Dentro, Minas Gerais) that was unaffected by the Fundão tailings was included in the study (Table S1). In all study areas, soil samples were collected under riparian vegetation (when present). This vegetation type received a higher volume of Fundão tailings (Sánchez et al. 2018). In each area, four samples from ten subsamples (0–10 cm of depth) were collected with the aid of a flat hand shovel from a representative grid (20 × 20 m). The first sampling occurred between 7 and 17 days after the dam rupture in November 2015, and the second sampling occurred in October 2018. The soil physical and chemical properties were analysed according to analytical procedures recommended by EMBRAPA (2011). The soil physicochemical characterizations of the 19 study areas are shown in Table 1.

Trace metal determinations were carried out by inductively coupled plasma–mass spectrometry (ICP-MS) for Al, As, Cd, Cu, Cr, Fe, Pb, Mn, Ni and Zn according to USEPA (1994, 2001) and by atomic absorption spectrometry using cold vapour

Table 1 Soil physicochemical characterization of 19 study areas after the Fundão dam rupture (Mariana, Brazil)

Site	PS										
	CEC		Bulk density		pH KCl		Coarse sand	Fine sand	Silt	Clay	Texture
	cmolc dm^3		g cm^{-3}				%				
	2015	2018	2015	2018	2015	2018	2015				
RA	6.09 ± 0.1	6.15 ± 0.2	1.07 ± 0.4	0.98 ± 0.1	4.13 ± 0.2	4.09 ± 0.4	0.08 ± 0.04	0.24 ± 0.02	0.10 ± 0.03	0.58 ± 0.04	Clay
FD1	2.43 ± 0.8	2.76 ± 0.1	2.32 ± 0.4	2.18 ± 0.1	6.17 ± 0.4	6.22 ± 0.3	0.15 ± 0.02	0.38 ± 0.01	0.29 ± 0.04	0.18 ± 0.02	Loam
FD2	2.54 ± 0.2	2.87 ± 0.4	2.29 ± 0.8	2.12 ± 0.2	6.27 ± 0.2	6.18 ± 0.4	0.22 ± 0.01	0.30 ± 0.04	0.34 ± 0.01	0.14 ± 0.01	Loam
F	2.76 ± 0.8	3.12 ± 0.7	2.10 ± 0.7	1.98 ± 0.3	6.30 ± 0.3	6.33 ± 0.5	0.26 ± 0.02	0.30 ± 0.03	0.31 ± 0.03	0.13 ± 0.02	Loam
Pe	2.65 ± 0.2	2.91 ± 0.1	1.92 ± 0.2	1.91 ± 0.2	5.98 ± 0.2	5.93 ± 0.4	0.11 ± 0.0,5	0.27 ± 0.02	0.45 ± 0.02	0.17 ± 0.01	Loam
Ges	3.05 ± 0.2	3.07 ± 0.1	2.01 ± 0.9	2.08 ± 0.4	6.07 ± 0.4	6.02 ± 0.3	0.16 ± 0.01	0.32 ± 0.03	0.29 ± 0.03	0.23 ± 0.04	Loam
PO	2.89 ± 0.4	2.83 ± 0.9	1.90 ± 0.3	1.74 ± 0.9	5.87 ± 0.2	5.92 ± 0.3	0.14 ± 0.02	0.30 ± 0.01	0.33 ± 0.01	0.23 ± 0.02	Loam
BL	2.91 ± 0.3	2.94 ± 0.2	1.91 ± 0.6	1.82 ± 0.2	5.99 ± 0.1	5.87 ± 0.2	0.14 ± 0.03	0.33 ± 0.03	0.38 ± 0.03	0.15 ± 0.03	Loam
SSS	2.96 ± 0.2	3.05 ± 0.1	1.85 ± 0.4	1.62 ± 0.5	6.23 ± 0.3	6.28 ± 0.1	0.15 ± 0.02	0.33 ± 0.01	0.27 ± 0.01	0.25 ± 0.04	Sandy clay loam
SJG	2.99 ± 0.5	2.86 ± 0.2	1.72 ± 0.5	1.59 ± 0.1	6.25 ± 0.8	6.18 ± 0.5	0.15 ± 0.01	0.36 ± 0.02	0.18 ± 0.02	0.31 ± 0.05	Sandy clay loam
CN	3.12 ± 0.2	3.08 ± 0.3	2.23 ± 0.5	2.17 ± 0.8	5.89 ± 0.1	5.89 ± 0.4	0.23 ± 0.0	0.45 ± 0.05	0.17 ± 0.03	0.15 ± 0.03	Sandy loam
V	2.61 ± 0.3	2.79 ± 0.7	1.82 ± 0.1	1.49 ± 0.6	6.03 ± 0.2	6.13 ± 0.4	0.28 ± 0.5	0.42 ± 0.04	0.19 ± 0.01	0.11 ± 0.02	Loamy sand
Per	2.87 ± 0.1	3.04 ± 0.1	1.87 ± 0.5	1.62 ± 0.1	6.05 ± 0.2	5.98 ± 0.4	0.20 ± 0.02	0.50 ± 0.05	0.22 ± 0.01	0.08 ± 0.01	Loamy sand
GV	2.62 ± 1.0	2.89 ± 0.4	1.72 ± 0.2	1.70 ± 0.3	6.24 ± 0.7	6.21 ± 0.4	0.24 ± 0.01	0.50 ± 0.06	0.14 ± 0.02	0.12 ± 0.01	Loamy sand
Tum	3.72 ± 0.2	3.29 ± 0.9	1.77 ± 0.3	1.79 ± 0.9	6.33 ± 0.1	6.37 ± 0.5	0.18 ± 0.03	0.31 ± 0.04	0.23 ± 0.03	0.28 ± 0.03	Sandy clay loam
CP	2.56 ± 0.4	2.12 ± 0.8	1.63 ± 0.7	1.56 ± 0.1	6.07 ± 0.1	6.14 ± 0.6	0.17 ± 0.02	0.34 ± 0.01	0.27 ± 0.02	0.22 ± 0.02	Sandy clay loam
SARD	2.98 ± 0.4	3.99 ± 0.4	1.69 ± 0.5	1.61 ± 0.3	5.93 ± 0.4	5.85 ± 0.6	0.26 ± 0.04	0.45 ± 0.03	0.19 ± 0.03	0.10 ± 0.01	Loamy sand
HF	2.61 ± 0.3	2.66 ± 0.2	1.61 ± 0.4	1.65 ± 0.1	6.21 ± 0.4	6.28 ± 0.3	0.24 ± 0.3	0.50 ± 0.02	0.17 ± 0.01	0.09 ± 0.01	Loamy sand
L	3.01 ± 0.9	3.02 ± 0.1	1.63 ± 0.2	1.69 ± 0.4	5.60 ± 0.1	5.69 ± 0.6	0.21 ± 0.01	0.53 ± 0.02	0.15 ± 0.1	0.11 ± 0.01	Loamy sand

Means and standard deviations of five replicates

RA Reference area, *FD1* Fundão dam 1, *FD2* Fundão dam 2, *F* Fonseca, *Pe* Pedras, *Ges* Gesteira, *PO* Ponte do Onça, *BL* Barra Longa, *SSS* São Sebastião do Soberbo, *SJG* São José do Goiabal, *CN* Córrego Novo, *V* Veneza, *Per* Periquito, *GV* Governador Valadares, *Tum* Tumiritinga, *CP* Conselheiro Pena, *SARD* Santo Antônio do Rio Doce, *HF* Honório Fraga, *L* Linhares atomization for Hg according to USEPA (1986). Quality control was certified by São Joaquim 2709 reference material provided by the National Institute of Standards and Technology-NIST (U.S. Department of Commerce), and the results indicate a satisfactory recovery ranging from 85 to 97%. Trace metal concentrations are given in Table 2.

Ecotoxicological assessments—ex situ

Test species

The soil mite *Scheloribates praeincisus* (Berlese 1910) (Acari: Oribatida, Scheloribatidae) was used in the ecotoxicological assessments of mine tailings. This pantropical species is commonly abundant and representative in tropical forest soils (Subías 2004; Oliveira et al. 2005, 2017; Ferreira et al. 2012) and in agroecosystems (Oliveira et al. 2001; Simões et al. 2008). The species was obtained from the soil and litter of the Atlantic Forest of south-eastern Brazil and extracted using the Tullgren method. Specimens were cultured in the laboratory in Petri dishes with a layer of moist plaster of Paris mixed with activated charcoal 8:1, weight/weight (ISO 1999). Mites were kept in the laboratory at 20 °C ± 2 °C with a photoperiod of 12:12 h light:dark for up to 4 months prior to the experiments. Cultures were kept moistened with deionized water, and a small amount of biological dry yeast (*Saccharomyces cerevisiae*) was provided as a food source once per week.

Ecotoxicity tests

All toxicity tests were composed of five treatments of different tailing concentrations (dilution mixture), which consisted of the mixture of a natural soil (from RA) with the test soil (from the 18 areas contaminated by mine tailings). For each test soil, there were combinations of dilution mixtures, which were equivalent to 0% (only RA), 25%, 50%, 75% and 100% of the mine tailing concentrations. All treatments had five replicates. For effective comparisons between uncontaminated soils, tropical artificial soil (TAS) was adopted as a control treatment. The TAS was prepared following OECD guidelines (2016) and adapted according to Garcia (2004); specifically, the TAS was composed of 75% fine sand (washed and dried), 20% kaolin clay and 5% coir dust (dried at 60 °C), the latter representing the organic fraction, replacing the *Sphagnum* peat used in artificial soil for temperate regions. When necessary, the TAS pH value was adjusted to 6.0 ± 0.5 with calcium carbonate ($CaCO_3$).

Acute and chronic tests were performed for 14 days and 35 days, respectively, and they were based on OECD guidelines (2016). The bioaccumulation tests were carried out for 42 days. All assessments were performed in cylindrical glass containers (10 cm diameter and 8 cm height) filled with 10 g dry mass of each test soil (from 19 areas). All containers were covered with parafilm and placed into incubators. The containers were aerated twice per week, and in this period, the moisture content was adjusted by monitoring the weight.

For toxicity expositions, adults of *S. praeincisus* (approx. 5 weeks old) from synchronized cultures (25 specimens in bioaccumulation tests and 10 specimens in acute and chronic tests) were used, which were transferred into each replicate test container with the aid of a stereomicroscope. In the acute and bioaccumulation tests, only adult males were exposed to a range of tailing concentrations mixed into the soil. In contrast, in the chronic exposure experiments, only females were introduced. All exposures were kept in the laboratory at 20 °C ± 2 °C with a photoperiod of 12:12 h light:dark. For each test container, a small amount of 2 mg of biological dry yeast (*S. cerevisiae*) was offered to the mites at the beginning of the acute and chronic tests and every 14 days in the bioaccumulation tests.

At the end of the tests, the number of surviving mites and the number of juveniles in each test container were counted 48 h after extraction with a modified Berlese–Tullgren apparatus at ± 45 °C (Aquino and Correia 2006).

Metal accumulation assessments on mites were carried out following the same analytical procedure described above for soil samples from the 18 contaminated areas (at 100% mine tailing concentration, i.e. undiluted test soils). A group of 50 surviving specimens was used in the analysis of metals, and the samples were pooled together and weighed three times to establish an accurate weight. For each treatment evaluated, the mites were dried and digested with concentrated nitric acid (7:1 by volume, Suprapur grade, Merck) and diluted with distilled and deionized H_2O. The bioaccumulation factor (BAF) was

Table 2 Metal concentrations (n = 5) in soils of the 19 areas affected by the Fundão dam rupture (Mariana, Brazil)

Site	Al		As		Cd		Cr		Cu		Fe		Hg		Mn		Ni		Pb		Zn	
	g kg^{-1}		mg kg^{-1}		mg kg^{-1}		mg kg^{-1}		mg kg^{-1}		g kg^{-1}		mg kg^{-1}		mg kg^{-1}		mg kg^{-1}		mg kg^{-1}		mg kg^{-1}	
	2015	2018	2015	2018	2015	2018	2015	2018	2015	2018	2015	2018	2015	2018	2015	2018	2015	2018	2015	2018	2015	2018
RA	64.0	58.0	0.2	0.2	0.3	0.2	1.0	0.90	11.0	11.0	36.0	28.0	0.1	0.1	108.0	81.0	0.4	0.7	0.1	0.2	7.9	5.4
FD1	310.0	280.0	10.0	9.3	1.0	1.0	24.0	23.0	30.7	28.2	450.0	420.0	0.3	0.4	847.0	801.0	9.2	8.4	7.8	6.9	19.0	18.0
FD2	280.0	270.0	8.1	7.0	0.7	0.5	19.0	19.0	28.9	22.5	410.0	370.0	0.3	0.2	371.0	218.0	5.9	4.9	5.1	4.3	24.0	24.0
F	210.0	220.0	8.0	7.7	0.5	0.3	16.0	15.0	15.1	12.4	105.0	80.0	0.2	0.2	189.0	209.0	2.2	1.7	3.1	3.5	18.0	16.0
Pe	190.0	170.0	7.4	6.9	0.4	0.3	13.0	11.0	11.3	10.3	250.0	240.0	0.4	0.3	450.0	432.0	1.4	2.5	4.7	4.1	18.0	14.0
Ges	120.0	100.0	6.8	6.8	0.5	0.5	15.0	13.0	8.1	7.9	250.0	270.0	0.3	0.2	328.0	314.0	1.5	1.5	4.5	4.8	15.0	12.0
PO	140.0	150.0	4.5	4.1	0.5	0.3	8.0	7.0	12.9	9.0	144.0	110.0	0.1	0.1	243.0	226.0	1.5	1.8	2.2	2.1	13.0	15.0
BL	190.0	210.0	7.9	7.1	0.7	0.5	15.0	12.0	7.2	6.1	200.0	170.0	0.4	0.3	391.0	407.0	1.5	0.9	4.9	4.3	18.0	16.0
SSS	140.0	120.0	6.3	5.4	0.8	0.5	11.0	10.0	7.1	5.5	340.0	360.0	0.2	0.2	232.0	215.0	1.5	1.8	2.9	2.5	15.0	14.0
SJG	140.0	130.0	12.0	11.0	0.7	0.4	32.0	30.0	11.4	10.4	320.0	330.0	0.3	0.2	772.0	722.0	3.3	3.0	6.3	6.2	27.0	24.0
CN	290.0	260.0	16.0	15.0	0.9	0.7	39.0	37.0	29.2	30.2	400.0	410.0	0.4	0.2	1179.0	1162.0	11.8	10.3	9.4	10.3	28.0	27.0
V	160.0	150.0	15.0	13.0	0.6	0.4	36.0	34.0	26.9	25.1	190.0	210.0	0.2	0.2	1050.0	1032.0	10.9	9.5	8.7	9.3	26.0	24.0
Per	180.0	170.0	18.0	16.0	0.8	0.7	57.0	55.0	32.4	30.8	149.0	132.0	0.3	0.3	1291.0	1301.0	16.3	14.9	20.9	21.3	52.0	52.0
GV	330.0	330.0	43.0	41.0	1.1	0.8	103.0	98.0	57.7	59.3	350.0	380.0	0.4	0.3	2933.0	3093.0	27.1	23.9	28.0	27.3	89.0	92.0
Tum	280.0	250.0	29.0	26.0	0.9	0.7	84.0	81.0	44.9	39.1	246.0	212.0	0.4	0.3	1786.0	1602.0	22.4	20.6	21.0	20.1	76.0	77.0
CP	140.0	120.0	11.0	10.0	0.4	0.4	30.0	28.0	17.4	17.0	51.0	63.0	0.1	0.1	413.0	402.0	9.1	8.5	8.4	7.2	24.0	22.0
SARD	120.0	110.0	13.0	13.0	0.6	0.6	12.0	9.0	6.6	4.6	11.3	18.0	0.1	0.0	118.0	107.1	3.5	3.9	3.8	3.1	7.0	20.8
HF	126.0	120.0	29.0	28.5	0.3	0.6	33.0	29.0	15.0	15.0	137.6	82.0	0.1	0.1	182.7	165.5	6.6	6.0	8.1	7.8	17.2	17.6
L	130.0	90.0	34.0	32.0	0.4	0.6	27.0	25.0	16.0	12.0	102.1	87.0	0.0	0.0	238.0	207.0	5.6	5.1	5.6	4.9	18.0	17.0
DL	0.001		0.01		0.0007		0.006		0.003		0.04		0.02		0.0015		0.02		0.01		0.01	

DL is the detection limit referring to the metal values analysed. For Al, Mn and Fe, no target values are established

RA Reference area, *FD1* Fundão dam 1, *FD2* Fundão dam 2, *F* Fonseca, *Pe* Pedras, *Ges* Gesteira, *PO* Ponte do Onça, *BL* Barra Longa, *SSS* São Sebastião do Soberbo, *SJG* São José do Goiabal, *CN* Córrego Novo, *V* Veneza, *Per* Periquito, *GV* Governador Valadares, *Tum* Tumiritinga, *CP* Conselheiro Pena, *SARD* Santo Antônio do Rio Doce, *HF* Honório Fraga, *L* Linhares calculated as the Ca/Cs ratio, where Ca is the metal concentration in surviving mites and Cs is the total metal concentration in the test soil.

Ecotoxicological assessments—in situ

For this study, the same RA and 10 other contaminated areas (FD1, FD2, Ges, BL, SSS, SJG, CN, V, GV and Tum) were assessed (previously described in Sect. 2.1). These 10 areas received higher Fundão tailing volumes (CPRM and ANA 2015b; Sánchez et al. 2018) and the highest chemical presence of heavy metals (Table 2). In the 11 sampling areas, five random topsoil samples (0–20 cm depth) were collected using a 5-cm-diameter corer. Sampling was carried out in October 2018 from a representative area (20 m × 20 m) of each site. Mites were separated from the soil using the Tulgren method.

In the field, the mine tailing ecotoxicity on mites was assessed by mite total density and metal bioaccumulation. The total density of oribatid mites was expressed as the number of individuals per m^2 in each area. The organisms extracted for heavy metal determinations were preserved in a mixture of water and glycerol with the addition of alcohol (approximately 5%) and kept in a refrigerator to avoid evaporation and micro-organism development. All oribatid mites found in the contaminated areas were analysed. (The species were not identified or separated by stage of development.) The bioaccumulation analysis of Al, As, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb and Zn concentrations in mites, as well as the estimation of BAF values from study areas, was performed according to the ex situ study (previously described).

Statistical analysis

The effect concentrations (ECs) causing 10%, 50% and 90% of responses in acute and chronic tests in mites were estimated in their respective tests. Lethal concentration (LC) was estimated by regression techniques such as logistic regression functions and probit analysis using the PriProbit® programme version 1.5. EC values for reproduction were calculated using nonlinear regressions.

The lowest observed effect concentration (LOEC) was defined as the concentration that was significantly different from the control. The no observed effect concentration (NOEC) was defined as the highest test concentration that did not produce a statistically significant adverse effect on reproduction when compared to the control. The LOEC and NOEC values from the individual tests were obtained by performing analysis of variance (ANOVA) and then by comparing the mean number of juveniles from each test tailing concentration with the control using Dunnett's test at the $p < 0.05$ level (software Minitab® 17.1).

Results

Ecotoxicological assessments—ex situ

At the end of the toxicity tests (acute and chronic), the mean adult mortality per replicate in each test treatment was < 10% for the control soil and < 16% for the reference soil. These percentages fulfilled the validity criteria established by the OECD (2016).

After 14 days of acute exposure, the responses of *S. praeincisus* adults in the different mine tailing concentrations were similar among the 18 test soils (from contaminated areas). This result suggested a tendency for an increase in mortality in accordance with the increase in the tailing concentration. For all areas affected by the tailing spill, the survival of *S. praeincisus* adults was higher than 50% in all tested concentrations (Fig. 2a, b; Table 3). The LC_{50} values > 100% tailing concentrations indicated a low toxicity effect in the short term (Table 3). Although the mortality was slightly lower in 2018, there was no significant difference between treatments for the 2015 test soils. The highest values of mortality at 100% tailing concentration (undiluted test soils) were found in the GV, Per and Tum areas, with values of 46%, 44% and 42% for 2015 (Fig. 2a) and 44%, 40% and 38% for 2018, respectively (Fig. 2b). Additionally, higher mite mortalities were noted in the areas nearest to the ruptured areas of Fundão dam, such as the FD1 (40% and 38%), FD2 (38% and 36%), F (34% and 36%) and Pe (36% and 34%) areas (for the 2015 and 2018 sampling years, respectively) (Fig. 1a, b). The lowest lethal concentration causing a 10% effect (LC_{10}) on mites was observed at 43%, 39.7% and 36.5% tailing concentrations in the areas of CN, GV and Tum, respectively (for the 2015 sampling year), and in the V, Per, GV and Tum areas with values of 44.1%, 43.9%, 39.3% and 36.2% tailing concentrations, respectively (for the 2018 sampling year)

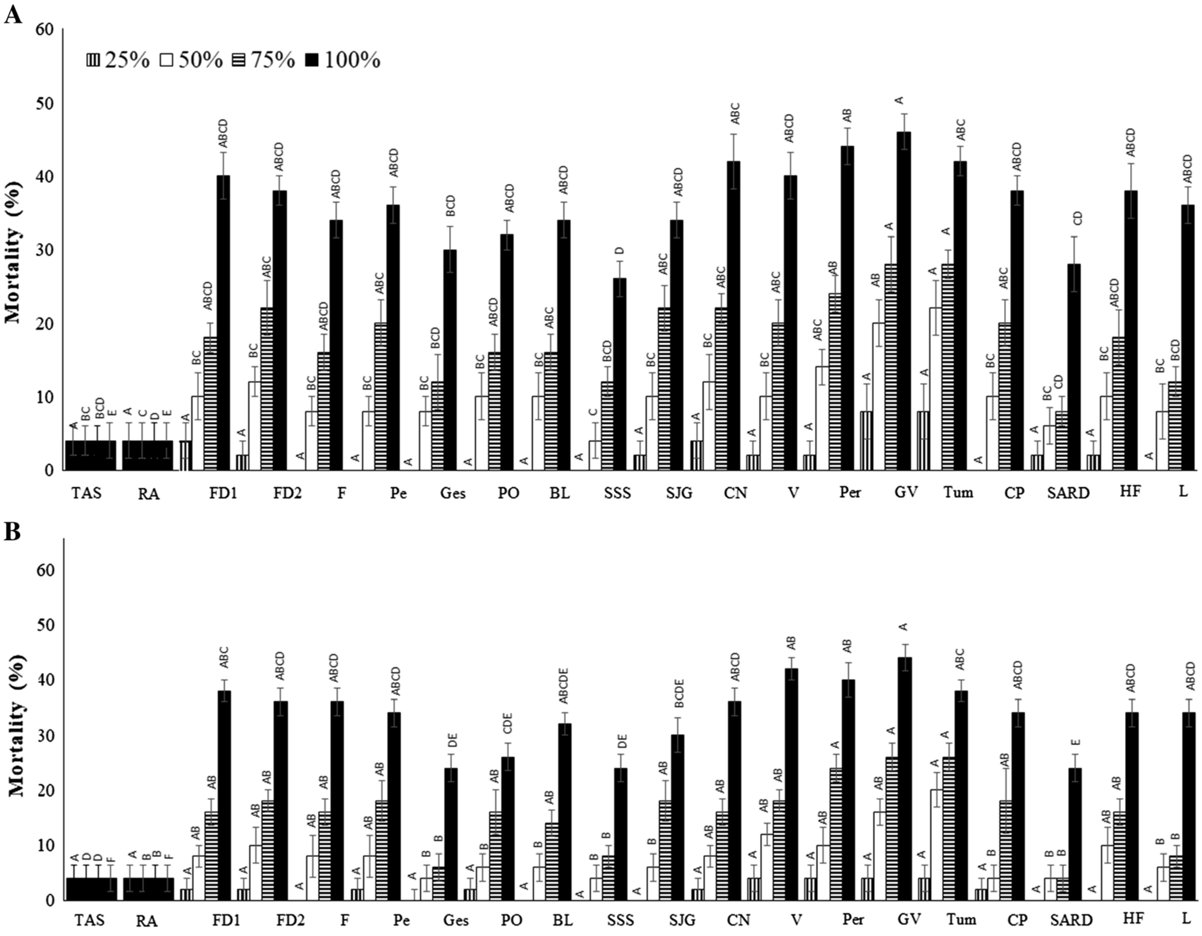


Fig. 2 Acute responses of *Scheloribates praeincisus* mites in nineteen test soils. **a**, **b** Represent soil sampling years: **a** 2015 and **b** 2018

(Table 3). For most areas, the NOEC and LOEC values were from the 50% and 75% tailing concentrations, respectively (Table 3). The highest survival (> 75%) was noted in the SSS, SARD and Ges areas at 100% mine tailing concentration (Fig. 2).

Reproduction was a more sensitive endpoint than the acute test to assess Fundão tailing toxicity on mites. Moreover, the same tendency noted in the acute mite responses was evidenced in the chronic tests, for which the increase in reproductive inhibition followed the increase in Fundão tailing concentration in soil (Fig. 3a, b). In turn, the highest reproductive inhibitions of *S. praeincisus* were not associated with the areas closest to where the Fundão dam breaking occurred (Fig. 3a, b). At the end of the chronic test, the mean number of *S. praeincisus* juveniles was ≅ 210 and 226 specimens in the control and reference treatments, respectively (Fig. 3a, b), for the test soils sampled in 2015. In all test soils contaminated at ≥ 50% tailing concentrations, a number of juvenile mites ≤ 176 was observed (Fig. 3). In terms of the number of juvenile mites, there were no significant differences between the 2015 and 2018 sampling years (Fig. 3a, b). A decrease in reproduction was noted in test soils from the Tum, Gv, Per and CN areas at 100% tailing concentration, revealing a mean juvenile number of *S. praeincisus* < 10, thus differing statistically from other areas. The highest mean values of reproductive inhibition were found in the FD1, FD2 and F areas, with 54, 62 and 80 juvenile mites, respectively. This result is in contrast to that observed in the areas farthest from the areas where the Fundão dam rupture occurred, with juvenile counts of 90, 86 and 95 in the PO, SSS and SARD areas, respectively. Reproductive inhibitions ≥ 90% *S. praeincisus* were noted at ≤ 100% tailing concentrations, mainly in the GV

Table 3 Lethal concentrations (LCs) causing 10%, 50% and 90% responses in oribatid mites (*Scheloribates praeincisus*) observed in acute tests

Site	Mortality 2015					Mortality 2018				
	LC_{10}	LC_{50}	LC_{90}	NOEC	LOEC	LC_{10}	LC_{50}	LC_{90}	NOEC	LOEC
FD1	56.92 (53.32–58.46)	> 100	> 100	50	75	65.31 (64.12–56.39)	> 100	> 100	50	75
FD2	55.13 (52.44–57.21)	> 100	> 100	25	50	60.50 (59.19–62.79)	> 100	> 100	50	75
F	63.65 (61.39–64.78)	> 100	> 100	25	50	63.40 (62.19–64.96)	> 100	> 100	50	75
Pe	60.72 (60.28–62.16)	> 100	> 100	50	75	63.47 (62.45–64.43)	> 100	> 100	50	75
Ges	67.84 (53.32–58.46)	> 100	> 100	50	75	74.95 (73.09–75.87)	> 100	> 100	75	100
PO	61.61 (59.98–62.74)	> 100	> 100	25	50	69.59 (67.92–71.56)	> 100	> 100	50	75
BL	61.22 (59.48–63.15)	> 100	> 100	25	50	68.30 (67.26–69.63)	> 100	> 100	50	75
SSS	68.97 (66.98–69.58)	> 100	> 100	50	75	73.12 (72.34–74.61)	> 100	> 100	50	75
SJG	57.70 (56.74–58.35)	> 100	> 100	50	75	65.36 (64.12–66.73)	> 100	> 100	50	75
CN	42.98 (41.82–44.58)	> 100	> 100	50	75	65.26 (64.23–66.49)	> 100	> 100	50	75
V	59.07 (57.85–61.13)	> 100	> 100	50	75	44.13 (43.23–45.98)	> 100	> 100	25	50
Per	52.00 (51.55–53.19)	> 100	> 100	25	50	43.92 (41.87–45.21)	> 100	> 100	50	75
GV	39.70 (37.64–41.34)	> 100	> 100	50	75	39.29 (37.76–41.14)	> 100	> 100	25	50
Tum	36.58 (35.37–37.68)	> 100	> 100	25	50	36.19 (34.67–37.43)	> 100	> 100	25	50
CP	58.30 (57.15–59.73)	> 100	> 100	25	50	56.81 (53.61–57.79)	> 100	> 100	50	75
SARD	84.18 (83.68–85.93)	> 100	> 100	75	100	76.87 (64.12–56.39)	> 100	> 100	75	100
HF	60.49 (58.928–61.86)	> 100	> 100	50	75	56.71 (55.87–58.97)	> 100	> 100	50	75
L	66.84 (65.74–68.28)	> 100	> 100	50	75	66.45 (64.71–68.96)	> 100	> 100	50	75

LCx values were expressed in % of mining tailings, and their interval represents upper and lower limits, corresponding to 95% confidence limits

FD1 Fundão dam 1, *FD2* Fundão dam 2, *F* Fonseca, *Pe* Pedras, *Ges* Gesteira, *PO* Ponte do Onça, *BL* Barra Longa, *SSS* São Sebastião do Soberbo, *SJG* São José do Goiabal, *CN* Córrego Novo, *V* Veneza, *Per* Periquito, *GV* Governador Valadares, *Tum* Tumiritinga, *CP* Conselheiro Pena, *SARD* Santo Antônio do Rio Doce, *HF* Honório Fraga, *L* Linhares

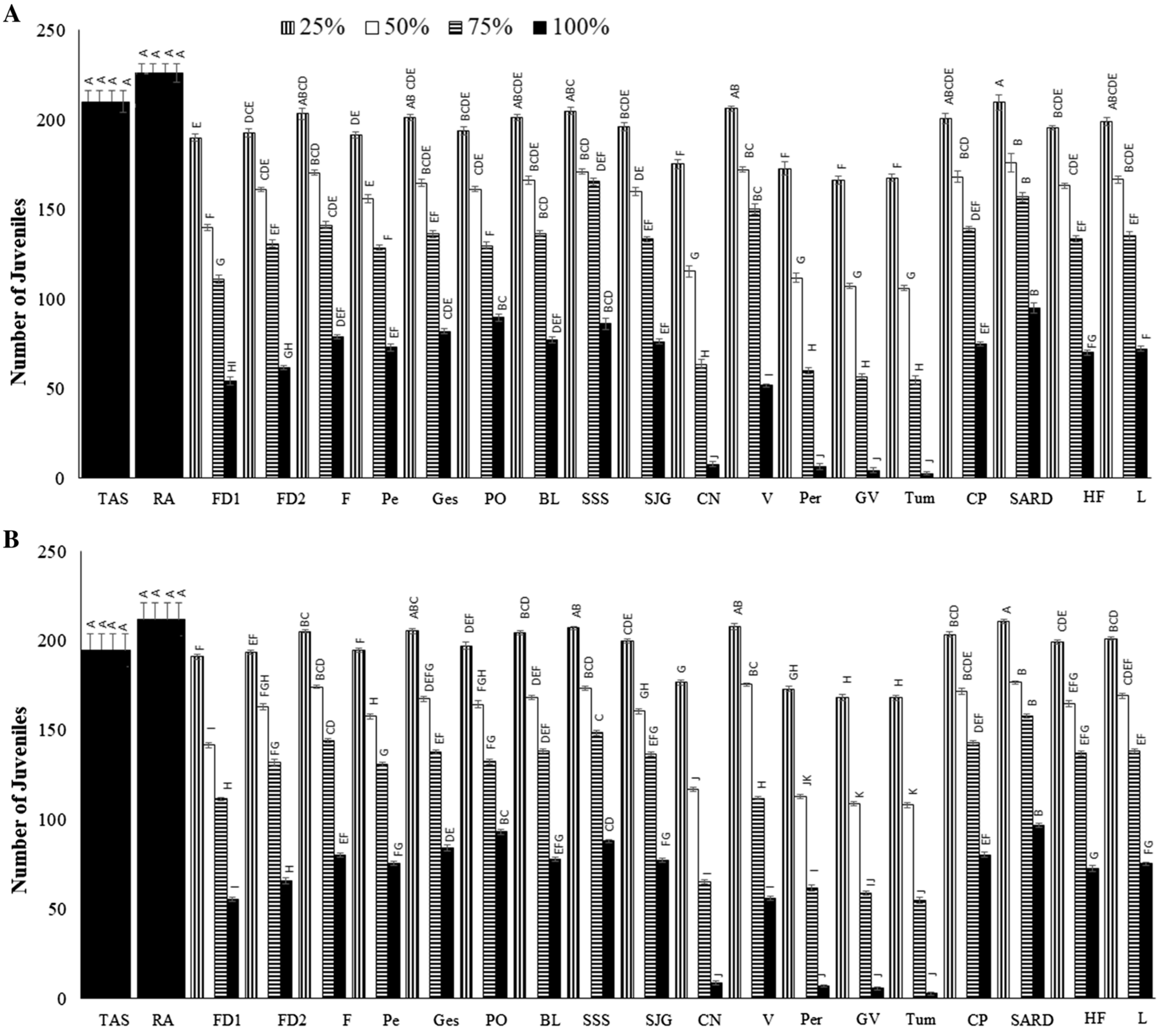


Fig. 3 Chronic responses of *Scheloribates praeincisus* mites in nineteen test soils. **a**, **b** Represent soil sampling years: **a** 2015 and **b** 2018

and Tum areas (Table 4). The lowest EC_{10} values were noted in the areas of CN: 19.6% and 29.9%; Per: 22.2% and 28.2%; GV: 20.8% and 26%; and Tum: 21.5% and 26% tailing concentration (for the 2015 and 2018 sampling years, respectively) (Table 4). In all areas, the NOEC and LOEC values were from the 25% and 50% tailing concentrations, respectively (Table 4).

For the 18 test soils (undiluted) at 100% tailing concentration, the values of accumulated metals in *S. praeincisus* mites were as follows: Cd > As > Pb > Cu > Cr > Hg > Ni > Zn > Mn and Al > Fe, after 42 days (Fig. 4). The BAF values of *S. praeincisus* ranged from 0.56 to 0.9 for Al, 0.32 to 0.8 for Fe, 1.0 to 1.2 for Mn and 0.5 to 1.4 for Zn (Fig. 4a). For Cu, Cr and Ni, the BAF values ranged from 1.3 to 3.0, 1.0 to 2.6 and 0.8 to 1.7, respectively (Fig. 4b). For As, Cd, Hg and Pb, the BAF values ranged from 1.7 to 4.7, 2.9 to 7.5, 1.2 to 2.2 and 1.7 to 4.4, respectively (Fig. 4c). Although apparent higher metal accumulation in mites was noted in the test soils sampled in 2015, for most investigated areas, there were no significant differences between the 2015 and 2018 sampling years. In the reference area, the trace metal accumulations showed BAF values ≤ 1.3 in mites (Fig. 4). In general, the metal bioaccumulation in *S. praeincisus*

Table 4 Effect concentrations (ECs) causing 10%, 50% and 90% responses in oribatid mites (*Scheloribates praeincisus*) observed in chronic tests

Site	Reproduction 2015					Reproduction 2018				
	EC_{10}	EC_{50}	EC_{90}	NOEC	LOEC	EC_{10}	EC_{50}	EC_{90}	NOEC	LOEC
FD1	27.28 (26.56–28.74)	69.71 (67.58–71.41)	> 100	25	50	40.16 (38.39–43.63)	76.95 (72.21–79.18)	> 100	25	50
FD2	31.53 (29.45–32.64)	79.44 (78.16–81.49)	> 100	25	50	48.81 (45.74–51.37)	87.10 (80.34–94.53)	> 100	25	50
F	39.23 (37.61–41.94)	89.01 (85.73–94.63)	> 100	25	50	54.56 (53.32–58.46)	94.77 (88.91–99.88)	> 100	25	50
Pe	28.59 (53.32–58.46)	82.42 (76.95–87.61)	> 100	25	50	46.14 (43.12–47.97)	89.95 (82.51–94.62)	> 100	25	50
Ges	36.43 (35.01–38.52)	88.61 (83.87–94.31)	> 100	25	50	50.47 (48.32–52.72)	94.73 (88.74–99.78)	> 100	25	50
PO	29.79 (28.19–31.57)	91.76 (84.73–98.32)	> 100	25	50	47.73 (45.14–49.76)	97.57 (72.43–102.56)	> 100	25	50
BL	36.62 (35.96–38.29)	86.96 (81.69–91.54)	> 100	25	50	50.67 (49.71–52.63)	92.45 (87.69–97.48)	> 100	25	50
SSS	39.04 (37.64–41.94)	83.75 (78.63–89.71)	> 100	25	50	55.01 (53.32–58.46)	98.84 (93.91–104.73)	> 100	25	50
SJG	36.18 (34.64–38.63)	67.88 (61.39–73.14)	> 100	25	50	47.44 (48.93–49.10)	92.24 (86.76–98.32)	> 100	25	50
CN	19.61 (17.31–21.71)	54.36 (50.38–58.73)	> 100	25	50	29.90 (28.96–31.42)	55.51 (49.27–59–28)	> 100	25	50
V	43.25 (41.16–45.09)	82.55 (77.69–88.85)	> 100	25	50	52.08 (50.21–54.19)	81.83 (76.43–87.48)	> 100	25	50
Per	22.24 (20.35–23.87)	47.55 (42.93–52.16)	> 100	25	50	28.20 (27.64–29.79)	53.45 (49.48–57.64)	> 100	25	50
GV	20.79 (18.75–22.39)	45.34 (39.86–49.76)	98.87 (91.37–107.91)	25	50	26.09 (25.19–28.35)	51.29 (46.34–56.77)	> 100	25	50
Tum	21.46 (19.59–23.78)	45.55 (39.38–50.27)	96.65 (89.05–104.39)	25	50	26.29 (25.14–28.09)	50.64 (44.92–55.67)	97.55 (89.45–109.83)	25	50
CP	37.30 (35.74–39.24)	87.03 (81.29–92.39)	> 100	25	50	53.26 (51.49–55.67)	94.44 (88.75–99.34)	> 100	25	50
SARD	47.87 (53.32–58.46)	97.20 (91.14–99.01)	> 100	25	50	59.07 (58.19–61.36)	> 100	> 100	25	50
HF	32.73 (30.84–33.97)	83.74 (78.18–87.76)	> 100	25	50	49.23 (47.92–51.42)	90.24 (84.69–97.98)	> 100	25	50
L	35.80 (33.63–38.76)	85.46 (80.19–91.27)	> 100	25	50	51.63 (50.03–52.76)	91.77 (86.83–98.39)	> 100	25	50

ECx values were expressed in % of mining tailings and their interval represents upper and lower limits, corresponding to 95% confidence limits

FD1 Fundão dam 1, *FD2* Fundão dam 2, *F* Fonseca, *Pe* Pedras, *Ges* Gesteira, *PO* Ponte do Onça, *BL* Barra Longa, *SSS* São Sebastião do Soberbo, *SJG* São José do Goiabal, *CN* Córrego Novo, *V* Veneza, *Per* Periquito, *GV* Governador Valadares, *Tum* Tumiritinga, *CP* Conselheiro Pena, *SARD* Santo Antônio do Rio Doce, *HF* Honório Fraga, *L* Linhares mites was quite homogeneous for most contaminated areas, with the exception of the GV, Tum, CP, V, CN, FD1, FD2, F and Per areas, which tended to accumulate more metals (Fig. 4). The Mn, Al and Fe accumulations had a more uniform distribution along the sample gradient, showing low variability between the areas.

Ecotoxicological assessments—in situ

Field studies indicated a mean total density of 1268 oribatid mites m^{-2} ($\geq$ 250 µm) in the reference area. Comparatively, this area showed a higher mean density than that found in contaminated areas, for which the total number of individuals did not exceed 300 oribatid specimens per m^2 at each sampling area (Table 5). Along the sample gradient, the GV, Tum and FD1 areas showed the lowest mean total density values (23, 25 and 26 oribatid mites m^{-2}, respectively), followed by the FD2 and CN areas (52 and 53 oribatid mites m^{-2}, respectively). On the other hand, the highest mean total density values were 298 and 255 oribatid mites m^{-2}, which were found in the V and BL areas, respectively.

Field assessments indicated the following metal accumulation sequence in oribatid mites: Cd > As > Pb > Ni > Hg > Cr > Cu > Zn > Mn > Al > Fe (Fig. 5). For most metals, the BAF values were higher under in situ assessments than those found in ex situ assays, with the exception of the BAF values of Al, Fe and Mn. The BAF values of Al, Fe and Mn were quite similar among the contaminated areas, ranging from 1.0 to 1.1 (Al), 0.8 to 1.0 (Fe) and 1.0 to 1.6 (Mn); however, the BAF values were significantly higher than those in the reference area (0.6 (Al), 0.5 (Fe) and 0.76 (Mn)) (Fig. 5a). In general, for Cr, Cu and Ni, the lowest BAFs were observed in areas closest to where the Fundão dam broke areas, and the highest BAFs were found in areas that presented higher contents of these metals in the soils (Fig. 5b). For As, Cd and Pb, the BAF values followed a higher bioaccumulation in the GV > Tum > V > FD1 > FD2 > SJG and CN > Ges > BL > SSS > RA areas (Fig. 5c). Among these areas, low variability between the BAFs was noted for Hg, which had the highest bioaccumulation in the GV and Tum areas (Fig. 5). Despite the low Cd and Hg concentrations in soils in most areas contaminated by mine tailings, these metals were bioaccumulated in oribatid mites up to fourteen and seven times higher, respectively, in the field than in laboratory conditions (Fig. 5c).

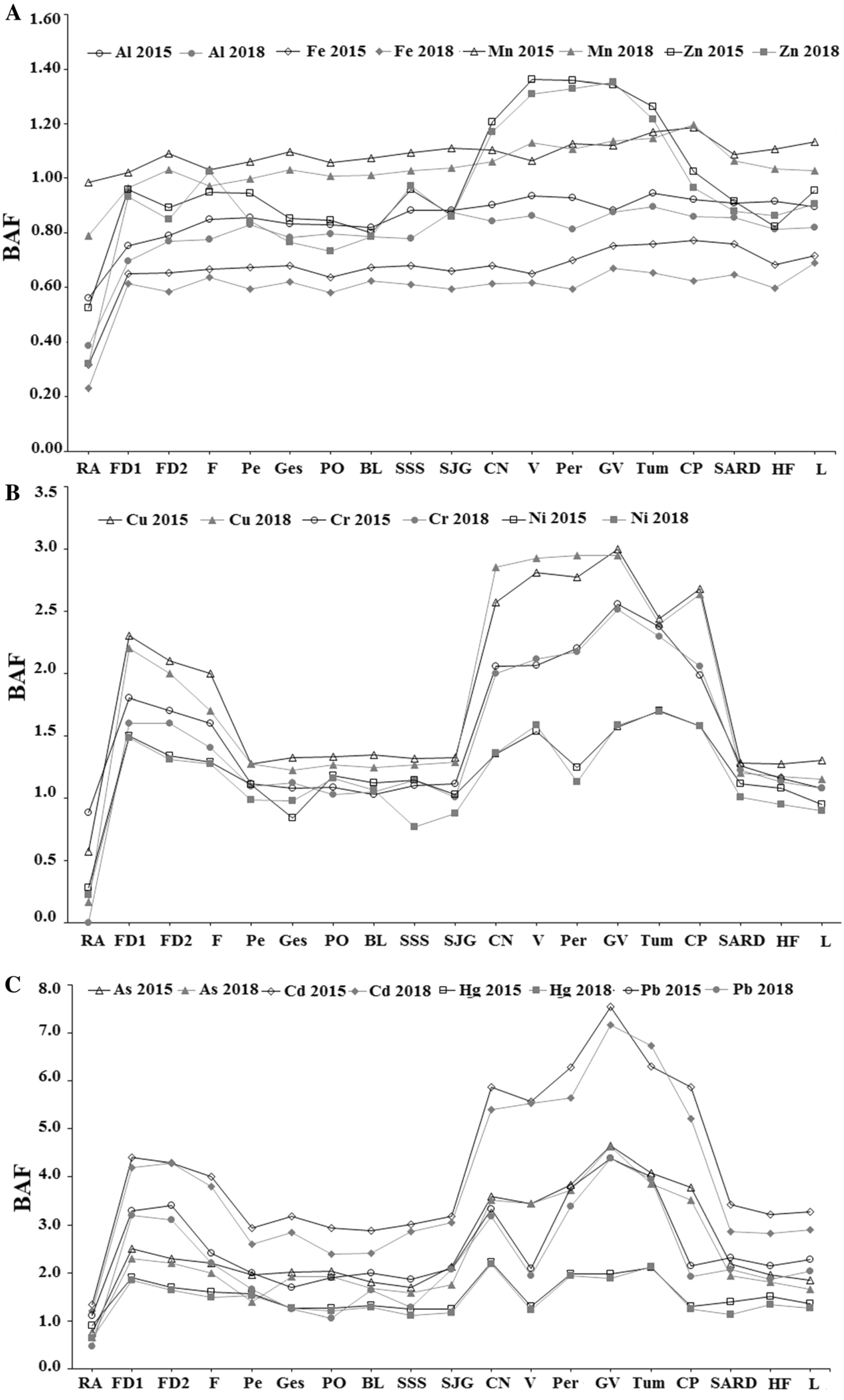
Discussion

Apparently, the Fundão tailings did not have significant short-term effects, as noted in the acute responses of *S. praeincisus*. This condition in the presence of mine tailing for soil mites has not been scientifically reported. Due to the predominance of a great mixture of trace metals in the composition of this tailing type, the literature provides several reports of their long-term effects on organisms (which will be discussed subsequently). We emphasize that trace metals have silent and cumulative effects on oribatid mites. This result does not mean that tailing do not negatively influence their behaviour and biological development (as noted in the chronic responses). Because of these findings, we can assume that in areas contaminated by mine tailings the selection of species and/or taxonomic groups that are more adapted or resistant may occur, reflecting their abundance, diversity and mainly their functionality to the environment.

The highest acute and chronic effects of Fundão tailings on *S. praencisus* may be associated with physical–chemical characterization of the tested contaminated soils, given that the highest mortalities were observed, e.g. in the FD1 and FD2 areas of higher bulk density, and in areas that presented higher metal concentrations, such as the GV and Tum areas. Previous studies have attributed the highest metal concentrations in these areas to a combination effect caused by the Fundão tailings and the intensive mining activities that have occurred in these regions since the 1930s (Maxine 2013).

Similar abilities to accumulate metals have been noted in species of the same genus, e.g. the bioaccumulation factors of Cd, Cu, Pb and Zn in *S. praeincisus* showed BAFs of 7.5, 3.0, 4.5 and 1.4, respectively (in the present study), while *Scheloribates laevigatus* (Koch) had BAFs of 7.8, 1.41, 4.76 and 1.31, respectively, according to El-Sharabasy and Ibrahim (2010). However, opposite responses in oribatid species that are closely related taxonomically can also be expected, mainly in iron accumulation, as noted by Zaitsev and Van Straalen (2001).

This study evidenced similar trends of metal accumulation in mine tailings to those reported in


A
Al 2015
Al 2018
Fe 2015
Fe 2018
Mn 2015
Mn 2018
Zn 2015
Zn 2018
BAF
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
RA FD1 FD2 F Pe Ges PO BL SSS SJG CN V Per GV Tum CP SARD HF L
B
Cu 2015
Cu 2018
Cr 2015
Cr 2018
Ni 2015
Ni 2018
BAF
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
RA FD1 FD2 F Pe Ges PO BL SSS SJG CN V Per GV Tum CP SARD HF L
C
As 2015
As 2018
Cd 2015
Cd 2018
Hg 2015
Hg 2018
Pb 2015
Pb 2018
BAF
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
RA FD1 FD2 F Pe Ges PO BL SSS SJG CN V Per GV Tum CP SARD HF L

◀**Fig. 4** Ex situ assessment. Bioaccumulation factors of eleven trace metals in *Scheloribates praeincisus* mites from nineteen test soils, for the 2015 and 2018 soil sampling years

Table 5 Total mite density sampled in situ

Area	Ind. m^{-2}
Reference	1268.2 (± 77.67)
Fundão site 1	26.4 (± 8.92)*
Fundão site 2	52.4 (± 1 3.54)*
Gesteira	170.4 (± 13.16)*
Barra Longa	254.8 (± 15.32)*
São Sebastião do Soberbo	80.2 (± 20.87)*
São José do Goiabal	138.8 (± 10.60)*
Córrego Novo	53.2 (± 15.00)*
Veneza	298.4 (± 14.27)*
Governador Valadares	23.2 (± 7.26)*
Tumiritinga	24.6 (± 8.35)*

Values are means and standard error ($n = 5$)

Asterisks (*) indicate significant differences in mite density between reference and contaminated areas ($p < 0.05$, Dunnett's test)

other studies with oribatids, even under the influence of different abiotic and biotic factors (Zaitsev and Van Straalen 2001; El-Sharabasy and Ibrahim 2010). The oribatid ability to accumulate high metal concentrations without dying may be associated with different detoxification strategies, such as by permanently storing metals in insoluble granules within the digestive tract (Ludwig et al. 1992; Lebrun and Van Straalen 1995). Oribatid life cycles can be another attenuating aspect of metal bioaccumulation and toxicity. Classically, oribatids have six distinct morphological stages, each separated by a moult. The prelarvae usually have an inactive and short-lived state. The larva, protonymph, deutonymph, tritonymph and adults are active and free living. However, each stage has an inactive period: the pre-ecdysial resting stage (Lebrun and Van Straalen 1995). This inactive time allows oribatid mites to accumulate high metal concentrations in their cuticle/tissue and, after that, to eliminate through moulting with no short-term interference, especially in relation to the survival of these organisms (Kratzmann et al. 1993). Detoxification strategies of trace metals allow the animal to survive, but they require much energy (Van Straalen et al. 1989).

The ability to accumulate metals was not associated with the feeding habits of ten oribatid species, mainly for Cu, Cd, Pb and Fe accumulations (Zaitsev and Van Straalen 2001). However, there was a strong relation to Zn accumulation in phytophage and mycophage mites (Zaitsev and Van Straalen 2001). Fungi tend to accumulate more Zn in fungal cell content than in cell walls, and it is an essential element for their development (Khan et al. 2000).

Among the metals investigated in this study, Cd accumulated the most in mites ($BAF = 7.5$ ex situ and $BAF = 13.2$ in situ), even though Cd was found at low concentrations in the evaluated soils. This relation between Cd concentrations in soils and mites was also noted by El-Sharabasy and Ibrahim (2010), but with expressive variability in the bioaccumulation factors (from 0.79 to 25.92) for the four oribatid species tested. According to the Agency for Toxic Substances and Disease Registry (ATSDR), Cd is the seventh most toxic element, being a non-essential element to organisms; it affects the enzymatic systems of cells and stimulates oxidative stress and nutritional deficiency in plants (Patrick 2003; Irfan et al. 2013). The effects and mechanism of Cd toxicity are not understood clearly, but its effects on cells are known in invertebrates (Patrick 2003). Its concentration may be increased 3000 fold when it binds to cysteine-rich proteins such as metallothionein. Relating this element in the food web, the chemical complexation of Cd may induce hepatotoxicity and nephrotoxicity. In addition, it has the ability to bind with cysteine, glutamate, histidine and aspartate ligands, leading to iron deficiency (Castagnetto et al. 2002; Jaishankar et al. 2014). In food assessments, green algae (*Protococcus* sp.) contaminated at ≥ 247 mg Cd kg^{-1} soil indicated significant reductions in fertility and growth of *Archegozetes longisetosus* (tropical parthenogenetic oribatid), and it increased their mortality and the developmental time of their offspring (Seniczak and Seniczak 2002).

In this study (in the laboratory and the field), As and Pb were also highly accumulated in mites. In living organisms, As is a protoplastic poison since it primarily affects the sulphhydryl group of cells, causing malfunctioning of cell respiration, cell enzymes and mitosis (Jaishankar et al. 2014). The effects of As on mites are still poorly understood. With

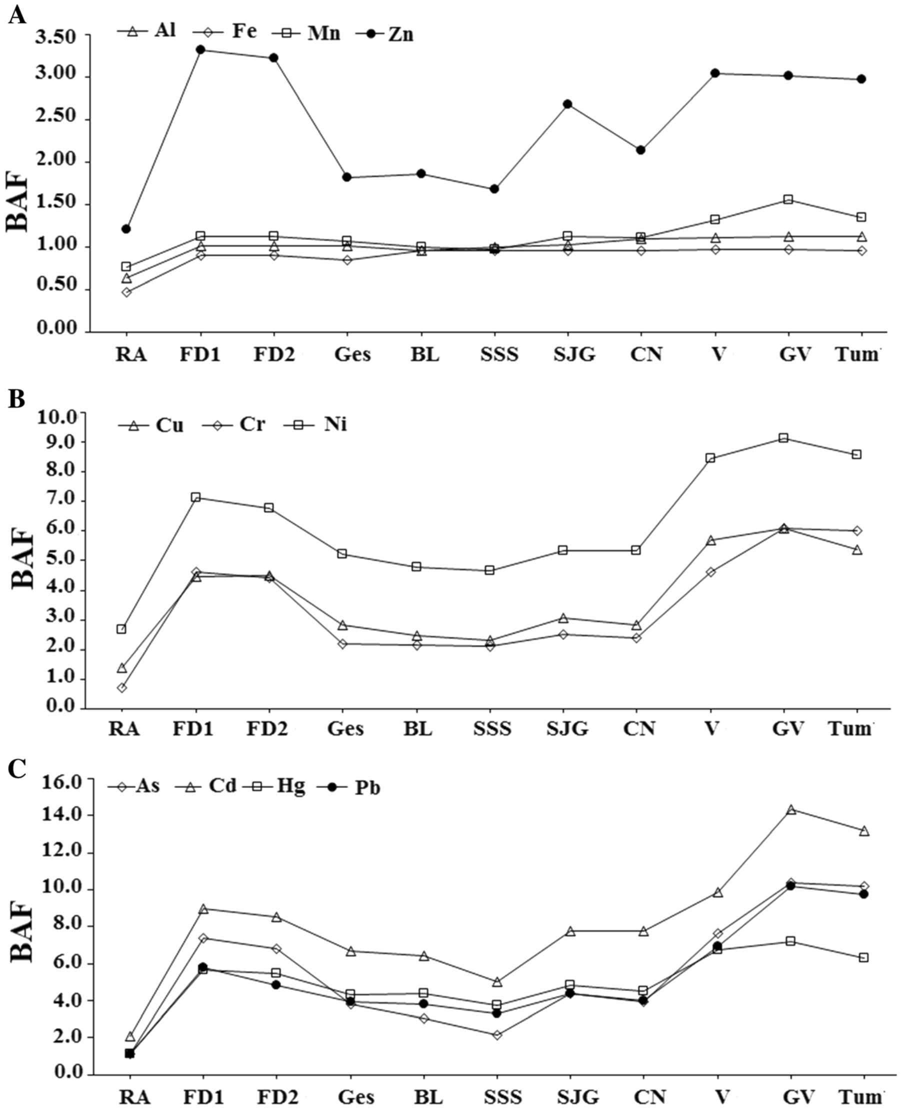


Fig. 5 In situ assessment. Bioaccumulation factors of eleven trace metals in *Scheloribates praeincisus* mites from nineteen test soils for the 2015 and 2018 soil sampling years

respect to Pb accumulations in mites, wide differences between species have been observed (BAF values for Pb ranged from 1.4 to 6.4), possibly diverging due their food strategies (Zaitsev and Van Straalen 2001; El-Sharabasy and Ibrahim 2010). *Platynothrus peltifer* seems more tolerant to Pb exposure in soils than other oribatid species (Luo et al. 2015).

Cu in oribatids has been described as a persistent accumulator element (Skubala and Kafel 2004). Zaitsev and Van Straalen (2001) showed little variation in Cu accumulation for among ten oribatid species. In a variety of soil invertebrates, such as snails, isopods and arachnids, the Cu concentrations may be used in haemocyanins to transport oxygen (El-Sharabasy and Ibrahim 2010). However, for oribatids, high Cu concentrations may indicate the presence of other substances capable of accumulating copper or may indicate this element has a crucial role in their metabolism, since the mites do not possess haemocyanin.

The lowest BAF values for Fe and Al found in mites (in this study) may be justified by the low absorption of these elements through the intestinal walls or by the fast excretion of oribatids (Janssen and Hogervorst

1993). Few metals can be removed through elimination functions, while most investigated metals tend to accumulate in the body and food chain, exhibiting chronic toxicity. According to Zaitsev and Van Straalen (2001), mites tend to accumulate Zn and Fe more intensively in non-contaminated areas because they need Zn and Fe for their metabolism.

The bioaccumulation in the field was five times higher than that in the laboratory for the 42-day experiments. This difference can be related to the longer exposure time to contaminants in situ conditions, as observed by Buch et al. (2017b). Although in the field assessments have not been possible to estimate how long the bioaccumulation of metals in soils has been occurring, the incontestable fact is that the presence of them in soils may lead to various adverse effects in the biological development of soil-living communities. Metal concentrations in soils lead to increased toxicity through the food web in terrestrial fauna due to biomagnification processes and to synergistic interactions caused by chemical changes (compounds or species). For example, Hg, through different environmental factors and interactions between soil organisms, can lead to methylation, potentiating its toxicity and availability in soils (Buch et al. 2016, 2017a, b, 2018).

Our field results showed a mean oribatid density of $\cong$ 1268 individuals m^{-2} in the reference area, while studies in Amazon forest soils have reported densities of 1800 oribatids m^{-2} (Moraes et al. 2011) and from 3157 to 7340 mites m^{-2} (Franklin et al. 2001). Many studies have shown that the composition of oribatid communities in soils polluted by heavy metals can be negatively influenced. Jamshidian et al. (2015) observed diversity reductions in areas polluted with high Zn and Cd concentrations, but no effect with any Cu concentrations. Moreover, these authors also evidenced no relationship between the metal levels on soils and the total density of oribatids, showing populations from 25,000 to 30,000 individuals m^{-2}. On the other hand, El-Sharabasy and Ibrahim (2010) reported the smallest total density of oribatid mites (from 3024 to 659 individuals m^{-2}) in soils impacted by high Cd, Cu, Pb and Zn concentrations. Some researchers have noted that the total oribatid density was often non-responsive, due to considerable inter-species differences in sensitivity. With an increasing metal load in the soil, sensitive species may be replaced by resistant species without changing the total number of mites (Skubala and Kafel 2004). In this study, the Fundão tailing toxicity to mites was associated with their characteristics, mainly with respect to metal composition. In the laboratory, the test soils that presented higher toxicity to *S. praeincisus* were those sampled in the areas with a higher indicated metal presence. Furthermore, the same influence was noted in field assessments (in accumulations and mite density fluctuations). Despite the complex interaction between abiotic and biotic factors in terrestrial environments contaminated by tailings, some studies have reported similar influences on the abundance and diversity of mites, e.g. in areas contaminated by mine tailings (Frouz et al. 2008) and by cyanide-laced tailings (high Pb, Zn and Cu concentrations on soils), where just one oribatid mite species was found (*Oppiella uliginosa*) (Feketeová et al. 2016). Caruso et al. (2009) reported that other spatially variable factors, such as feeding habits and macrofauna reductions, may also affect oribatid assemblages, which may be indirectly influenced by metals. It seems obvious to have a significantly higher mite abundance in reference areas (uncontaminated areas) than in areas polluted by metals, as evidenced in many studies (Seniczak et al. 1997; Frouz et al. 2008; Manu et al. 2017; McAdams et al. 2018); however, by variable abiotic factors (e.g. temperature, particular soil parameters), the opposite can also often be found (Skubala and Zaleski 2012; Franklin et al. 2013). Some studies have suggested that the total density of oribatid mites on soil will rarely be reduced to zero or to the existence of a single mite species (Khalil et al. 2009). In general, the mite behaviour to avoid soil layers that present metals is not expected due to slow dispersal capacity (Janssen et al. 1990; Minor 2011).

Conclusion

From the present study, it can be concluded that mine tailings spilled on riparian soils may affect the life development of oribatid mites, mainly due to chronic toxicity. The evidence of a higher metal bioaccumulation in oribatids in the field than that in the laboratory can indicate the cumulative influence over time (at least three years of elapsed time after the Fundão dam rupture). In the case of terrestrial ecosystem contamination by rupture of mine tailing dams, the particularity of the actions to be taken will undoubtedly be based on the tailings composition and, above all, the chemical composition and metal combined concentrations because each metal acts differently on different types of organisms, as discussed in this study.

Therefore, we stress the need for research on ecological risk assessments that provide ecotoxicological studies with other taxonomic orders of soil fauna. Inadequate management of mine tailings is an equal problem impacting sites worldwide.

This study reinforces the urgency of efforts in decision-making by responsible players in the Fundão dam tragedy and by supervisory state agencies to try to minimize, mitigate or reclaim environmental damage from tailing spills that compromise soil quality and human, animal and environmental health.

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Compliance with ethical standards

Ethical approval All applicable international, national and/or institutional guidelines for the care and use of animals were followed.

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