JOHN CHIDI HARRIMAN

IMPACT OF THE MARIANA'S IRON ORE TAILINGS SPILL UPON COCKROACH (BLATTODEA) COMMUNITIES OF RIPARIAN FORESTS IN THE DOCE RIVER BASIN, BRAZIL

Dissertation submitted to the Entomology Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Magister Scientiae*.

Adviser: Carlos Frankl Sperber
Co-adviser: Thiago Gechel Kloss

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To God, my parents and my wife

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To God for his protection over my life and for seeing me through in this wonderful journey.To him, I give all the praise.

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A person who has never made a mistake has never tried anything new.

(Albert Einstein)

ABSTRACT

JOHN, Chidi Harriman, M.Sc., Universidade Federal de Viçosa, June, 2023. **Impact of the Mariana's iron ore tailings spill upon cockroach (blattodea) communities of riparian forests in the Doce River Basin, Brazil.** Advisor: Carlos Frankl Sperber. Co-advisor: Thiago Gechel Kloss.

In 2015, several thousand kilograms of iron ore mine tailings were discharged in the ecosystem, launched by the collapse of the Fundão dam in Mariana. This tailing buried villages, vegetation and animals and then moved over 800 km along the Doce River, causing ecological catastrophe on municipal councils it directly impacted. The activities of arthropods, such as nutrient cycling and decomposition that contribute to the functioning of ecosystems, might, thus, be compromised. This anthropogenic disturbance is speculated to influence the diversity of biotic communities. The impact of ecosystem degradation from the tailings are still unknown seven years after this disaster. We investigated the assumption that the abundance and the diversity of cockroaches decreased in areas that got in contact with the tailings' flush along the Doce River's channel. We also evaluated eventual covariates, such as distance to the river and amount of litter. We selected five locations along the Doce River basin including: Mariana, Rio Casca, Ipatinga, Conselheiro Pena, and Aimorés, all in Minas Gerais State, Brazil. We chose two(2) areas in each of these five regions; affected and unaffected. To test our hypothesis, we used analyses of co-variance (ANCOVA), adjusting generalized linear mixed models (GLMMs) with the following explanatory variables: affected or unaffected and its interaction with distance to the river, litter weight and litter heterogeneity, and distance to the origin of the disaster. These models were adjusted for: cockroach communities' abundance, diversity and evenness. We also evaluated if the tailings' passage alter cockroach species composition. There was a significant interaction effect between the affected x unaffected areas and distance to the origin of the disaster (Chi=5.1447, df=1, p=0.02332). In the unaffected areas, the abundance of cockroaches increased with the proximity to the origin of the disaster, as expected by an eventual dilution effect of the tailings, while in the affected areas, there was no impact of distance to origin on cockroach abundance (Chi = 0.2204; P = 0.6387). There was a substantial interaction between the treatments and other litter components (Chi= 4.8158, df = 5, p = 0.0282), which we interpret as correlated to the humus content in the litter, unto cockroach diversity, increasing with the local amount of humus in the litter. However, the increase was not significant in the affected areas. Unaffected areas had higher cockroach diversity, compared to affected areas. Cockroach diversity was higher in unaffected areas from three sampled regions (Ipatinga, Rio Casca, and Mariana), while only in our Rio Casca areas had the highest genus richness. There was a significant effect of the dilution effect (distance to the origin of the disaster) unto cockroach diversity (Chi= 4.1612, df=8, p=0.04136): in unaffected areas, cockroach communities' evenness decreased with distance from the origin of the disaster. While a non-significant decreasing trend was also found along the affected gradient which decreased as the distance from the source of the tailing decreases. A significant interaction effect exists between distance to the river and cockroach communities' evenness (Chi = 4.3381, df = 8, p = 0.03727).

Keywords: Blattaria. Iron tailings. Abundance.

RESUMO

JOHN, Chidi Harriman, M.Sc., Universidade Federal de Viçosa, junho de 2023**. Impacto do derramamento de rejeitos de minério de ferro de Mariana sobre comunidades de baratas (blattodea) de matas ciliares na Bacia do Rio Doce, Brasil.** Orientador: Carlos Frankl Sperber. Coorientador: Thiago Gechel Kloss.

Em 2015, ocorreu um desastre ambiental devido ao rompimento da barragem de Fundão, em Mariana, resultando no derramamento de toneladas de rejeitos de minério de ferro. Esses rejeitos causaram impactos devastadores, soterrando aldeias, vegetação e animais, e percorreram mais de 800 km ao longo do Rio Doce, resultando em uma catástrofe ecológica e efeitos cascata nos municípios afetados. Os artrópodes, incluindo as baratas, desempenham papéis fundamentais nas atividades de ciclagem de nutrientes, polinização, decomposição e manejo de pragas, contribuindo para a estrutura dos ecossistemas. É especulado que essa perturbação antropogênica tenha influenciado a diversidade das comunidades bióticas. Atualmente, sete anos após o desastre, o impacto da degradação do ecossistema pelos rejeitos ainda é desconhecido. Neste estudo, investigamos a hipótese de que a diversidade e abundância de baratas diminuíram nas áreas afetadas pela onda de rejeitos e questionamos se a distância da fonte dos rejeitos afetou a abundância desses insetos. Realizamos comparações entre as espécies de baratas associadas aos componentes da serapilheira. Selecionamos cinco municípios do estado de Minas Gerais para este estudo: Mariana, Rio Casca, Ipatinga, Conselheiro Pena e Aimorés. Em cada município, escolhemos um local afetado e um local de referência. Calculamos índices de diversidade de Shannon-Wiener (H'), riqueza de espécies (S) e uniformidade de Pielou (J). Todas as análises estatísticas foram realizadas no ambiente R. Nossos resultados revelaram uma interação significativa entre o distúrbio de longo prazo (afetado vs. referência) e a proximidade de curto prazo com os rejeitos (Chi=5,1447, df=1, p=0,02332). Nas áreas de referência, observou-se um aumento na abundância de baratas com a proximidade dos rejeitos, enquanto nas áreas afetadas, não houve efeito da distância sobre a abundância (Chi=0,2204; P=0,6387). Também identificamos uma interação significativa entre o tratamento (afetado vs. referência) e outros componentes da serapilheira (Chi=4,8158, df=5, p=0,0282). A riqueza de gêneros de baratas aumentou significativamente com o aumento de outros componentes da serapilheira nos locais de referência, mas esse aumento foi insignificante nos locais afetados. Os locais de referência apresentaram maior riqueza de gêneros de baratas em comparação com os locais afetados, sendo que Ipatinga, Rio Casca e Mariana foram os municípios de referência com maior riqueza de gêneros. Houve uma diferença significativa entre a equidade de baratas e a distância da fonte dos rejeitos (Chi=4,1612, df=8, p=0,04136). No gradiente de referência, o índice do gênero Pielou diminuiu significativamente com o aumento da distância da fonte de rejeitos. Observou-se uma tendência decrescente não significativa ao longo do gradiente afetado, em que a equidade diminuiu à medida que a distância da fonte de rejeitos diminuiu. Além disso, encontramos uma interação significativa entre a distância do rio e o índice Pielou do gênero Blattaria (Chi=4,3381, df=8, p=0,03727).

Palavras-chave: Blataria. Rejeitos de ferro. Abundância.

LIST OF ILLUSTRATIONS

LIST OF TABLES

SUMMARY

1. INTRODUCTION

1.1 SAMARCO's Fundão Dam breach

Brazil, the second-largest producer of iron ore in the world, has seen more than 80 mine-related environmental disasters, and it is anticipated that more than 126 mining dams there are at risk of collapsing in the coming years (Garcia et al., 2017). In 2015, several thousand kilograms of iron tailings were discharged in the environment immediately the Fundão dam in Mariana, which was being managed by Samarco Mining Corporation (BHP Billiton/Vale), collapsed. The amount of iron ore tailings discharged, which was over 40 million cubic, flowed down to the entrance of the Doce River, causing 19 human fatalities (IBAMA 2015; Samarco 2016). According to Escobar (2015) and Laaouidi et al. (2020) the worst socio-environmental catastrophe in Brazilian history was brought on by the tailings, which decimated the riverine ecology along their path by killing thousands of fish and invertebrates. The office of the attorneys general of the State of Minas Gerais formed a committee within 48 hours after the breakdown, with the primary goal of determining the effects of the ecological catastrophe and the ripple effects on the 17 districts and 36 municipal councils directly impacted by the sludge ripple.

Sa *et al.* (2021) reported that the tailings included metalloids and hazardous metals. According to Bernardino *et al.* (2019) and Gabriel et al. (2020), this raised ecological threat for many insect species. This massive volume of mining mud flowed over 800 kilometers along from the Doce River to the Atlantic Ocean, burying homes, communities, plants, and animals (Carmo, 2017). The accumulation of iron and manganese discovered in the samples of the tailing was very high, more than the standard quantity for a hygienic environment in the soil of Minas Gerais (Esteves *et al.,* 2020). Iron residues consist mainly of SiO_2 (14.1%), Fe (57.2%), Al (1.3%) as well as trace amounts of Pb, and Cd have been found (Pires et al., 2003; Ray et al., 2014). Some micro elements, including lead, iron, Manganese and Aluminum, are particularly lethal when transferred from tailings to water and can have cytotoxic effects (Segura, 2016, Lee et al., 2006). According to Chen et al. (2016), the elevated trace amount of metal found around the impacted regions of Rio Doce river has the capacity to have a lasting consequence on the fauna's toxicity and residual toxicity. As a result of the resuspension of sedimented pollutants, as well as the creation of a tailings layer covering the bottom of the rivers, many benthic organisms were buried and killed (Bernardino et al., 2019; GIAIA, 2016; Queiroz et al., 2018). These might eventually have an impact on the region's flora and wildlife (IBAMA 2015), since continuous exposure to the iron ore source can induce both short- and long-term toxic impacts on organisms (Quadra, 2018). However, the degree of contaminant, the concentration, and the kind of organisms present in the environment all guarantee a substantial part in the negative consequences of these tailings on biodiversity. According to Tregubova et al. (2019), some species of organisms can withstand environmental disturbances from humans, while others in the contaminated environment will completely vanish. Metals typically accumulate more quickly in some tissues or organs of invertebrates than in others. For instance, heavy metal pollution doesn't seriously affect ants in less polluted areas (Grze, 2010). Between people residing in contaminated and unpolluted environments, these unique tissues and organs' capacity for storing metals as well as the internal distribution of metals in the body (midgut ephitelium) could vary. (Donker, 1992). In comparison to certain other species, ants collect large levels of metals in both contaminated and unpolluted areas (Stary and Kubiznàkovà, 1987). According to Sildanchandra and Crane (2000), the acute and chronic impacts of pollution on many insects include developmental defects, growth inhibition, decreased reproduction, and hatchability.

Most of these insect species that are important to the health of ecosystems are found in forests (Sekour et al., 2010). Cockroaches are hemimetabolous insects that are part of the Blattodea order. According to Cochran (2009), they may be grouped into five families: Cryptocercidae, Polyphagidae, Blattidae, Blattellidae, and Bladeridae. Members of the insect order Blattodea include cockroaches. Termites were formerly thought to belong to a distinct order called Isoptera, but genetic and molecular data shows that they are really descendants of cockroaches (Krishna et al. 2013). Therefore, Blattodea includes cockroaches (all other taxa) and termites (only the epifamily Termitoidae). There are now several recognized Blattodea species, of which few are termites and others are cockroaches (Krishna et al., 2013). The termite and cockroach families are sister groups, and this clade is embedded inside the Blattodea, according to phylogenetic studies conducted by Inward et al. (2007) and Djernaes et al. (2012). There are more than 4500 different cockroach species, of which 40 are associated with human habitat and 4 are well-known pests. Cockroaches lack the sucking mouthparts, which are a unique adaption observed in other insects like aphids and other true bugs (Salehzadeh et al., 2007; Bell et al., 2007). Morphologically, cockroaches sex (female or male) may differ in terms of the body size, color, and shape of the entire body (Salehzadeh *et al*., 2007). According to Hashemi-Aghdam and Oshaghi (2015), cockroaches are nocturnal and omnivorous species that live in a range of habitat, such as leaves, decaying wood and waste. Due to their nocturnal eating habits, others can be found in forest canopies, crevices, or generally in places where they can hide during the day. More than any other insect, they consume a wide variety of food items (Hanafi-Bojd & Sadaghiani, 2001). In terrestrial ecosystems, cockroaches are thought to be important players that recycle dead plants. Many animals and their feces help in ecosystems functioning by releasing nutrients and breaking down organic materials (Bell *et al*., 2007; Deitz *et al.,* 2003). As decomposers, cockroaches consume dead plants and animals, contributing to the breakdown of organic matter, a crucial component of the ecosystem. Additionally, it has been shown that cockroaches are better decomposers than earthworms recycling leaf litter (dead leaves) from forest floors. This is due to the fact that their ratio of surface to volume is higher than earthworms, making it simpler for them to chew through substantial amounts of decaying biomass (ERFE, 2022). Apart from being predators that consume other insects, their excretions are rich in vitamins and minerals that are good for plants. Worldwide there are about eleven plant species that have been known to be pollinated by cockroaches according to Wujian *et al.* (2020). Thus, cockroaches are crucial to maintaining the equilibrium of the environment. Therefore, any changes of the composition and richness of cockroaches will distort the biological process of the soil formation.

We expect that cockroaches could react differently under different distances from the source of the disaster (dilution effect). According to Armolaitis et al. (2013), Within a short distance (6 km), a high concentration of pollutants may negatively impact a forest of a disaster even years after the emission. Similar to this, Brändle et al. (2001) found that as the distance from the emission source decreased, the species richness of herbivorous Heteroptera rose but abundance declined. The percentage of specialist herbivorous insect is highest in area closest to the source of the emission, he added. In this same way, cockroaches abundance and diversity may be subject to distance from the river in the habitat. Riparian habitat is a highly threatened ecosystems which overbank floods is altering and degrading globally (Tockner and Stanford 2002). The aquatic and terrestrial ecosystems are directly interconnected in the riparian ecosystem, having water as the main component, due to the fact that several riparian areas are vulnerable to overbank flooding and that water tables are frequently close to the surface and easily accessible (Gregory et al. 1991; Naiman and Décamps 1997). Hydrological and geographic variations across rivers of varying orders of magnitude (hydrophilicity) have an impact on characteristics like evenness, variety, and abundance of insects (Benda 2004). Because of this, cockroach communities are probably very different near water sources than they are farther away. For instance, numerous Bembidion ground beetles insects demonstrate escape strategies in riparian environment that frequently floods in order to live. Due of their fully formed wings, they may be able to flee flooding by hiding beneath gravel and flying away (Januschke et al. 2011). Polyxenid millipedes' upward movement along tree trunks is one of their other escape mechanisms (Battirola et al. 2009). Braccia and Batzer (2001) reported that some invertebrates, including centipedes, can escape using floating wood being inundated as seasonal floods increase. As eggs, a variety of grasshopper and mite species may also withstand floods (Adis and Junk 2002). It is evident from the nature, distribution, and abundance of cockroach populations in riparian areas may be influenced by important traits like flooding disturbance and distance from the river bank (hydrophilicity).

1.2 Justification of this research

The impact of ecosystem degradation from the tailings's disaster in the Rio Doce river are still unknown seven years after this disaster on the biodiversity of cockroaches. Despite the fact that mining is important due to its economic impact on the country, it is impossible to overlook the effects of these iron ore tailings on the ecosystem and wildlife. This is very important to governments for making environmental policies and planning to save further loss of biodiversity through conservation and restoration of habitats or implementing measures to reduce disturbances to protect threatened species. For example, it has been demonstrated that when metal contamination in the soil increases, beetles, spiders, earthworms, and ants become less diverse and abundant (Eeva *et al*. 2004). Similar to this, the impacts of iron tailings disaster on the basin of Rio Doce are unclear, Despite the necessity for environmental research involving catastrophes in iron tailings. To comprehend the impact that mine debris has on the organisms that live and feed there, an ecotoxicological approach must be used in this case. Additionally, this will validate existing knowledge to aid in safeguarding the composition and efficiency of ecosystem functions and services. Because cockroach eggs, nymphs, and adults were exposed to 10 -70mg/L of ethylformate in a desiccator, the hatching rate was considerably and dose-dependently decreased. And in the adult, all the developmental stages were negatively impacted (Kim *et al.,* 2021). These data imply that cockroaches react to environmental disturbances by altering their behavior or physiology, which has a direct impact on their community. It is crucial to establish the link between the diversity of cockroaches and soil pollution from iron ore tailings.

1.3 Aims

This study's goal was to examine if the passage of the iron ore tailings impacted the cockroach fauna in riparian forests. Our question was whether cockroach communities will differ among riparian forests, with two explanatory hypotheses: (i) local environmental characteristics and (ii) the impact of the tailings' passage.

1.4 Specific aims

To evaluate our hypotheses, we aimed to test the following predictions:

1. Does cockroach abundance, diversity and evenness differ between areas directly in contact with the tailings passage (affected), compared to areas with no contact with the tailings (unaffected)?
2. Was there a dilution effect of the toxicity of the tailings, correlated to distance to the origin of the disaster (the ruptures Fundão dam in Mariana, MG) ?;
3. Are cockroach assemblages located closer to the river less abundant, diverse, and even than assemblages at places farther away (hydrophilicity)?

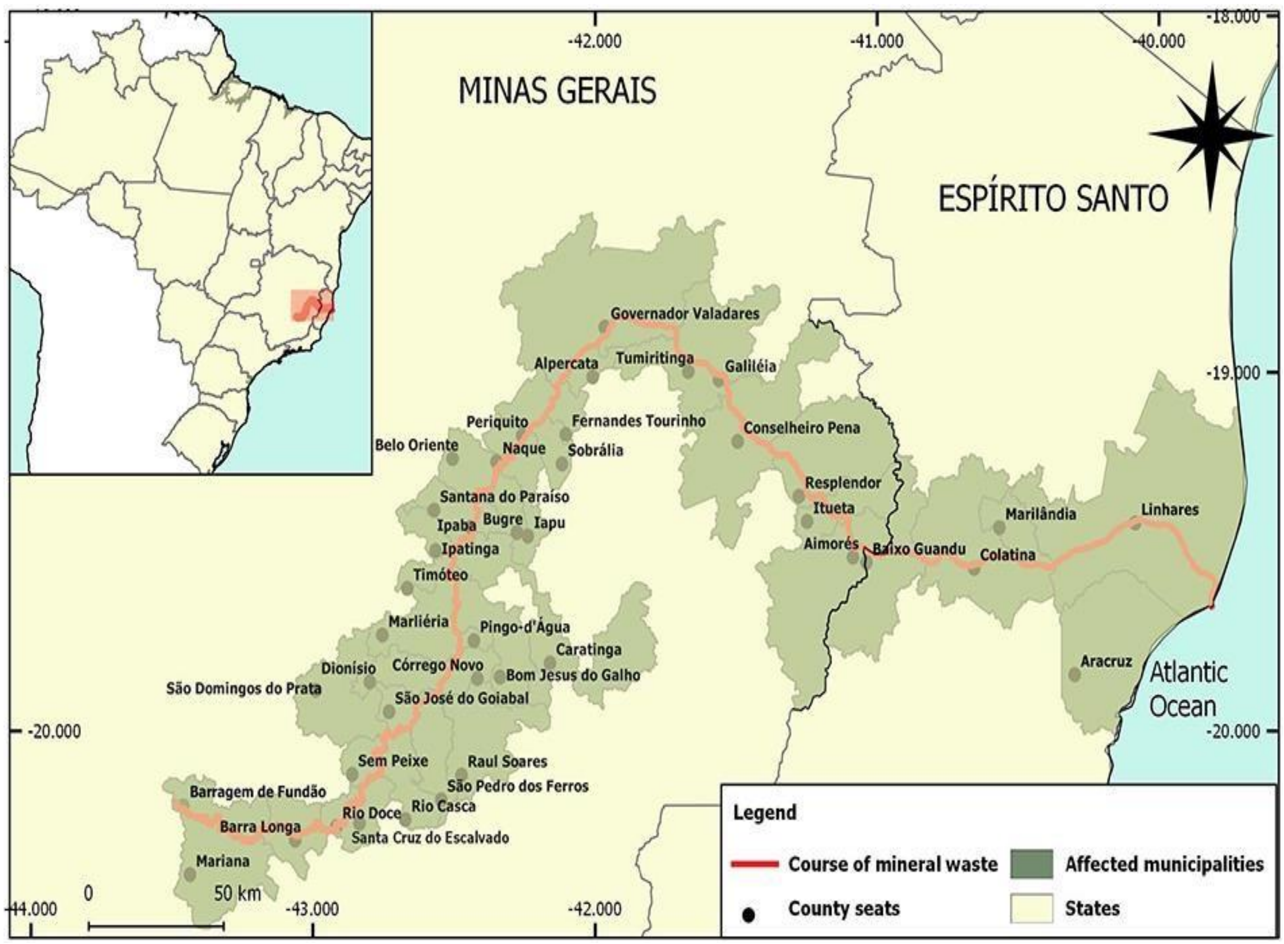
4. Does the local environmental effect (litter, biomass, humus) affect the abundance, diversity and evenness of cockroaches?

With this project, we intend to test whether the tailings affected populations and communities of evaluated cockroaches, by detecting fluctuations in the population size. We expected that the population size of cockroaches decreased in the affected, compared to unaffected areas.

2. MATERIALS AND METHODS

2.1 Study area

To evaluate large scale spatial heterogeneity among the most affected, we selected five locations, along the Rio Doce basin within Minas Gerais State: Mariana, Rio Casca, Ipatinga, Conselheiro Pena, and Aimorés municipalities. Each location was at least 1.5 km from each other. We chose two areas in each of these five locations: one that was directly affected by the passage of the tailings from the dam and one that was unaffected and served as a reference area for the basin's former condition. Locations were selected based on availability of riparian forest patches. Edaphic and topographic factors were not taken into account in the selection of locations due to the dearth of intact riparian forest patches in several sections of the Doce River.



Fundão Dam Mineral tailings flow from Mariana, Minas Gerais State, to the mouth of the Atlantic Ocean, in Esprito Santo State (Map created in 2017 by Max Vasconcelos).

2.2 Sampling design

We set up four transects of 120 m in each sampling area (affected/unaffected), perpendicularly to the river's course, 50 m apart from each other, beginning 1 m from the water and extending toward the center of the riverine forest (Figure 1). We installed three pitfall traps, 2 m apart at every 30 meters. According to recommendations in the literature (SZINWELSKI; FIALHO; *et al.,* 2012), each trap contained 500 ml of fuel alcohol as a conservative and killing solution. Traps were 750 mL cylindrical plastic containers (diameter 120 mm, depth 120 mm), half filled with 75% alcohol which acted as a preserving substance. The traps were then sunk into the ground so that the opening was flush with the surface. The traps were taken out of the field after 48 hours, the organisms were separated, and they were then stored in plastic bottles with screw-top lids that contained 90% ethanol.

Each set of three traps was considered a single sampling unit, so that each transect had a total of five sampling units. Thus, each of the five regions had four transects in each of two areas (affected x unaffected) x five sets of traps x three traps per set, totaling 120 traps, thus consisting 40 sampling units per location. Thus, our total sampling effort was 200 sampling units (n = 200) and 600 pitfall traps, composing 40 replicates (n = 40). All collected cockroaches were identified by the specialist Edivar Heeren de Oliveira (Department of Entomology, National museum of the Federal University of Rio de Janeiro - UFRJ).

2.3 Environmental descriptors

Together with each collection area and sampling unit (set of three buried traps - pitfall) we sampled a series of environmental variables (Table 1.1) that may represent resources and habitat conditions for the cockroach community (ANSO *et al.*, 2022; FARIAS - MARTINS *et al.*, 2017; FUMY *et al.*, 2020).

Table 1. Local environmental variables.

Sampled Variable	Proxy for Sampling	Scale Summary	Sampling Methodology
Litter biomass (g)	Local resource availability	In every set of traps	We used an electronic weighing balance to weight the biomass sampled using 50×50 cm squares and using oven to dry it at 50°C for 72 hrs. We separated litter components into leafs, twigs, wood and humus.
Distance to the body of river/water (m)	Dilution of the effect of the passage of tailings	Along each transect	Correlated to the arrangement of traps in the transect
Distance to the origin of the disaster (km)	Dilution of the effect of the passage of tailings	Hydrographic basin	Estimated by following the course of the affected gutter using google map

Environmental Variables

The following environmental variables were measured:

- Total litter biomass, and its subfractions:
- Leaves
- Twigs
- Other litter components - largely decomposed matter, which we interpreted as humus content.

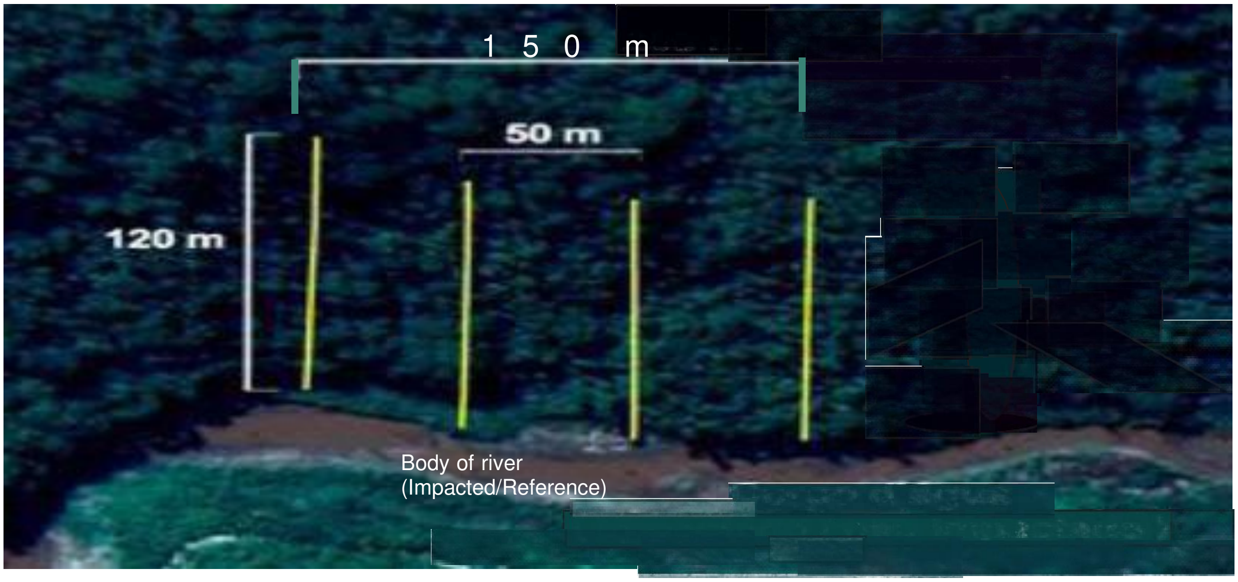


Figure 1. Arrangement of transects perpendicular to the banks of the body of water. Photo Google Earth (2018).

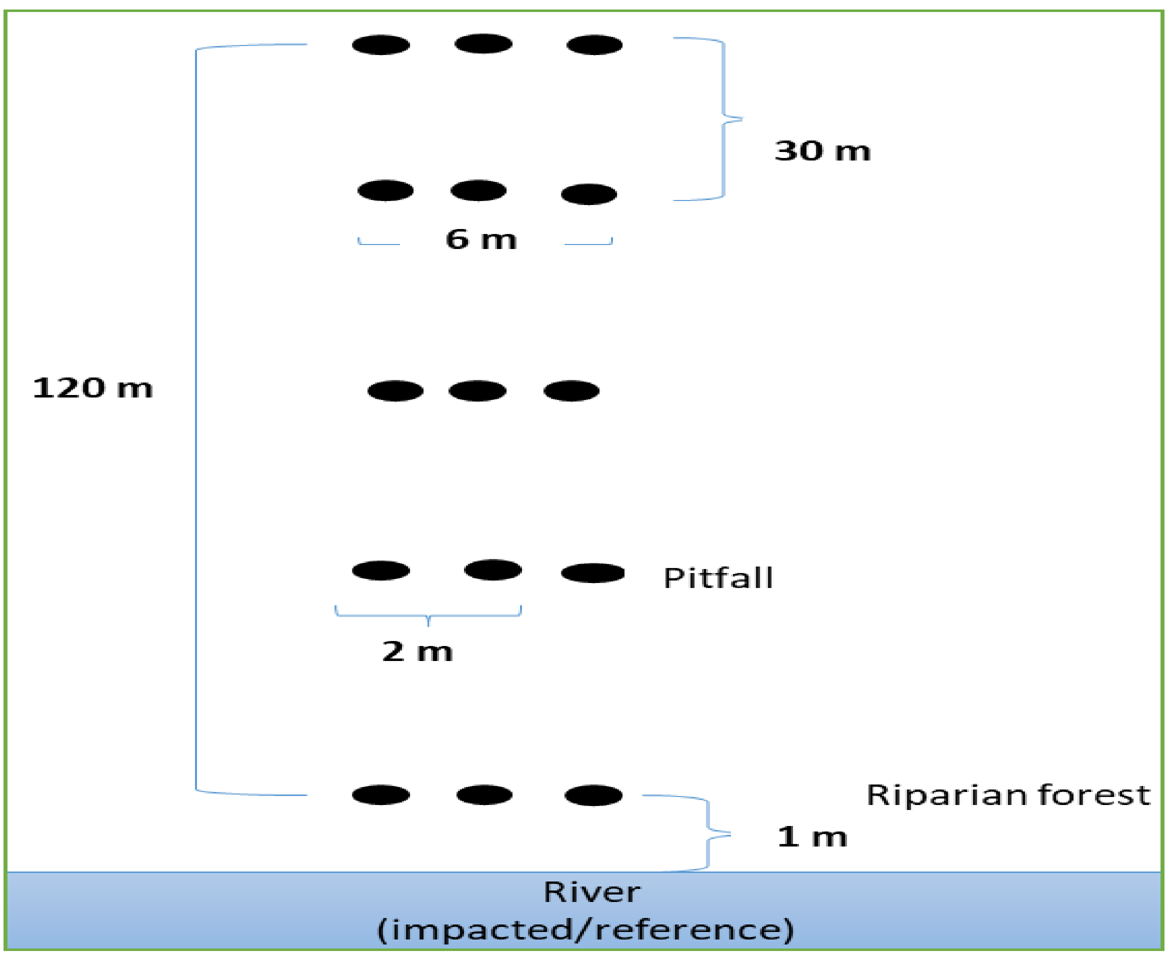


Figure 2. Arrangement of pitfalls along the transects. We considered each set of three traps a sampling unit.

- Contact with the tailings (unaffected area vs. affected area)
- Distance (km) between each location and the origin of the impact, the Fundão dam, estimated using Google Maps.
- Distance (km) from the traps to the river.

2.4 Measures of biodiversity

Cockroach communities' descriptors

To estimate cockroach diversity we considered the number of cockroach species; we estimated abundance by the number of individuals; we evaluated cockroach community structure estimating species evenness, with Pielou's J index**.**

Species evenness/ Pielou's J (Hammer et al., 2001; Clements and Newman, 2003)

$$J = \frac{H'}{H'max}$$

H' $_{max}$ = maximum value of H' = ln(s)

Where;

ln = natural logarithm

H'_{max} = ln(s) maximum diversity possible.

Data processing and statistical analysis

To test our hypotheses, we adjusted generalized linear mixed models' procedure (Tømmervik *et al.,* 2003) with a Gaussian error distribution, including the nested sampling design (transect nested within treatment (affected or unaffected), nested within region) as random effects. The best match for the data was determined by comparing many potential models using the Akaike information criterion (AIC). We adjusted a complete model for each of the following univariate response variables: cockroach abundance (estimated by the number of individuals per sampling unit), diversity and evenness (Pielou's J). The complete models included the following explanatory variables: treatment (a factor with two levels: affected or unaffected - to test for the impact of the tailings' passage), distance from each sampling unit to the river (to test hydrophilicity), distance to the disaster's origin (the Fundão dam, to test for dilution effect), total litter biomass, as well as the weight of each litter component (leafs, twigs, wood and humus - to test for resource availability) and the standard deviation of litter components' weight (to test for resource heterogeneity), as well as all two-level interaction terms with treatment. Complete models were simplified by deletion of non-significant terms through one-level model comparisons (anova procedure). We were not able to evaluate if cockroach community species composition was affected by the tailings' passage, due to reduced species diversity, impeding us to run non-metric multidimensional scaling (NMDS). The R environment was used for all statistical analyses (R Core Team 2023). Cockroach community structure was analyzed using Pielou's evenness index (Oksanen *et al.* 2015).

3. RESULTS AND DISCUSSION

3.1 Results

In Table 2 we present the significant terms of the minimum adequate models explaining our three cockroach communities' parameters: abundance, diversity and evenness. Below we present the results for each of these. The complete results of model simplification are available in the Appendix: Table 3.

Table 2**.** Significant variables in the minimum adequate GLMM models explaining each of the analysed responsevariables:

Response variables	**Explanatory term**	**Distribution**	**DF**	**AIC**	***Deviance***	**Chisq**	**p-Value**
n.ind	Treatment:s.dist.tail	Negative binomial	1	630.15	616.15	5.1447	0.02332*
n.spp	Humus(g) ()	Negative binomial	5	444.52	432.52	4.8158	0.0282*
Pielou's evenne ss	dist.tail	Gaussian	8	113.50	97.497	4.1612	0.04136*
	Treatment: dist.riv	Gaussian	8	113.67	97.674	4.3381	0.03727*

Caption: * statistically significant values. *n.spp = number of species, dist. tail = distance to the tailing source, dist., n.ind = Number of individuals, riv = distance to the river,* Pielou's evenness = J value.

3.2. Drivers of cockroach abundance

Figure 3 illustrates the relationship between cockroach abundance and distance from tailings source and their relationship with treatment (affected x unaffected). The relation of cockroach abundance with distance from the tailings source (dilution effect) differed between affected and unaffected areas (Chi-square = 5.1447, p = 0.02332, Fig. 3): while cockroach abundance decreased with distance to the tailings' origin in unaffected areas (Chi-square = 9.5821; p=0.0019; Fig. 3 upper right corner), there was no dilution effect in affected areas (Chi-square = 0.2204, p = 0.6387, Fig. 3 lower right corner).

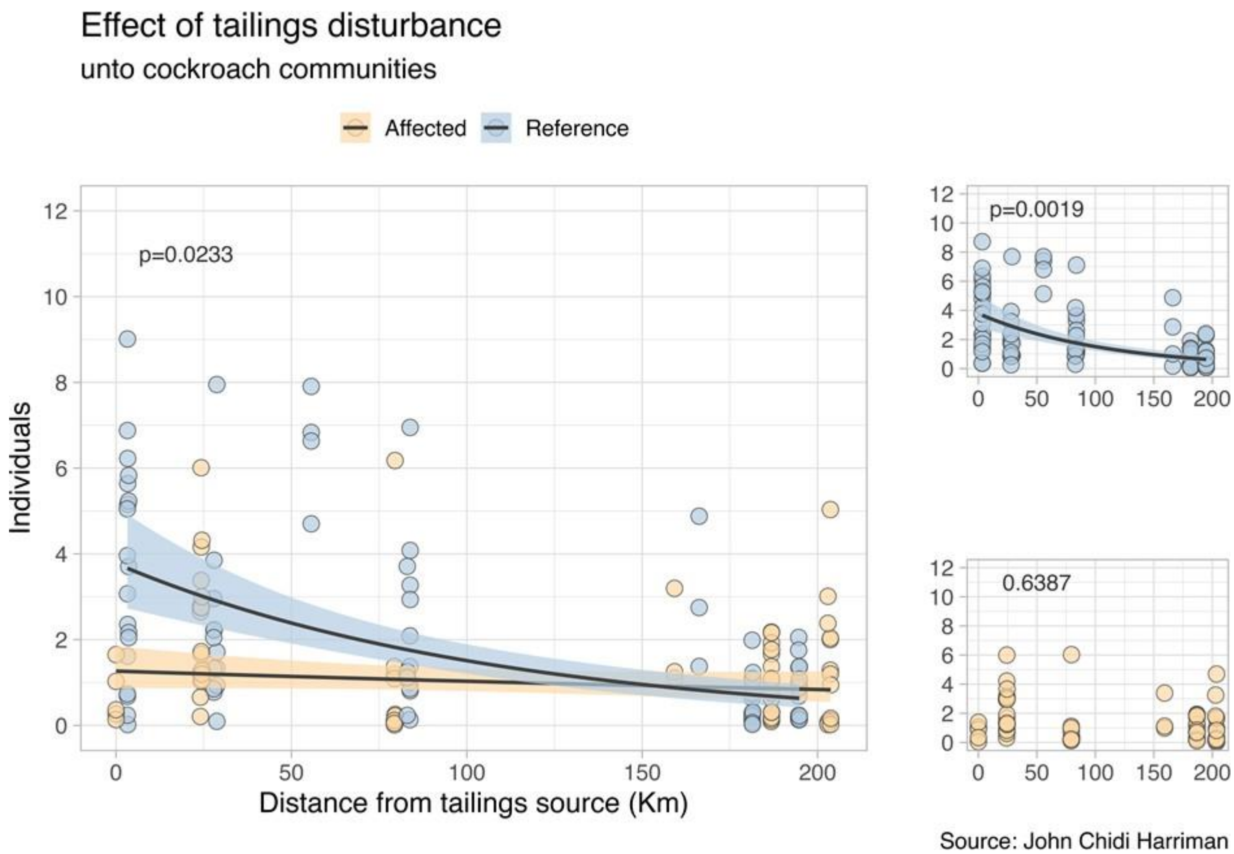


Figure 3. Effect of distance from tailings source on the abundance of sampled Blattodea individuals across impacted and non-impacted sites by the passage of tailings in the Rio Doce, MG, Brazil.

3.3 Drivers of cockroach diversity

Cockroach diversities' response also differed between affected and unaffected areas (Chi-square = 4.8158; $p = 0.0282$, Fig. 4): while cockroach diversity increased with the amount of humus in the litter in unaffected areas (Chi-square = 7.0531; $p = 0.0079$; top right corner in Fig. 4), this relation was absent in affected areas (Chi-square = 0.019007; $p = 0.8903$; lower right corner in Fig. 4).

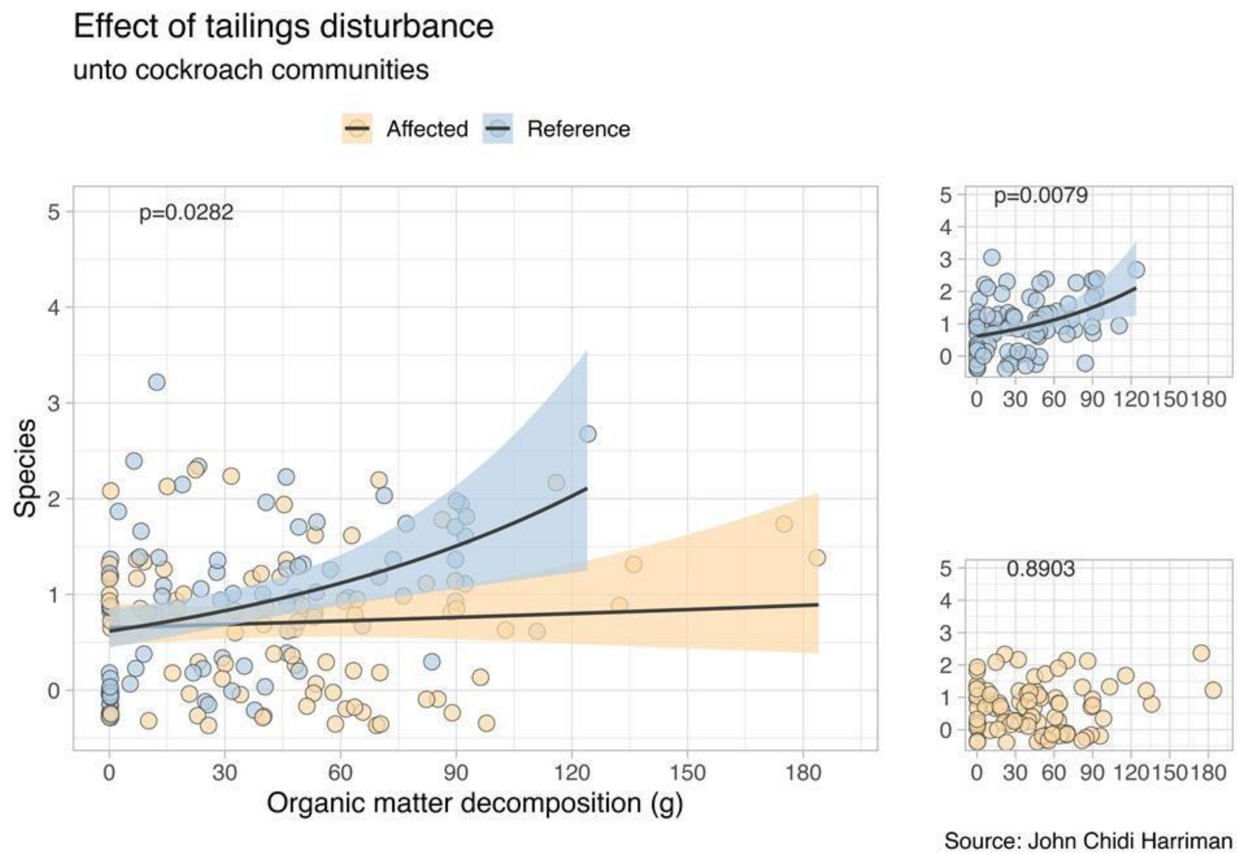


Figure 4. Effect of amount of humus on cockroach diversity (number of species) in riparian forest of Doce River, MG, Brazil.

3.4 The impact of distance from the river on the cockroaches evenness as affected by tailing disturbances in reference and affected sites

The graph below showed the impact of distance from the river on the cockroaches evenness as affected by tailing disturbances in reference and affected sites. There was a significant relationship between cockroach evenness and distance from the river (Chi = 4.3381, df = 8, p = 0.03727, Fig. 5) (Table 1). But when analysed separately, in the reference areas, The evenness of cockroaches was not significantly affected by the distance to the river (p=0.543). Similarly, no significant effect was detected between distance to the river and cockroaches evenness (p = 0.3109) in affected area. Although in the affected areas and reference sites, there was no effect of distance from the river on cockroaches evenness, however, the treatment had significant effect (affected vs reference) on the cockroaches evenness. Here, the cockroaches evenness is higher in the area further away from the river than areas that is in close proximity to the river.

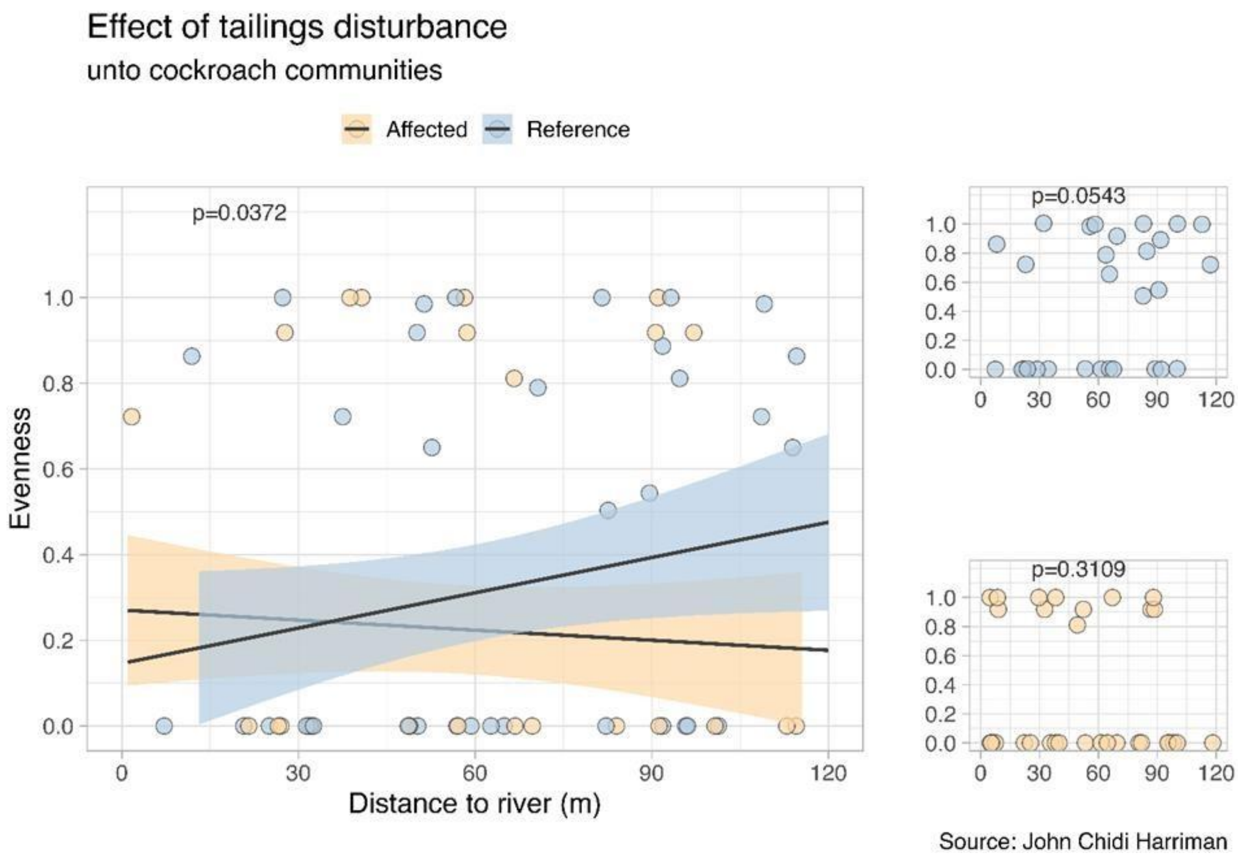


Figure 5. Effect of distance to the river on the evenness of sampled Blattodea communities across impacted and non-impacted sites by the passage of tailings in the Rio Doce, MG, Brazil.

3.5. Impact of distance from tailing source on the evenness of cockroaches in affected and reference sites

There was significant difference between evenness and the distance from the source of the tailings (Chi= 4.1612, df=8, p=0.04136) (Table 1). Along both the affected and reference gradients, the cockroaches evenness fell significantly with increase distance from the source of the tailing (Fig. 6). The region closer to the tailing sou rce had more cockroaches evenness than the region further away from the tailing source. Similarly, if the entire sample (reference and affected) is considered as a single unit, the cockroaches evenness was still more in the region closer to the source of the tailings.

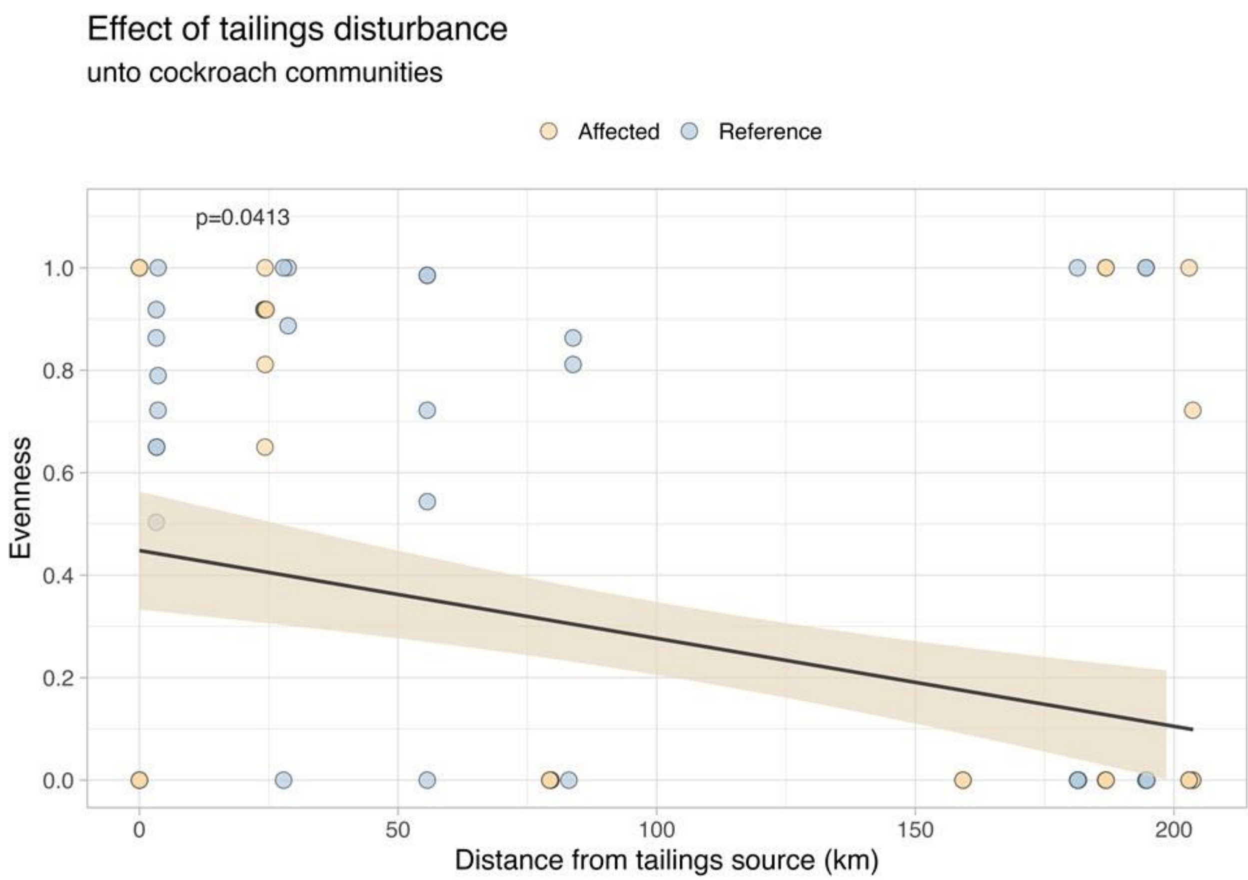
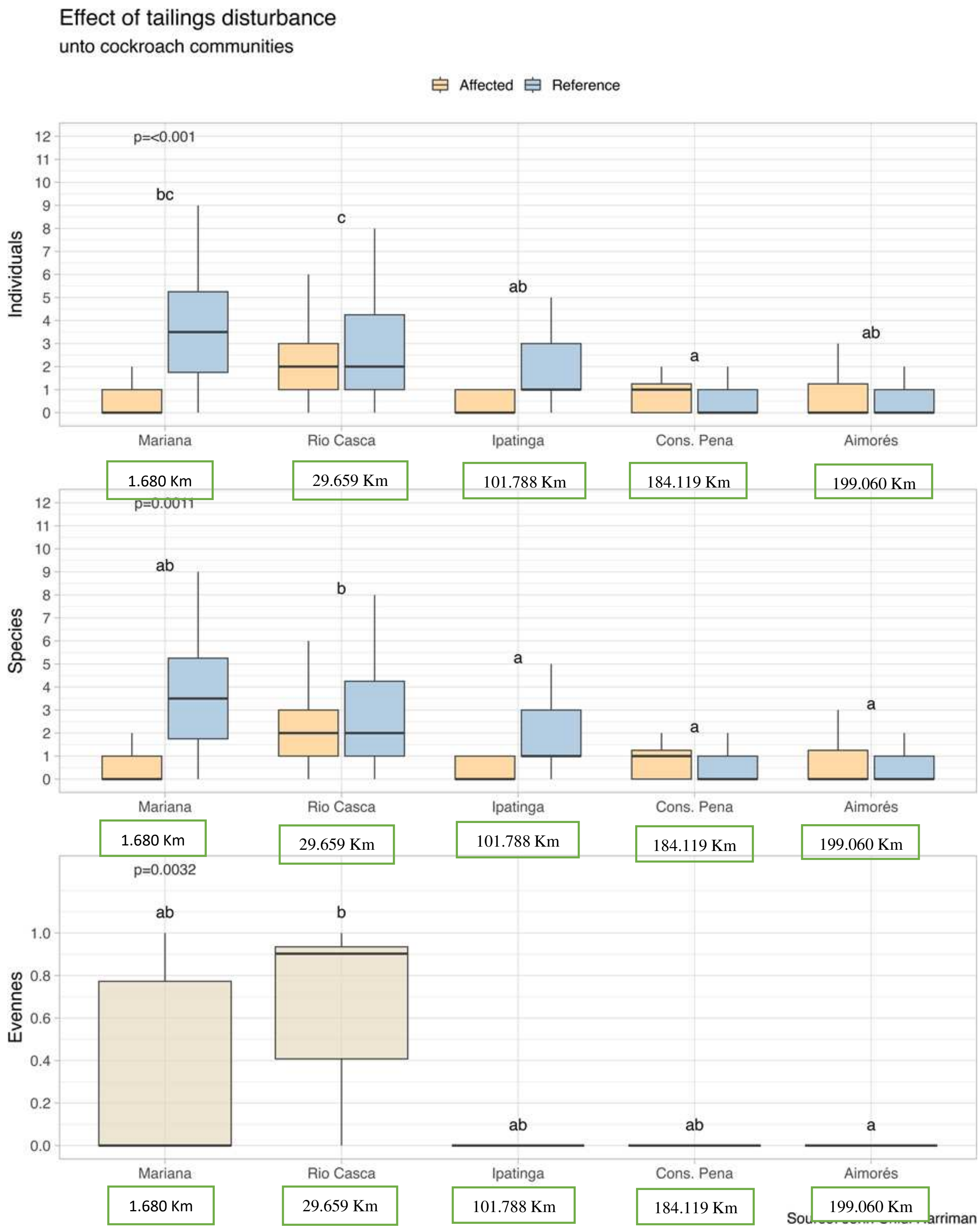


Figure 6. Effect of distance from tailings source on the evenness of sampled Blattodea communities across impacted and non-impacted sites by the passage of tailings in the Rio Doce, MG, Brazil.

3.6. Effect of distance of the regions from the source of the tailing on the community structure of sampled cockroaches

The structure of the cockroach communities (abundance, diversity and evenness) varied according to the distance of sampled location from the source of the tailing. Abundance (individual) showed significant differences between sampled regions (Chi-square = 38.832, $p < 0.001$) when localities were ordered according to their distance to the disaster's origin (the Fundão dam, Fig. 7). From the results, abundance was higher in the regions closer to the source of the tailings (Mariana = 1.680 Km) compared to the regions further away from the source of the tailing (Aimores = 199.060 km) especially in the reference sites (Fig. 7). Cockroach diversity (number of species) followed a similar pattern and also varied according to the distance of sampled location from the source of the tailing (Chi-square = 18.238, $p = 0.0011$), with Mariana which is closest to the source of tailing (1.680 Km) having higher diversity. However, Aimores which is the furthest region (199.060 km) had the least diversity. Because there are few species, the pattern for communities' evenness was less clear, but we detected significant differences among the distances of sampled locations from the source of the tailing (Chi-square = 15.857, $p = 0.0032$, Fig. 7).



Regions with the same letter are statistically not different from each other.
Figure 7. Effect of distance of *location* from the source of the tailing *on the community structure (abundance, species, evenness) of sampled* cockroaches *across impacted and non-impacted sites by the passage of tailings in the Rio Doce Basin, Brazil. Locations ordered according to distance to the disaster's origin* in km *(the Fundão dam).*

3.7. The effect of tailings passage on the abundance of cock roach species in affected and reference sites

Figure 8 presents the mean and deviation of cockroach species' abundance in affected and reference areas. The most abundant species was *Cariblatta sp* in both affected and unaffected areas, followed by *Epilampra sp.* The least abundant species was *Pycnoscelus sp* in affected and unaffected areas.

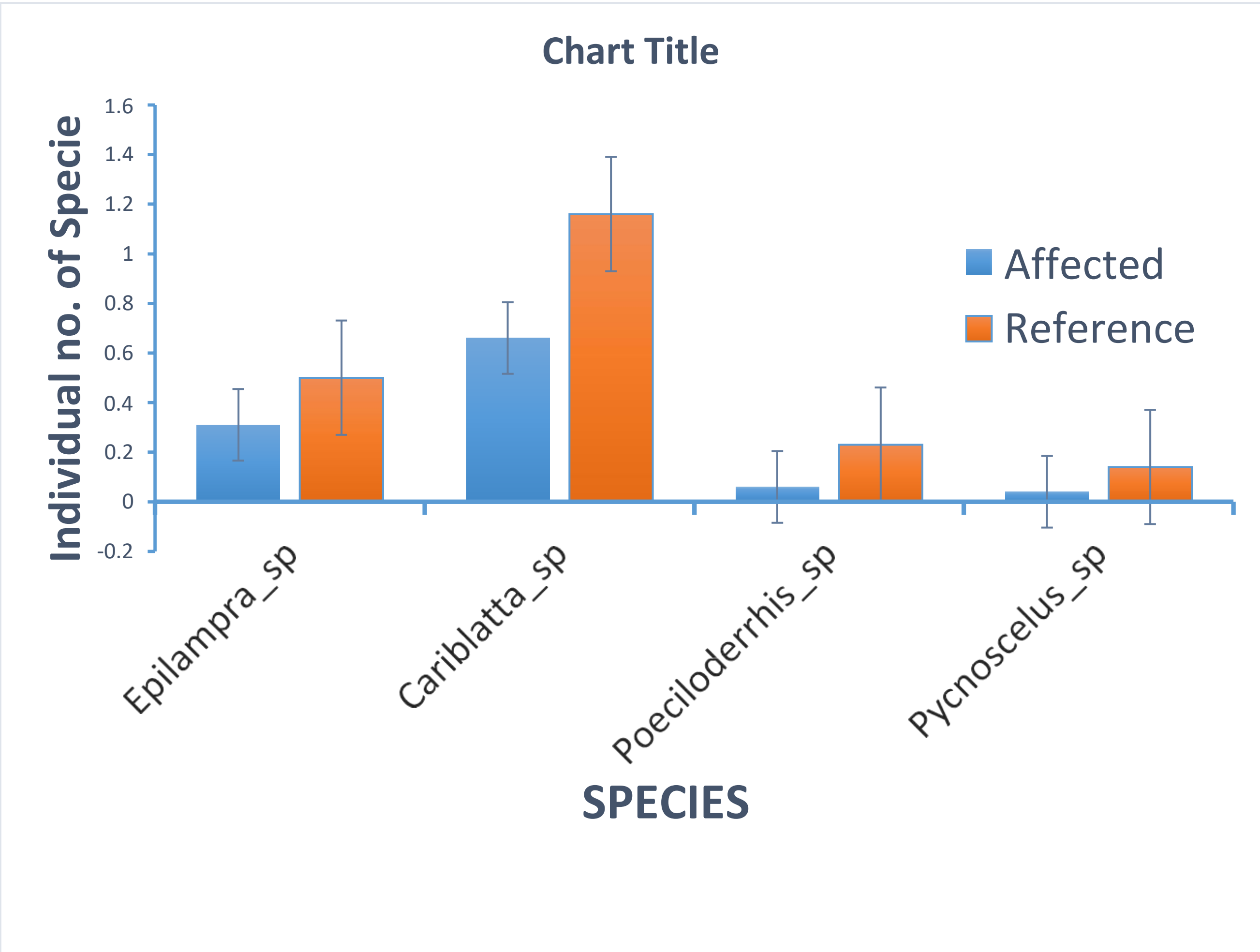


Figure 8. The effect of iron ore tailings passage on the number of cockroach along Doce River in Brazil.

3.8. Discussion

Effect of distance from tailings source on the abundance of sampled Blattodea individuals across impacted and non-impacted sites by the passage of tailings in the Rio Doce Basin, MG, Brazil.

The abundance of cockroach individuals was influenced by the Fe tailings as there was a significant interaction between proximity to the tailings source and treatment (affected x unaffected areas) by tailings. In affected areas however, this work demonstrated that the distance from the source of the tailing did not influence the distribution and abundance of cockroaches. Consequently, cockroaches abundance were the same at all the affected areas regardless of distance from the source of the tailing. In unaffected areas however, it was observed that the cockroach abundance is highest in the areas closer to the origin of the tailing and decreased as measurement of separation from source of the tailing increased. The pollutants from the tailing mud may have caused or contributed to the observed results in the affected and reference areas. This may be explained by the possibility that the pollutants from the disturbances may have induced the cockroaches to flee and migrate to areas further away from the source of the emission (Fig. 7). This is especially true in Ipatinga, Mariana and Rio Casca where most cockroach species fled from affected to unaffected areas (Fig.7) in order to survive. A study by the University of Arizona found that the American cockroach (*Periplaneta americana*) can travel up to 0.03 km in a single night (University of Arizona, 2019) in order escape from disturbed environment. In a similar manner, Laurent et al. (2015) stated that American cockroach migration from disturbed to non-disturbed shelters has been demonstrated. According to Jung *et al.* (2008), it is also common for cockroach attributes like abundance to be insignificant (same) in affected areas. Despite the increased species diversity values in the contaminated regions, In locations with and without pollution, Jung et al. (2008) observed no statistically significant variation in the species abundance of ground-dwelling spiders. Fergnani *et al.,* (2008) reported that a complex interaction of variables, including microclimate, environmental factors, functional relationships, and vegetation (litter biomass, leaves, twigs, (humus) other litter components) that affect cockroach abundance, may have led to such a result.

3.9. Effect of humus (litter) on the species of sampled cockroaches across impacted and non-impacted sites by the passage of tailings in the Rio Doce Basin, MG, Brazil

The outcomes of the analysis showed that genus richness strongly increased with increase in quantity of decomposing organic matter (humus) in unaffected areas. Therefore, species (richness) appears to increase in direct response to the quantity of decomposing organic matter (humus). The increase was not significant in the affected area, thus, the richness did not change with increased quantity of decomposing organic matter. The presence of litter from the decomposing organic matter induced changes in richness in the unaffected. This is because a wide variety of microarthropods prefer to live in an environment that thick-rich litter provides (Uetz, 1974). According to Schal *et al.* (2008), the qualities of vegetative litter determine the ecological niches of insects which might vary from region to region. Uetz (1974), reported that the number of litter-dwelling arthropods increased with increasing litter depth (quantity), according to a comparison of species from several forests. Their response to litter is expected since cockroaches rely on detrital materials as food source. According to Bultman, (1981), the mere existence of litter, independent of its nutritional value, affects the distribution and abundance of numerous arthropods. Geiger (1950) came to the conclusion that the main factor affecting the number of microarthropods was litter as a modifier of microclimate. In addition to improving water availability and cockroach population development, litter from decomposing organic matter offers hiding places for insects. An increasing availability of leaf litter, hollow logs and sheltering crevices is needed for ground-dwelling orthopterans as a daytime refuge (Rebrina *et al*., 2020; Llucià-Pomares 2015). According to Bell *et al.* (2007) in sparsely vegetated areas, herbaceous flora and associated litter are recognized to be an essential food source and microhabitat for these insects. According to Dajoz, (1998), the best illustration of litter-eating terrestrial insects is the forest cockroach. This cockroach consumes detritus materials (excrement, carcasses, dead; leaves, twigs, roots). They largely colonize the soil producing massive litter as a result (Dajoz, 1998). Masna (2016) further demonstrates how important litter-rich forests are for cockroach distribution in terms of food resources and offering of shelters.

3.10. Effect of distance to the river on the evenness of sampled Blattodea communities across impacted and non-impacted sites by the passage of tailings in the Rio Doce Basin, MG, Brazil

The interaction between treatment (affected and unaffected) and distance to the river was significant. This indicates that treatment and distance to the river had impact on cockroach species. However, no significance difference was observed between evenness and distance to the river in affected and unaffected areas. Our result is in disagreement with the report from Bell *et al.* (2007), who reported that cockroaches show less preference for regions closer to the river. Cockroaches find such environments less habitable because of the higher air humidity and lower soil temperature levels associated to sites next to surface water (Rebrina *et al*., 2020). Bell *et al.* (2007) found that for most species of cockroaches, temperature negatively affects proper egg growth and negatively affects both nymphs and adults' essential physiological processes. Insect development, reproduction, and behavior, as well as the health of the plants that act as their hosts, are all directly influenced by water. (Ferro, 1987). Flooding can also drive insects to the soil's surface, where they risk predator attack. According to Pen (1947), the confused flour beetle's eggs thrive best in dry environments as no hatching took place when the humidity was increased to 90% or higher, mostly due to fungi infections in the eggs. According to Puttaswamy and Channa (1980), prays on the spider mite, which thrived at low relative humidity and fell at higher relative humidity, provides as an example of the varied reaction to water. The results of Pronk (2016) study of orthopteran aggregations, which reported low species diversity and abundance in riparian ecosystems in their natural state are also not supported by the findings of the current study.

3.11. Effect of distance from tailings source on the evenness of sampled cockroach communities across impacted and non-impacted sites by the passage of tailings in the Rio Doce Basin, MG, Brazil

The cockroach evenness differed significantly with respect to distance from the source of the tailings. Evenness increased with a decrease in distance from the tailing source. This means that more cockroach species moved to places close to the tailing source. The cockroaches' preference for the new disturbed environment may have led to this result.

Environmental contamination causes a range of responses from negative to positive in insect populations (Kozlov, 1997). According to Evans (1988), disturbed environments quickly develop plants or detrital resources that benefit insect species that become more numerous after disturbance. According to Riemer and Whittaker (1989), pollutants make plants more palatable to insects. This is particularly true in moderately polluted areas very close to the source of emissions and further away, the foliage quality is poorer. For sucking insects, this has been demonstrated (Jussila *et al.*, 1990). According to Fountain *et al.* (2007) and Jung *et al.* (2008), Araneae communities' diversity and structure have been impacted by a variety of factors, including the plant type, its microclimate, and the availability of prey.

3.12. Effect of distance of the regions from the source of the tailing on the community structure (individual, species, evenness) of sampled cockroaches in the Rio Doce Basin, MG, Brazil

The abundance, diversity and evenness varied according to the distance of sampled location from the source of the tailing when localities were ordered according to their distance to the origin of the disaster. From the results, there was more cockroaches abundance in regions closer to the source of the tailings compared to the regions further away from the source of the tailnigs. The same trend was observed in evenness and diversity, although evenness was less clear because of the low number of species, According to Krzysztofiak (1991), pollution may have an indirect impact on arthropods by altering abiotic variables like temperature or moisture. Theoretically, if pollution reduces plant density and subsequently favors thermophilic ant species, the variety of ants may rise along a pollution gradient. According to Migliorini *et al.* (2004), metal contamination caused Collembola abundance to increase. Additionally, Nahmani and Lavelle (2002) discovered a positive correlation between metal pollution and the abundance of various arthropod species such as Hoplinae larvae and Coleoptera Staphylinidae. Although no specific cause for such trend was mentioned, the author did highlight the potential significance of interactions amongst soil organisms.

3.13. The impact of iron ore tailings passage on the number of individual of cockroaches along Doce River in Brazil.

The results obtained in species variation in affected and unaffected areas showed that *Cariblatta sp* are the most dominant species in affected and unaffected areas. While the *Pycnoscelus sp* is the least dominant in affected and unaffected areas (Fig. 8). The observed differences in number of species could be attributed to differential responses of the various species to the tailing pressure.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1. Conclusion

Our research shows that the abundance of cockroaches may be significantly impacted by iron ore tailing mud, with a correspondingly considerable increase in abundance in reference regions compared to affected sites. There is evidence that these shifts in abundance may have been caused by tailing. That is to say, the cockroaches may have fled and moved to the reference region from the area of emission in affected site as a result of the pollutants from the disturbances. This is particularly true in Mariana and Rio Casca, where the majority of cockroach species migrated from impacted to reference habitats. More likely than changes in abiotic circumstances, this outcome can be explained by indirect impacts of mud from the tailing, namely changes in species interactions.

Field's litter (humus) content increased or decreased, producing a small but substantial corresponding rise or fall in the diversity of cockroaches in reference area. This is because litter not only makes it easier to find food supplies, but it also gives insects a place to hide.

It is obvious how tailing mud affects cockroach assemblages, and studies of cockroach diversity can help us understand ecosystems functioning. This research adds to the body of information showing that iron ore tailing can drastically change the makeup of the arthropod population. However, our research shows a negative relationship between cockroach evenness and distance from the source of tailings. The threat that iron ore tailings represent to the diversity of cockroaches are highlighted by this, underscoring the urgent need for more study aimed at improving our understanding of them. This would provide as a foundation for effective monitoring and conservation of this underutilized insect in the Rio Basin of Brazil.

4.2. Recommendation

It is advised that sampling be a continuous process in order to record all seasonal fluctuation and utilize it as a benchmark for comparison in environmental assessment programs. Additional research is essential, and it may involve using coloured pan traps or other sampling techniques in addition to pitfall traps. This technique may give appropriate results in capturing more species required for studies, especially, if cockroaches community structure is to be adequately characterized.

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APPENDIX

Table 3. Test models for cockroaches *variables at study areas along the tailing tailing-impacted gradients*

Response variables	Explanatory variables	Family	Df	AIC	*Deviance*	Chisq	p-Value
n.ind	Treatment:s.litter.heterogeneity.SD.	Negative binomial	19	641.73	603.73	0.0061	0.9378
n.ind	s.litter.heterogeneity.SD.	Negative binomial	18	639.74	603.74	0.0089	0.9247
n.ind	Treatment:s.Leafs.g.	Negative binomial	17	637.81	603.81	0.0701	0.7912
n.ind	s.Leafs.g.	Negative binomial	16	635.99	603.99	0.1796	0.6717
n.ind	Treatment:s.Twigs.g.	Negative binomial	15	634.25	604.25	0.2653	0.6065
n.ind	s.Twigs.g.	Negative binomial	14	632.43	604.43	0.1787	0.6725
n.ind	Treatment:s.dist.riv	Negative binomial	13	631.33	605.33	0.8985	0.3432
n.ind	s.dist.riv	Negative binomial	12	629.63	605.63	0.3031	0.5819
n.ind	Treatment:s.Wood.g.	Negative binomial	11	628.95	606.95	1.3222	0.2502
n.ind	s.Wood.g.	Negative binomial	10	628.43	608.43	1.4758	0.2244
n.ind	Treatment:s.Other.litter.componenets.g.	Negative binomial	9	628.43	610.43	1.9977	0.1575
n.ind	s.Other.litter.componenets.g.	Negative binomial	8	627.01	611.01	0.5782	0.447
n.ind	Treatment:s.dist.tail	Negative binomial	1	630.15	616.15	5.1447	0.02332*
n.spp	Treatment:s.Leafs.g.	Negative binomial	19	457.87	421.87	0.0165	0.8976
n.spp	Treatment:s.Wood.g.	Negative binomial	18	455.92	421.92	0.0525	0.8188
n.spp	s.Wood.g.	Negative binomial	17	453.97	421.97	0.0553	0.8141
n.spp	Treatment:s.Twigs.g.	Negative binomial	16	452.09	422.09	0.1153	0.7342
n.spp	Treatment:s.litter.heterogeneity.SD.	Negative binomial	15	450.32	422.32	0.2346	0.6282
n.spp	s.litter.heterogeneity.SD.	Negative binomial	14	448.50	422.50	0.1809	0.6706
n.spp	s.Twigs.g.	Negative binomial	13	446.63	422.63	0.1285	0.7199
n.spp	Treatment:s.dist.tail	Negative binomial	12	445.25	423.25	0.6177	0.4319

n.spp	s.Leafs.g.	Negative binomial	11	444.26	424.26	1.0085	0.3153
n.spp	Treatment:s.dist.riv	Negative binomial	10	443.23	425.23	0.9691	0.3249
n.spp	s.dist.riv	Negative binomial	9	443.23	425.23	0.9691	0.3249
n.spp	Treatment:s.dist.riv	Negative binomial	8	443.23	425.23	0.9691	0.3249
n.spp	s.dist.riv	Negative binomial	7	441.59	425.59	0.3604	0.5483
n.spp	s.dist.tail	Negative binomial	6	441.70	427.70	2.113	0.1461
n.spp	Treatment:s.Other.litter.componenets.g.	Negative binomial	5	444.52	432.52	4.8158	0.0282*
Pielou	Treatment:s.dist.tail	Gaussian	19	123.49	85.488	0.0001	0.9862
Pielou	Treatment:s.Leafs.g.	Gaussian	18	121.49	85.493	0.0046	0.9459
Pielou	Treatment:s.Twigs.g.	Gaussian	17	119.76	85.761	0.2685	0.6043
Pielou	Treatment:s.Wood.g.	Gaussian	16	117.97	85.971	0.2102	0.6466
Pielou	s.Wood.g.	Gaussian	15	115.99	85.990	0.018	0.8932
Pielou	s.Leafs.g.	Gaussian	14	114.79	86.790	0.8003	0.371
Pielou	s.Twigs.g.	Gaussian	13	113.84	87.838	1.0482	0.3059
Pielou	Treatment:s.litter.heterogeneity.SD.	Gaussian	12	113.12	89.119	1.2811	0.2577
Pielou	s.litter.heterogeneity.SD.	Gaussian	11	112.13	90.129	1.0101	0.3149
Pielou	Treatment:s.Other.litter.componenets.g.	Gaussian	10	112.05	92.054	1.9249	0.1653
Pielou	s.Other.litter.componenets.g.	Gaussian	9	111.33	93.335	1.2813	0.2577
Pielou	s.dist.tail	Gaussian	8	113.50	97.497	4.1612	0.04136*
Pielou	Treatment:s.dist.riv	Gaussian	8	113.67	97.674	4.3381	0.03727*

Caption: * statistically significant values, n.ind = Number of individuals, n.spp = number of species, dist. tail = distance to the tailing source, dist. riv = distance to the river.

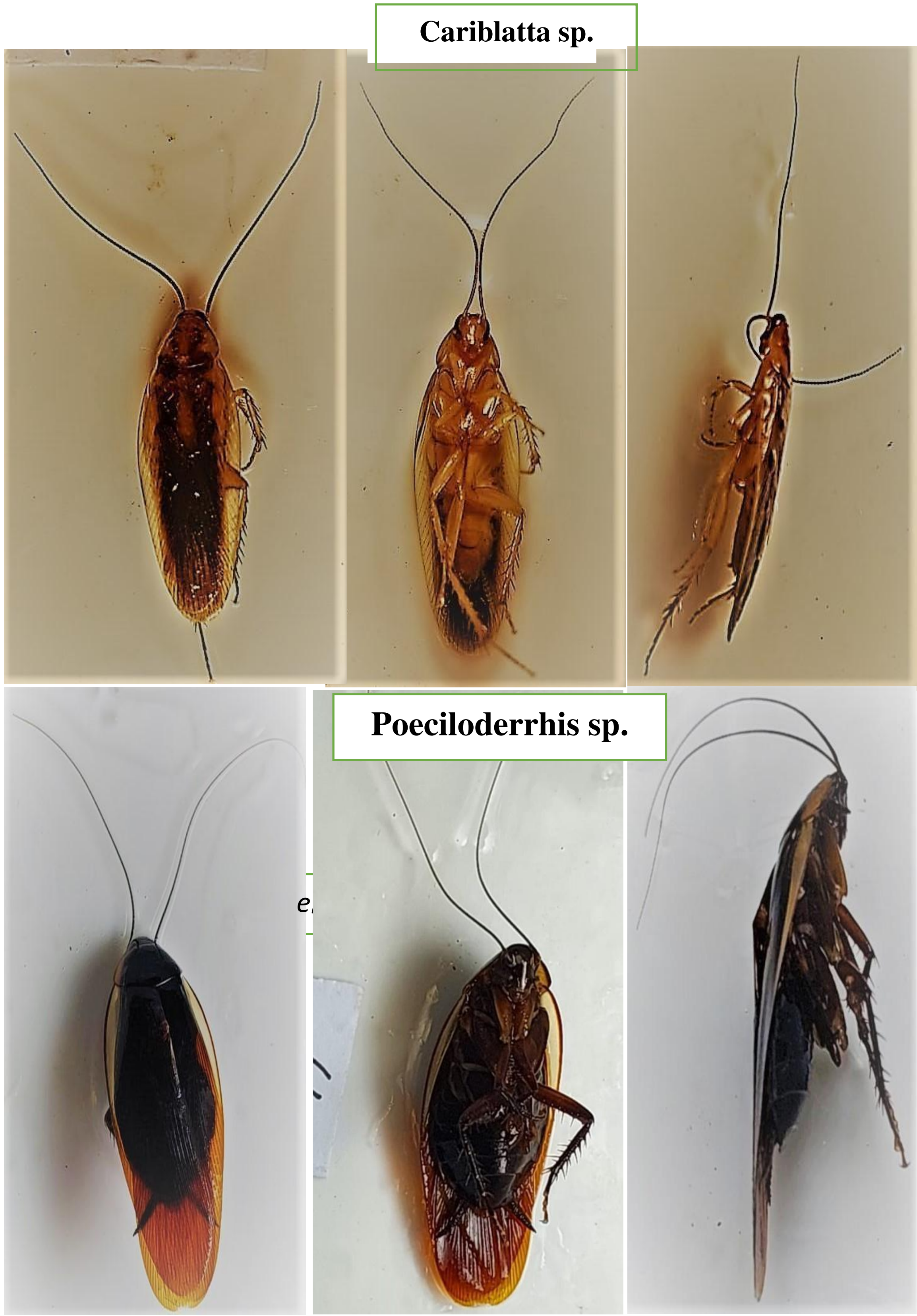

Figure 9. The dorsal view, ventral view, and the lateral view of the blatteria species found in the experimental sites.

Figure 10. The ventral view, dorsal view and the lateral view of the blattodea species found in the sampled areas.