Role of climatic factors in the toxicity of fipronil toward earthworms in two tropical soils: effects of increased temperature and reduced soil moisture content

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Abstract
The aim of this study was to assess the effect of temperature on the toxicity of fipronil toward earthworms (Eisenia andrei) in two Brazilian soils (Entisol and Oxisol) with contrasting textures. In the case of Entisol, the influence of soil moisture content on toxicity was also investigated. Earthworms were exposed for 56 days to soils spiked with increasing concentrations of fipronil (8.95, 19.48, 38.22, 155.61, and 237.81 mg kg⁻¹ for Entisol; 12.99, 27.94, 48.42, 204.67, and 374.29 mg kg⁻¹ for Oxisol) under scenarios with different combinations of temperature (20, 25 and 27 °C) and soil moisture content (60 and 30% of water holding capacity (WHC) for Entisol and 60% WHC for Oxisol). The number of juveniles produced was taken as the endpoint, and a risk assessment was performed based on the hazard quotient (HQ). In Entisol, at 60% WHC the fipronil toxicity decreased at 27 °C compared with the other temperatures tested (EC₅₀ = 52.58, 48.48, and 110 mg kg⁻¹ for 20, 25, and 27 °C, respectively). In the case of Oxisol at 60% WHC, the fipronil toxicity increased at 27 °C compared with other temperatures (EC₅₀ = 277.57, 312.87, and 39.89 mg kg⁻¹ at 20, 25, and 27 °C, respectively). An increase in fipronil toxicity was also observed with a decrease in soil moisture content in Entisol at 27 °C (EC₅₀ = 27.95 and 110 mg kg⁻¹ for 30% and 60% WHC, respectively). The risk of fipronil was only significant at 27 °C in Entisol and Oxisol with water contents of 30% and 60% WHC, respectively, revealing that higher temperatures are able to increase the risk of fipronil toxicity toward earthworms depending on soil type and soil moisture content. The results reported herein show that soil properties associated with climatic shifts could enhance the ecotoxicological effects and risk of fipronil for earthworms, depending on the type of soil.

Keywords Global warming · Eisenia andrei · Phenylpyrazole · Natural soils · Soil ecotoxicology · Hazard quotient

Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), increases in global temperatures and the occurrence of extreme weather events are expected in the coming years. In a global scenario, an increase of around 2 °C in global temperature is expected between the years 2021 and 2040. In Brazil, although the predicted consequences of climate change vary for different regions, if this global warming trend is confirmed, temperatures could rise by around 3.0–3.5 °C, and reductions of between 10 and 20% in rainfall patterns may occur, which increases the probability of extreme and prolonged drought events (IPCC 2021).

The consequences of climate change, especially those related to temperature and precipitation, are considered an imminent problem due to long-term impacts on terrestrial species. These changes can affect the physical, chemical,
and biological properties of the soil ecosystem and can also affect the structure and composition of the edaphic community. Disorders in the metabolism of soil organisms can impair their growth, reproduction, and behavior, making them susceptible to additional environmental disturbances, such as soil contamination by toxic substances caused by human activities (Noyes et al. 2009). Therefore, it is expected that an increase in temperature and a reduction in rainfall will enhance the risk of toxic substances present in the soil (González-Alcaraz et al. 2015).

Earthworms are good bioindicators to assess the combined impacts of multiple stressors (González-Alcaraz and Van Gestel 2016a). The species Eisenia andrei is recommended by international standardization guidelines for laboratory ecotoxicity assays (ISO - International Organization for Standardization 2012; OECD 2016; Environment Canada 2004) mainly because of its sensitivity to several soil contaminants, good adaptability to laboratory environments, and rapid growth and reproduction (Lisbôa et al. 2021). Because of this, studies have used this species to assess the effects of environmental factors on the toxicity of pesticides (Lima et al. 2015; Bandeira et al. 2020).

Fipronil is a phenylpyrazole pesticide that is efficient in pest control and widely used for seed treatment, with sales in Brazil of 2,000 tons in 2019 (IBAMA 2019). The lack of training for pesticide application (Waichman et al. 2007) and the accumulation due to repeated inputs may result in greater residues of the active ingredient (a.i.) in the soil, which can impact nontarget organisms (Daam et al. 2019). The ecotoxicological effects of fipronil on the survival, reproduction, and growth of different soil organisms have been reported in the literature (e.g., San Miguel et al. 2008; Alves et al. 2014; Qin et al. 2014; Qu et al. 2014; Zortéa et al. 2018a, 2018b) and reveal that this molecule can cause population imbalances for different species. However, studies on the effects of fipronil used for seed treatment combined with abiotic and climatic factors, in particular toxicity toward earthworms, were not found in the literature.

To address this knowledge gap, this study aimed to assess the influence of an increase in temperature and reduction in moisture content on the toxicity of fipronil toward the earthworm species Eisenia andrei in two contrasting tropical soils. The hypotheses of this study are (1) the toxicity and risk of fipronil toward E. andrei increase at higher temperatures in both tropical test soils, and (2) these toxicity and risk increase in Entisol under drought conditions.

Materials and methods

To test the hypotheses of this study, chronic toxicity assays with earthworms E. andrei were performed in two contrasting natural soils (Entisol and Oxisol) with different combinations of temperatures (20, 25, and 27 °C) and soil moisture contents (30 and 60% of water holding capacity (WHC) for Entisol and 60% WHC for Oxisol). The number of juveniles produced by the earthworms was considered as the endpoint.

Test soils

Samples of two Brazilian soils, Entisol and Oxisol, were collected in the municipalities of Araranguá (29º 00'S, 49º 31'W) and Palmitos (27º 04'S, 53º 09'W), respectively, from the topsoil layer (0–20 cm), in areas with no history of contamination. The sampled soils were sieved (2 mm), defaunated applying the procedure described by Alves et al. (2013), air-dried, and maintained in the dark at room temperature for at least 6 months before the beginning of the assays. The soil characteristics are shown in Table 1, where the WHC and pH (1 M KCl) were measured following the ISO 11267 recommendations (ISO - International Organization for Standardization 2014), and the cation exchange capacity (CEC), soil organic matter (SOM) and sand, clay, and silt contents were determined based on methods described by Tedesco et al. (1995).

Test species

Bioassays were performed using laboratory cultured individuals of the species E. andrei (Lumbricidae, Oligochaeta), obtained from Minhobox® Corporation, Minas Gerais State, Brazil. The organisms were maintained in a room with a temperature of 20 ± 2 °C applying a 12-h photoperiod (ISO - International Organization for Standardization 2012), in boxes with a moist substrate composed of defaunated horse manure (free of contaminants), coconut fiber, and sand in the proportion of 2:1:0.3 (w:w:w), respectively. Once a week,

Table 1 Mean values (± standard deviation; n = 2) for physical and chemical characteristics of the tropical soils (Entisol and Oxisol) used in the ecotoxicological tests

| Parameter          | Entisol         | Oxisol         |
|--------------------|-----------------|----------------|
| pH (1 M-KCl)       | 4.2 ± 0.2       | 5.5 ± 0.1      |
| SOM (%)            | 2.2 ± 0.1       | 4.7 ± 0.1      |
| CEC (cmolc dm⁻³)   | 1.4 ± 0.1       | 18.3 ± 2.8     |
| WHC (%)            | 31.6 ± 1.1      | 58.8 ± 2.2     |
| Sand (%)           | 93.8 ± 0.4      | 28.6 ± 0.7     |
| Clay (%)           | 4.1 ± 0.2       | 33.0 ± 0.0     |
| Silt (%)           | 2.1 ± 0.1       | 38.4 ± 0.7     |
| Soil texture       | Sandy           | Clay loam      |

SOM: Soil Organic Matter;  
CEC: Cation Exchange Capacity;  
WHC: Water Holding Capacity
the earthworms received cooked oatmeal as food (≈ 50 g), and distilled water was used to maintain the breeding substrate moist but not too wet (water content ≈ 74%), following ISO (2012).

**Test substance**

Ecotoxicological assays were performed using the commercial formulation Shelter®, an insecticide used for chemical seed treatment, which contains 250 g of fipronil L$^{-1}$ as the active ingredient (a.i.). Test soils were spiked to give increasing concentrations (actual) of the a.i. (8.95, 19.48, 38.22, 155.61, and 237.81 mg kg$^{-1}$ for Entisol; 12.99, 27.94, 48.42, 204.67, and 374.29 mg kg$^{-1}$ for Oxisol), which were chosen from range-finding tests (data not shown). A control treatment was also performed using only distilled water.

The spiking was performed via an aqueous solution, with volumes calculated to reach 30 and 60% WHC for Entisol and only 60% WHC for Oxisol. In the latter case, we could not test lower moisture contents because the species did not reproduce at 30 and 45% WHC in this soil (data not shown). Soil moisture content and pH were checked at the beginning and the end of each bioassay (Table S1).

The actual concentrations tested in soil samples were estimated applying the modified QuEChERS extraction method without the cleaning step (Gebrehiwot et al. 2019), followed by quantification on an LC–MS (2020, Shimadzu) with electrospray ionization source, quadrupole mass analyzer, and LabSolution data acquisition system (as described in Hennig et al. 2021)). The limit of detection of the equipment for the soil samples analyzed was 0.01 mg of a.i. per kg of dry soil (mg kg$^{-1}$).

**Chronic toxicity assays**

The toxicity assays were performed according to ISO 11268–2 (ISO - International Organization for Standardization 2012). Adult individuals (3–4 months old, with well-developed clitellum) of the earthworm species *E. andrei* used in the assays were previously acclimatized to the respective test soil (Oxisol or Entisol), under the same temperature as the assays (20, 25, or 27 °C) 24 h before the beginning of the assays. Then, the individuals were exposed to increasing concentrations of fipronil in two types of soil (Entisol and Oxisol) and, in the case of Entisol, two different soil moisture contents (30 and 60% WHC) simulating different scenarios of water availability. For Oxisol, assays were performed only at 60% WHC. All assays were performed at temperatures of 20, 25, and 27 °C, simulating different scenarios of global warming.

Plastic containers (15 cm diameter and 10 cm height) had their lids perforated with an entomological needle to allow gas exchange. Each container received around 650 g of wet soil (control or spiked with the a.i. concentrations tested). Ten grams of horse manure moisturized (in a 1:2 ratio w/v) of dry manure and distilled water, respectively) were offered as food at the start of the assays. Ten earthworms with known individual weights (250–600 mg; Table S2) were inserted in each replicate. Four replicates were performed for each treatment. Once a week (throughout the entire experiment – 56 days), the soil moisture was adjusted with distilled water (weight-based) and the amount of food (horse manure) consumed per test vessel was visually estimated (based on the quantity remaining on the top of the soil). The food replacement (maximum of 5 g per week) was performed in a way to offer similar amounts of food in the containers of all treatments. After 28 days from the beginning of the test, surviving adult earthworms were removed and counted. During the next 28 days, only the soil and the cocoons and juveniles produced remained in the containers. At the end of the test (56 days), the experimental units were immersed in a water bath (60 ± 5 °C) for 1 h (adapted from Annex D of the ISO 11268:2—ISO 2012), and the *E. andrei* juveniles were manually counted.

**Data analysis**

The homoscedasticity and normality of the data were tested via Bartlett and Kolmogorov–Smirnov tests, respectively. Logarithmic transformations were applied only to the data obtained for Oxisol at 20 °C, to achieve the assumptions. Significant differences ($p < 0.05$) between treatments were tested using ANOVA. Factorial ANOVA was applied to evaluate the interaction of fipronil concentrations, temperature, and soil moisture in relation to the fipronil toxicity toward earthworms. A generalized linear model (GLM) was applied to the data to estimate the contribution of the same factors to the production of juveniles. The effective concentrations (ECs), that is, those at which 10% and 50% reductions in the species reproduction were observed (EC$_{10}$ or EC$_{50}$, respectively), were estimated using nonlinear regression models, according to Environment Canada (2007). The statistical analysis was performed using Statistica®, version 13.5.0.17 (TIBCO DATA SCIENCE 2013).

To check the influence of temperature and soil moisture (in isolation) on the reproductive performance of *E. andrei*, the mean number of juveniles from the control treatments was compared in terms of temperature (in each soil type) and soil moisture content (only for Entisol, in each temperature) through the Tukey’s HSD test ($p < 0.05$). To identify significant differences between the EC values obtained applying the three temperatures tested (20 vs 25 vs 27 °C) for each soil, and as a function of the soil moisture content for the Entisol soil (30 vs 60% WHC), a generalized likelihood ratio test ($p < 0.05$) was used, as described by Natal-da-Luz et al. (2011).
The predicted environmental concentrations (PEC) after 56 days were calculated according to the method of the European and Mediterranean Plant Protection Organization (EPPO 2003) using the software ESCAPE (2013). A scenario with a soybean crop and soil densities of 1.5 and 1.0 g cm$^{-3}$ for Entisol and Oxisol, respectively, was considered. Also, the worst-case scenario of the Shelter® application was considered, at a sowing density of 60 kg of seed per ha (EMBRAPA 1988), with the highest recommended pesticide dose for the soybean crop (37.5 g a.i. per 60 kg of seeds, according to the manufacturer’s recommendation) and with 5% of interception by plants, during only one planting cycle (Jackson et al. 2009). Dissipation half-life ($DT_{50}$ values) values of 68 days (Ying and Kookana 2006), 31 days (EFSA - European Food Safety Authority 2006), and 28 days (Shuai et al. 2012) were considered for the temperatures of 20, 25, and 27 °C, respectively. The values for the predicted no-effect concentrations (PNEC) were estimated based on the ratio between the EC$_{10}$ values and an assessment factor of 100 (European Commission 2002).

The risk assessment regarding the toxicity of fipronil toward $E$. $andrei$ was carried out using the hazard quotient (HQ) approach, dividing PEC by PNEC, according to the procedure recommended by the European Commission (European Commission 2002). When HQ $> 1$, the risk is considered to be significant.

**Results**

All validity criteria for chronic ecotoxicological assays with earthworms (ISO - International Organization for Standardization 2012) were met (Table S2).

In all exposure scenarios, there was a decrease in the number of juveniles $E$. $andrei$ produced with increasing fipronil concentrations (Fig. 1). In addition, the a.i. toxicity (based on the EC$_{50}$) toward earthworms was higher in Entisol compared to Oxisol (Table 2).

In Entisol, applying the drier condition (30% WHC), fipronil toxicity was higher at 25 and 27 °C compared to 20 °C. Also, in the same soil, at the standard moisture content (60% WHC), the fipronil toxicity was lower at 27 °C compared to 20 and 25 °C (Table 2). In Oxisol, the fipronil toxicity (based on the EC$_{50}$) was significantly ($p < 0.05$) higher at 27 °C compared to 20 and 25 °C.

The soil moisture content affected the reproduction of earthworms in Entisol, revealing a poor reproductive performance in control replicates at 30% WHC in comparison with 60% WHC, regardless of the temperature (Fig. 1; Table S2). Also, fipronil toxicity (based on the EC$_{50}$) was higher under the drier condition (30% WHC) at 27 °C, while at 20 and 25 °C, the soil moisture did not significantly ($p > 0.05$) influence the effect (Table 2).

The factorial ANOVA results indicated a significant ($p < 0.05$) interaction between fipronil concentration, temperature, and soil moisture content with regard to the

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**Fig. 1** Dose–effect response curves representing the effects of fipronil on the reproduction of $Eisenia andrei$ exposed for 56 days to increased concentrations (actual) of fipronil in Entisol (30 and 60% WHC) and Oxisol (60% WHC) at 20, 25 or 27 °C.
production of juveniles in Entisol, while in Oxisol the reproduction was influenced by the concentration of fipronil and the temperature in isolation (Table S3).

According to the GLM model (Table 3), for both types of soil, the effects of fipronil concentration, soil moisture content, and temperature can play different influences on the number of juveniles produced. According to the coefficients of the generated models, the effect of the fipronil concentration on earthworm reproduction in Entisol is twice the effect observed in Oxisol, while for the temperature, the contrary trend was observed (with a stronger effect in Oxisol). Regarding the influence of soil moisture content in Entisol, a higher number of juveniles were produced at the higher value (60% WHC).

Based on the HQ approach (Table 4), fipronil represented a risk to earthworms in Entisol (30% WHC) and Oxisol

| Soil and moisture content | Ecotoxicological parameter | Fipronil concentration (mg kg⁻¹) |
|---------------------------|----------------------------|---------------------------------|
|                           | Temperature                | 20 °C                           |
|                           |                            | 25 °C                           |
|                           |                            | 27 °C                           |
| Entisol 30% WHC           | EC₅₀                       | 58.71aA                         |
|                           | Limits (95%)               | (32.89 – 84.52)                 |
| Entisol 60% WHC           | EC₅₀                       | 52.58bA                         |
|                           | Limits (95%)               | (24.22 – 80.93)                 |
| Oxisol 60% WHC            | EC₅₀                       | 277.57a                         |
|                           | Limits (95%)               | (82.94 – 472.20)                |

*Confidence limit (95%) could not be estimated

| Soil and moisture content | PECᵀWA₅₆d | PNEC | HQ | PECᵀWA₅₆d | PNEC | HQ | PECᵀWA₅₆d | PNEC | HQ |
|--------------------------|----------|------|----|----------|------|----|----------|------|----|
| Entisol 30% WHC          | 0.04     | 0.12 | 0.33| 0.03     | 0.06 | 0.50| 0.03     | 0.02 | 1.50|
| Entisol 60% WHC          | 0.04     | 0.04 | **1.00** | 0.03 | 0.03 | **1.00** | 0.03 | 0.05 | 0.60|
| Oxisol 60% WHC           | 0.05     | 0.08 | 0.62| 0.04     | 0.05 | 0.80| 0.04     | 0.01 | **4.00**|

HQ values higher than 1 (in bold) indicate significant/unacceptable risk;
PNEC: EC₁₀/100
Discussion

Regardless of the exposure scenario, there was a reduction in E. andrei reproduction with an increase in the fipronil concentration (Fig. 1). This can be explained by the mode of action of this molecule, as fipronil is known to block the passage of chloride ions through the channels regulated by the neurotransmitter γ-aminobutyric acid (GABA) in invertebrates (Tingle et al. 2003). However, the toxic mechanisms of fipronil toward earthworms still must be elucidated, since the majority of studies with oligochaetes did not explore it (Mostert et al. 2002; Alves et al. 2013; Qin et al. 2014; Zortéa et al. 2018b).

Various effects of fipronil on earthworms have been reported in the literature. It has been found to affect their growth (Qin et al. 2014), reproduction (Alves et al. 2013; Zortéa et al. 2018b), and survival (Qu et al. 2014). Therefore, these studies reinforce our findings, despite being conducted under standard conditions of soil, temperature, and moisture, indicating that fipronil may have harmful effects on the earthworm population in the soil.

The production of juveniles in the control assays performed at 27 °C (in Oxisol) and 25 °C (in Entisol 30% WHC) was significantly lower ($p < 0.05$, Tukey’s HSD test – Table S2) than that found at the standard temperature (20 °C), suggesting that the increase in temperature, in isolation, can influence the reproductive performance of earthworms (Edwards and Bohlen 1996; Millican and Lutterschmidt 2007; González-Alcaraz and Gestel 2016a; Johnston and Herrick 2019; Singh et al. 2019). Furthermore, the results of this study revealed that an increase in temperature enhanced the fipronil toxicity toward earthworms in Entisol at 30% WHC and in Oxisol at 60% WHC (Table 2). These effects can be explained by the interaction between the effects of higher temperature and a.i. concentration (Table S3). The GLM indicated that the increase in both factors (fipronil concentration and temperature) contributed to the decrease in the reproduction of earthworms (Table 3). A higher temperature may increase the activity of earthworms, inducing greater contact with and uptake of chemicals in the soil (Belfroid et al. 1994). In addition, an increase in temperature can promote the desorption of chemicals from the solid matrix of the soil, increasing their bioavailability and the degree of contact with and uptake by soil organisms (Navarro et al. 1992; Belfroid et al. 1994). Simultaneously, high temperatures reduce the activity of detoxification enzymes, interfering with the recuperation of organisms exposed to contamination (Hackenberger et al. 2018). These effects have also been reported for imidacloprid (Bandeira et al. 2020), carbaryl (Lima et al. 2015), carbofuran, and chlorpyrifos (De Silva et al. 2012) in studies on earthworms, where the toxicity of the pesticide increased with temperature, corroborating the results of this study.

However, although the results with Oxisol and Entisol 30% WHC support our first working hypothesis, those obtained with Entisol 60% WHC do not, since fipronil toxicity was lowest at the highest temperature applied (Table 2; Fig. 1). A possible explanation for this may be related to a loss of the a.i. through its degradation at higher temperatures in association with the greater moisture content in this soil. Some authors have reported that the sorption (Freundlich coefficient, Kf) and persistence (half-life values) of fipronil are lower in sandy soils compared to fine-textured soils (Doran et al. 2006; Spomer and Kamble 2009; Mandal and Singh 2013). These factors may enhance the bioavailability of fipronil in the soil pores of Entisol, where it is more susceptible to the degradation process, catalyzed by high temperatures and water moisture content (Scorza Júnior and Franco 2013). Increasing the temperature can increase the activity of decomposer microorganisms as well as catalytic substances that act in the degradation of xenobiotics (Navarro et al. 1992). Higher water contents in soil with lower WHC, such as Entisol, can also accelerate the fipronil degradation process due to the breaking of the molecule by hydrolysis processes (Tingle et al. 2003). The results reported herein are consistent with those observed by Hennig et al. (2022), who found that fipronil toxicity toward collembolans in Entisol was lower at 27 °C compared to 25 and 20 °C. However, the cited authors, as in this study, did not measure fipronil degradation for the respective contamination scenarios and climatic factors; therefore, we are not able to verify this assumption.

The soil moisture content interacted with the fipronil concentration (Table S3), which influences the fipronil toxicity in Entisol and also affects the reproduction performance of earthworms in this soil, regardless of the temperature (Fig. 1). This is also corroborated by the GLM results (Table 3), which indicated that the increase in the soil moisture content favors the reproduction of earthworms. A reduction in the soil moisture content can reduce the extent of water films around soil particles, known as hygroscopic water (Coleman et al. 2004). This can affect the survival, growth, and reproduction of earthworms in the soil (Singh et al. 2019), since these organisms are soft-bodied, with highly permeable and sensitive skin (Peijnenburg et al. 2012). In this study, for Entisol at 27 °C, drier conditions revealed significantly higher a.i. toxicity in comparison with
the standard soil moisture (based on the EC\textsubscript{50}; Table 2). The effects of increased toxicity toward earthworms with reduced soil moisture content have been reported for fluoranthene (Long et al. 2008), carbaryl (Lima et al. 2011) and propiconazole (Hackenberger et al. 2018). According to Lima et al. (2011), dehydration due to drought conditions can enhance concentrations of a.i. in the bodies of earthworms, increasing the toxicity of pollutants. Moreover, as observed from our data (Table 3), when high temperatures are combined with drought conditions, the toxicity of chemicals toward poikilothermic organisms, such as earthworms, may be enhanced due to the greater uptake rates at higher temperatures (Donker et al. 1998; Šustr and Pižl 2010; González-Alcaraz and Van Gestel 2016b).

The PEC values (Table 4) indicated that, in the highest exposure scenario, residues of fipronil at levels of 0.03 to 0.05 mg kg\textsuperscript{-1} may be present in the soil, even after 56 days of application. Some studies indicate that these levels may be realistic since concentrations of 0.003 to 0.15 mg kg\textsuperscript{-1} have been found in a peanut field (Li et al. 2015), 0.01–0.15 mg kg\textsuperscript{-1} in a cotton field (Chopra et al. 2011), and 0.01 to 2.06 mg kg\textsuperscript{-1} in other agricultural fields (Ying and Kookana 2006).

Even though the EC\textsubscript{10} values for fipronil toxicity toward earthworms (0.44–12.40 mg kg\textsuperscript{-1}; Table 2) were higher than the estimated PEC and the concentrations reported in the literature in agricultural fields, the HQ approach indicated a risk associated with fipronil, in agreement with the toxicological effects (Table 2). In the case of Entisol and Oxisol with moisture contents of 30% and 60% WHC, respectively, the risk observed only at 27 °C may be due to additive effects of fipronil concentration and high temperature, as previously reported. However, the risk identified for Oxisol 60% WHC was around three times higher compared to Entisol 30% WHC, probably due to the pedogenetic characteristics of this soil. In this case, in addition to the effects of the contaminant, the high clay content (Table 1) could hamper the colonization of earthworms (Chelinho et al. 2014). In Entisol 60% WHC, the highest temperature tested could lead to a loss of the a.i. through catalyzation of the degradation processes (Navarro et al. 1992; Scorza Júnior and Franco 2013; Tingle et al. 2003), while at 20 and 25 °C, the bioavailability of the a.i. to soil organisms is likely to be better, representing a risk to earthworms in these scenarios (Navarro et al. 1992; Belfroid et al. 1994). It should be noted that soil moisture content was not considered in the calculation of PEC using ESCAPE and thus the PEC values for Entisol are the same for the two moisture contents studied. In addition, since the degradation of the molecules was not assessed in this study, the reported data on increased/reduced risk should be interpreted with caution.

The HQ approach revealed a potential environmental risk for earthworms from the application of fipronil to natural tropical soils within a scenario of climate change and indicated that soil type can modulate the influence of temperature on fipronil toxicity toward earthworms. Abiotic factors related to soil type and climate, which directly influence the dynamics and bioavailability of pollutants to soil organisms, therefore need to be considered in risk assessments.

Conclusions

The results reported herein demonstrate that, at a standard soil moisture condition, increasing temperatures can increase fipronil toxicity to earthworms in clayey soils and decrease the toxicity in sandy soils. Furthermore, in sandy soils, the influence of increasing temperatures on fipronil toxicity seems to be dependent on soil moisture content, since at lower soil moisture, the highest tested temperature led to an increase in fipronil toxicity, while at higher soil moisture, the increase in temperature led to a reduction in toxicity. Therefore, the predicted climate change scenarios, which can combine increasing temperatures and reducing soil moisture contents, may interact in a complex way with fipronil and modify its toxicity and risk toward nontarget organisms in tropical soils.

Our findings reinforce the need to include abiotic and climatic factors in risk and ecotoxicological assessments of pesticides, such as different soil types and different temperature and moisture contents, to represent more realistic scenarios that can predict more precisely the effects of global warming on the toxic potential of pesticides toward soil fauna.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11356-022-19813-8.

Declarations

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Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

Author contribution TBH: conceptualization, data curation, formal analysis, investigation, writing – original draft. PRLA: conceptualization, formal analysis, funding acquisition, investigation, project administration, resources, supervision, writing – review and editing. FOB: investigation, data curation, formal analysis. LCC: investigation. JSD: investigation. MATS: supervision and data curation. DB: resources, supervision, writing – review and editing.
Ethics approval and consent to participate: All procedures performed in studies involving animals were in accordance with the ethical standards of the institution or practice at which the studies were conducted (Brazilian regulation for the scientific use of animals – Law no. 11.794). Consent to participate and publication is not applicable.

Data availability The data that support the findings of this study are available and should be requested by e-mail.

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