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SHORT COMMUNICATION / COMUNICACIÓN BREVE

SOIL FAUNA HAZARD INDEX TO IDENTIFY THE RISK OF EXPOSURE TO BIOCIDAL SUBSTANCES

Indice de peligrosidad en la fauna del suelo para identificar el riesgo de exposición a sustancias biocidas

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ABSTRACT

Chemical pollution in the soil compartment can lead to considerable biodiversity loss and poor soil quality. Soil fauna inside and near agroecosystems, agricultural landscapes, and cattle grasslands provide various ecosystem services that contribute to sustaining human well-being. Interviews were conducted with farmers in two Costa Rican provinces to identify the active ingredients used in agricultural and livestock farms. Using a soil fauna hazard index, 27 agrochemicals and 18 veterinary drugs were categorized as hazardous substances to soil invertebrates. The scientific literature reports the effects of exposure to many of these substances on various levels of biological organization, therefore, it is critical to promote appropriate practices in their use to reduce environmental effects.

Palabras clave: toxicidad, productos agroquímicos, medicamentos veterinarios, índice de peligrosidad.

RESUMEN

La contaminación química en el compartimento edáfico puede provocar una pérdida considerable de biodiversidad y una mala calidad del suelo. La fauna del suelo dentro y cerca de los agroecosistemas y paisajes agrícolas, así como los pastizales ganaderos, proporcionan una variedad de servicios ecosistémicos que contribuyen a sostener el bienestar humano. Para identificar los ingredientes activos utilizados en las explotaciones agrícolas y ganaderas, se realizaron entrevistas a agricultores de dos provincias costarricenses. Mediante un índice de peligrosidad para la fauna del suelo, se clasificaron 27 productos agroquímicos y 18 medicamentos veterinarios como sustancias peligrosas para los invertebrados del suelo. La literatura científica reporta los efectos de la exposición a muchas de estas sustancias en varios niveles de organización biológica, por lo tanto, es crítico promover prácticas apropiadas en su uso para reducir los efectos ambientales.

INTRODUCTION

The invertebrate community in soil ecosystems plays a vital role in maintaining soil health and fertility (Lavelle et al. 2006). This includes soil microfauna (e.g., mites, nematodes, rotifers, tardigrades, and copepod scavengers); mesofauna (e.g., Acari, Collembola, Tardigrada, Protura, Diplura, and Enchytraeidae) and macrofauna (e.g., isopods, spiders, bugs, annelids, and gastropods) which have direct and indirect participation in biogeochemical cycles and habitat engineering (Solanki et al. 2020) that enhance healthy soil characteristics for crop production systems.

Besides the above-mentioned soil invertebrates, dung beetles play essential roles in soil and animal health. Dung beetles feed on mammal feces and use it as a nesting site (Huerta and García 2013). By fragmenting dung, creating galleries and micropores, and dragging in the fecal matter below ground, they offer at least three ecosystem services, including organic matter decomposition and soil formation, which results in increased grassland productivity and biological control (Sands and Wall 2018). Their biological action prevents nematode larval growth in dung, resulting in a positive impact on cattle health. This leads to increased meat or milk production yields and reduced use of veterinary medication to treat animals against endoparasitic infections (Beynon et al. 2015).

Many of these benefits are disrupted by food security-related human activities of great importance, such as traditional agriculture and cattle ranching, which utilize substances from different chemical families (Karasali and Maragou 2016) to prevent and control undesirable organisms. These active ingredients can be classified according to the type of target organism for which they were manufactured, including algicides, acaricides, bactericides, parasiticides, fungicides, herbicides, insecticides, molluscicides, nematicides, and rodenticides (Boxall et al. 2003, Michalak and Chojnacka 2014).

Soil fauna can be exposed to agricultural pesticides inside application areas when pesticide particles move across the soil profile, during and after soil, seed, or foliar treatments (Popenoe 2018). When the wind erodes contaminated soils or runoff forms, pesticides can also reach soils outside of application areas (Singh et al. 1996). These organisms are exposed to pollutants through frequent contact with soil particles, water drops stored in the soil, and pore spaces filled with air (Peijnenburg et al. 2012). Among the different groups of soil fauna, geophages, soft-bodied invertebrates (e.g., earthworms), and geobionts (which spend their entire lifecycles in soil and cannot leave this condition), are especially sensitive to xenobiotics present in the soil compartment, being surface contact and ingestion the main exposure routes (Solanki et al. 2020).

On the other hand, soil-dwelling organisms are exposed to veterinary drugs primarily by soil amendment with manure or slurry (Baguer et al. 2000). Another route is through treated animals that excrete urine and feces directly into pasturelands (Zhou et al. 2020). Because the metabolism of the active ingredients in veterinary drug formulations by an animal's system depends on various factors (e.g., substance properties, age, or physical condition of the treated animal), excretion products contain both the parent compound and secondary metabolites (Zhou et al. 2020, de Souza and Guimarães 2022). A third pathway occurs when droplets of a veterinary medicine solution leach into the soil compartment during and after spray baths (Boxall et al. 2003).

Negative effects on soil fauna due to exposure to these substances have been demonstrated at different levels of biological organization. Sublethal exposure can have detrimental effects on species' fitness, interfering with the individual's ability to feed, hide from predators, reproduce, or survive, resulting in population declines that can lead to local or global extinctions (Grant et al. 2013, Rumschlag et al. 2020). In contrast, lethal exposure can cause death to the organism by direct action of the active principle at a certain concentration (Duffus 1993). Identifying which substances pose greater hazards to the health of soil organisms is relevant, considering that the loss of soil biodiversity can lead to a higher incidence of diseases in food crops and livestock, resulting in increased production costs for farmers and posing risks to public health.

Within the context of the various routes of contamination resulting from the extensive use of these products, Cartago is one of the provinces with the highest pesticide use, with potatoes, onions, carrots, and broccoli being among the most commonly cultivated crops. In addition, although to a lesser extent, it is also characterized by numerous dairy farms. On the other hand, cattle ranching is a significant activity in the Guanacaste province, and to a lesser extent, agriculture, with forage grasses, rice, orange, sugar cane, or pitahaya among the most prevalent crops. These economic activities in both provinces imply an extensive use of agricultural pesticides and veterinary drugs. Interviews are a valuable tool for identifying the active ingredients used in food production systems (Blair et al. 1997).

Considering the information mentioned above, this study aims to identify which substances are more hazardous to soil fauna that provide regulation and support ecosystem services, based on information about the use of agricultural pesticides and veterinary drugs in farms from six districts of the Cartago and Guanacaste provinces in Costa Rica. For this purpose, a soil fauna hazard index (SFHI) was created that considers available toxicological information about the active ingredients.

METHODS

Study area

This study was conducted in 30 food production farms from six Costa Rican districts belonging to the provinces of Cartago (Llano Grande and San Juan de Chicuá districts) and Guanacaste (Caballito, Pozo de Agua, San Antonio, and Santa Elena districts), where 13 agricultural farmers and 17 livestock farmers were interviewed. The Cartago province is part of the Central Conservation Area (ACC, for its Spanish acronym) and is characterized by humid tropical and very humid premontane forests. The Guanacaste province has two conservation areas: the Guanacaste Conservation Area (ACG) and the Tempisque Conservation Area (ACT), where at least five ecosystem types can be identified. These include tropical dry, tropical humid, cloud forests, and riparian and coastal ecosystems.

Data collection

Study participants in both provinces were recruited between August 2022 and April 2023, based on their productive activity (agriculture or cattle ranching), geographical proximity to one another, and the respondents' willingness to participate in the research. Each participant was asked to access the storage rooms for agrochemicals and veterinary drugs to photograph the information written on the labels of plastic or glass containers, specifically concerning the active ingredients used by farmers in their crop or animal production cycles.

Data analysis

Information about each active ingredient was gathered from three sources: the Central American Institute for Studies on Toxic Substances (IRET, Spanish acronym) database, scientific literature, and product information sheets provided by manufacturers. Biocides were categorized into three groups based on patterns of available information for each.

The first two groups correspond to active ingredients used exclusively in animal production farms and include antiparasitic drugs (e.g., antihelmintic drugs and endectocides) and antibiotics; whereas the third group includes agricultural pesticides and three veterinary use ectoparasiticides (chlorpyriphos, fipronil, and cypermethrin) that are also used as insecticides in agricultural production systems.

Based on patterns of available information for each group, parameters were established according to the possible impact on soil fauna health during and after exposure, and a soil fauna hazard index (SFHI) with a score ranging from 0 to 1 was calculated (**Tables I-III**). A score of 0 indicates a low risk, and a score of 1 indicates a high risk to soil fauna health.

TABLE I. PARAMETERS AND FORMULA USED FOR ESTIMATING A SOIL FAUNA HAZARD INDEX IN THE CATEGORY OF AGRICULTURAL PESTICIDES AND VETERINARY USE ECTOPARASITICIDES.

Characteristic	Categorization and score
Systemic action (SA)	no = 0 yes = 1
Soil persistence (SP)	low = 0 moderate = 0.5 high = 1
Soil mobility (SM)	non-mobile or low = 0 moderate = 0.5 high = 1
Known harmful metabolites (HM)	no = 0 yes = 1
Earthworm toxicity (*Eisenia foetida*) (ET)	low = 0 moderate = 0.5 high = 1
Soil fauna hazard index (SFHI) formula = (SA + SP + SM + HM + ET)/5	

RESULTS

Cartago province

Agricultural farms

In agricultural production farms visited in Cartago province, 46 active ingredients (22 fungicides, 17 insecticides, and seven herbicides) were found. Twenty-three active ingredients from agricultural

TABLE II. PARAMETERS AND FORMULA USED FOR ESTIMATING A SOIL FAUNA HAZARD INDEX IN THE CATEGORY OF OTHER ANTIPARASITIC DRUGS.

Characteristic	Categorization and score
Reported reproductive toxicity (RT)	no = 0 yes = 1
Reported behavioral effects (BE)	no = 0 yes = 1
Broad spectrum activity (BS)	no = 0 yes = 1
Soil fauna hazard index (SFHI) formula = (RT + BE + BS)/3	

TABLE III. PARAMETERS AND FORMULA USED FOR ESTIMATION OF A SOIL FAUNA HAZARD INDEX IN THE CATEGORY OF ANTIBIOTICS.

Characteristic	Categorization and score
Broad spectrum activity (BS)	no = 0 yes = 1
Reported alterations in the microbiome (MA)	no = 0 yes = 1
Reported toxicity (RT)	no = 0 yes = 1
Soil fauna hazard index (SFHI) formula = (BS + MA + RT)/3	

pesticide formulations provided the toxicological information considered in the parameters for the soil fauna hazard index and obtained scores equal to or above 0.5 (**Table IV**).

TABLE IV. LIST OF AGRICULTURAL PESTICIDES' ACTIVE INGREDIENTS WITH SOIL FAUNA INDEX SCORES ≥ 0.5.

Soil fauna index score	Active ingredient(s)
0.8	Cyproconazole, fluopicolide, thiamethoxam
0.7	Azoxystrobin, dimethoate, metalaxyl, metribuzin, oxamyl, triadimenol
0.6	Thiophanate-methyl, propiconazole
0.5	Abamectin, benfuracarb, carbendazim, chlorpyriphos, clethodim, epoxiconazole, glyphosate, indoxacarb, lambda-cyhalothrin, linuron, lufenuron, prochloraz

Livestock farms

In livestock production farms visited in Cartago province, 21 active ingredients (14 antibiotics, three ectoparasiticides, three endectocides, and one antihelmintic drug) were found. Nine active ingredients from veterinary drug formulations provided toxicological information that was considered in the parameters, resulting in soil fauna hazard index scores of ≥ 0.5 (**Table V**).

TABLE V. LIST OF ACTIVE INGREDIENTS OF VETERINARY DRUGS WITH SOIL FAUNA HAZARD INDEX SCORES ≥ 0.5.

Soil fauna index score	Active ingredient(s)
1.0	Eprinomectin, ivermectin, tetracycline
0.7	Doramectin, enrofloxacin, gentamicin, oxytetracycline
0.5	Chlorpyriphos, fipronil

Guanacaste province

Agricultural farms

In agricultural production farms and pasturelands visited in Guanacaste province, eight active ingredients (six herbicides and two insecticides) were found. Four active ingredients from agricultural pesticide formulations provided toxicological information that was taken into account in the parameters, resulting in soil fauna hazard index scores ≥ 0.5 (**Table VI**).

TABLE VI. LIST OF AGRICULTURAL PESTICIDES' ACTIVE INGREDIENTS WITH SOIL FAUNA HAZARD INDEX SCORES ≥ 0.5.

Soil fauna index score	Active ingredient(s)
0.7	2,4-D, picloram
0.6	Imidacloprid
0.5	Glyphosate

Livestock farms

In livestock production farms visited in Guanacaste province, 21 active ingredients (11 antibiotics, six ectoparasiticides, three endectocides, and one antihelmintic drug) were found. From the total number of veterinary drugs identified, nine active ingredients from veterinary drug formulations provided the toxicological information taken into account in the parameters and obtained soil fauna hazard index scores ≥ 0.5 (**Table VII**).

TABLE VII. LIST OF ACTIVE INGREDIENTS OF VETERINARY DRUGS WITH SOIL FAUNA HAZARD INDEX SCORES ≥ 0.5.

Soil fauna index score	Active ingredient(s)
1.0	Ivermectin
0.7	Doramectin
0.6	Enrofloxacin, gentamicin, oxytetracycline, sulfamethoxazole, trimethoprim
0.5	Chlorpyriphos, fipronil

DISCUSSION

From the list of active ingredients used in agricultural production systems from both provinces that obtained high scores in the soil fauna hazard index (SFHI), available information on toxicity to soil invertebrates was found for thiamethoxam and clothianidin (Ritchie et al. 2019), imidacloprid (Konestabo et al. 2022), abamectin (Jensen et al. 2007), dimethoate (Engenheiro et al. 2005, Ferreira et al. 2015), metribuzin (Travlos et al. 2017), 2,4-D (Singh and Singh 2015), carbendazim (Song et al. 2022), azoxystrobin (Han et al. 2014), and chlorpyrifos and cypermethrin (Bang et al. 2007, Zhou et al. 2011).

The macrocyclic lactones ivermectin (Rosales et al. 2012, Verdú et al. 2015, Adler et al. 2016, Manning et al. 2017) and eprinomectin (Serafini et al. 2019), the antibiotics enrofloxacin (Li et al. 2015, Gao et al. 2018) and oxytetracycline (Ma et al. 2019, Zhang et al. 2019), and the insecticides chlorpyriphos and cypermetrin (Bang et al. 2007, Zhou et al. 2011) were among the active ingredients used in animal production systems from both provinces that obtained high scores in the SFHI and for which available information on toxicity to soil invertebrates was found at lethal and sublethal exposures.

Besides mortality events, sublethal effects in different levels of biological organization have been reported in soil invertebrates due to exposure to the substances mentioned above and include evidence of oxidative stress (Han et al. 2014, Ferreira et al. 2015), increase in antimicrobial resistance genes and changes in gut microbiome composition (dysbiosis) (Song et al. 2022), behavioral as well as morphological and physiological disruptions (Engenheiro et al. 2005, Travlos et al. 2017), and developmental and reproductive effects (Jensen et al. 2007, Ritchie et al. 2019, Konestabo et al. 2022).

Ivermectin, a veterinary drug widely used in both provinces more than twice a year as a prophylactic treatment to control internal and external parasites in cattle obtained the highest score in the index (1.0). Studies that evaluate sublethal exposure to ivermectin in soil fauna suggest that this drug is highly toxic to soil invertebrates (Rosales et al. 2012, Verdú et al. 2015, Adler et al. 2016, Manning et al. 2017).

The vast majority of scientific literature consulted focuses on the toxicity of parent compounds in controlled laboratory settings using model organisms such as *Eisenia fetida* or *Folsomia candida*, with less attention paid to toxic secondary metabolites and enantiomers of active ingredients (Xu et al. 2011, Yu et al. 2012), as well as field studies that evaluate toxicity in realistic scenarios with other groups soil invertebrates.

Studies with evidence about the toxicity in soil fauna of many of the active ingredients used in both food production systems of the Cartago and Guanacaste provinces are absent. There is also an information gap on the ecotoxicological behavior of most veterinary drugs (e.g., soil persistence and mobility, identified toxic secondary metabolites, and toxicity to model invertebrate organisms) making it difficult to standardize the parameters used to calculate the SFHI.

CONCLUSION

With the information available for each group of substances, the SFHI attempts to identify which substances are more hazardous to soil fauna so that their use in food production systems can be controlled and reduced. Therefore, careful application and administration of agrochemicals and veterinary drugs, respectively, using recommended doses and following instructions given by product manufacturers, can improve biological activity in agricultural soils and pastureland ensuring the long-term provision of support and regulation ecosystem services.

Future studies should focus on evaluating the toxicity of many of the active ingredients listed in this study for which there is an information gap; conducting toxicological assays with secondary metabolites and enantiomers of both pesticides and veterinary use medications; performing more field studies in realistic scenarios with other species of soil invertebrates outside of model organisms used in toxicological assays, and standardizing ecotoxicological information for veterinary drugs.

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