frontiers | Frontiers in Ecology and Evolution

TYPE Original Research
PUBLISHED 14 November 2024
DOI 10.3389/fevo.2024.1424047

Use of anticoagulant rodenticides: a silent threat to biodiversity in a city of Northern Colombian Andes

María Antonia Jaramillo-Q.*, Carlos A. Delgado-V. and Andrés Arias-Alzate

Facultad de Ciencias y Biotecnología, Universidad CES, Medellín, Colombia

OPEN ACCESS

EDITED BY
Laura Pereyra,
CONICET Instituto de Ecorregiones Andinas (INECOA), Argentina

REVIEWED BY
Maria Jose Ruiz-Lopez,
Spanish National Research Council (CSIC), Spain
Tanja Blažić,
Institute of Pesticides and Environmental Protection, Serbia

*CORRESPONDENCE
María Antonia Jaramillo-Q.
jaramilloq.maria@uces.edu.co

RECEIVED 27 April 2024
ACCEPTED 16 October 2024
PUBLISHED 14 November 2024

CITATION
Jaramillo-Q. MA, Delgado-V. CA and Arias-Alzate A (2024) Use of anticoagulant rodenticides: a silent threat to biodiversity in a city of Northern Colombian Andes. *Front. Ecol. Evol.* 12:1424047.
doi: 10.3389/fevo.2024.1424047

Introduction: Anticoagulant rodenticides are generalist toxicants that have lethal and sublethal effects on non-target species, leading to an impact on wildlife conservation due to poisoning and bioaccumulation of these substances. However, in Colombia, little research has been conducted on this environmental issue. This study evaluated the use of anticoagulant rodenticides in an urban area in Colombia from an ecological and regulatory perspective.

Methods: First, the study analyzed the usage patterns of anticoagulant rodenticides for public health in the urban area of Medellín over a seven-year period. It also evaluated the potential impact of anticoagulant rodenticides deposits on the city's Main Ecological Structure and the predator species that may be indirectly affected. Additionally, the study analyzed compliance with regulations on the sale and use of anticoagulant rodenticides in Colombia, specifically for products marketed online. A Hot Spot Analysis was conducted to determine the potential risk of the Main Ecological Structure and the predators selected to be exposed to anticoagulant rodenticides.deposit. On the other hand, the ecotoxicological information of the anticoagulant rodenticides commercialized online in Colombia was characterized, and it was verified whether they complied with the necessary sanitary and environmental national regulations.

Results: Between 2016 and 2022, over 3 million grams of brodifacoum, were applied in the urban area of Medellín and critical ARs hotspots were identified. The use of anticoagulant rodenticides has significantly increased the doses and number of application sites each year. More than half of the points (51.13%) in which anticoagulant rodenticides were applied were within the Main Ecological Structure. The Strigiformes order represents the greatest risk of indirect exposure to anticoagulantrodenticides.

Discussion: Currently, many anticoagulant rodenticide products lack ecotoxicity studies for non-target species and fail to adequately inform consumers of the potential environmental impacts resulting from the use of these poisons. To gain a better understanding of the prevalence, transfer routes, and possible acute and chronic effects of anticoagulant rodenticides.

KEYWORDS

rat poison, urban biodiversity, urban ecological network, ecotoxicology, environmental policies, spatial ecology, Medellín -Colombia

1 Introduction

Environmental degradation, along with other factors (i.e. ecosystems loss), is threatening the long-term preservation and conservation of biodiversity, particularly in urban environments (McKinney, 2002; Murray and St. Clair, 2015). Activities such as pesticide use to control urban pests represents an additional threat to wildlife, as it could be silently poisoning the ecological networks of cities, which are comprised of local natural reserves, parks, water systems and any natural element of the landscape that can have an impact on the conservation of urban biodiversity (Liu et al., 2017; Huang et al., 2021). As a result, the use of pesticides, such as anticoagulant rodenticides (ARs), could be increasing the vulnerability of urban wildlife populations to other factors such as habitat loss, pollution and roadkill (Serieys et al., 2019).

ARs are a type of pesticide used to combat the adverse effects of synanthropic rodents, including economic losses due to crop damage and public health problems as disease transmitters (Himsworth et al., 2013; Jacob and Buckle, 2018; Namala et al., 2022; Witmer, 2022). ARs inhibit the activity of vitamin K epoxide reductase, which can compromise the blood coagulation process and lead to internal bleeding and potentially death (Rattner et al., 2014). There are two types of ARs: first-generation ARs, which must be consumed for several days to generate an effect due to their low toxicity; and second-generation ARs, which are significantly more toxic and effective after a single dose (Jacob and Buckle, 2018).

This method of eradication not only targets the intended species (i.e. *Rattus norvegicus*, *R. rattus* and *Mus musculus*), but also poses a high risk of exposure and indiscriminate mortality to native wildlife species and their populations, even when used in small quantities (Elliott et al., 2014; Poessel et al., 2015; Serieys et al., 2019). When ARs enter the trophic chain, they can indirectly poison non-target species that consume previously poisoned prey (Riley et al., 2007; Elliott et al., 2016). This can lead to a biochronic accumulation of chemical compounds in the tissues, resulting in a range of lethal and sublethal effects such as late blood coagulation and mobility problems (Rattner and Mastrota, 2018). In addition, the individuals may be more susceptible to injury, disease, malnutrition, and predation (Hindmarch et al., 2019). Predators and scavengers, such as birds of prey and carnivorous mammals that feed primarily or partially on small vertebrates, are among the non-target species most affected by indirect exposure to ARs (Elliott et al., 2016; Rodríguez-Estival and Mateo, 2019; Thornton et al., 2022). Even in secondary consumers, such as decomposer insects, the prevalence of these toxic compounds has also been recorded, which are subsequently consumed by insectivorous birds (Elliott et al., 2014; Masuda et al., 2014).

Accordingly, as the environmental impact of ARs on wildlife has become more evident, governments in North America and Europe face the challenge of finding a balance between controlling rodent pests and mitigating these negative impacts on wildlife (EPA, 2008; Elliott et al., 2016). Nevertheless, in Latin America, and particularly in Colombia, knowledge about the presence and effects of ARs on wildlife has been poorly understood and limited only to anecdotal evidence (Santiago-Alarcón and Delgado-V., 2017). Furthermore, Colombian policies have supported the growth of the agrochemical industry by granting an increasing number of licenses for the sale of commercial chemical pesticides (Nivia, 2004). Current national regulations state a clear commitment to a clean and sustainable economy, and the increased sale of pesticides appears to be contradictory to these measures, as stated in Law 99 of 1993 (Nivia, 2004).

For these reasons, as urban areas continue to expand and replace natural habitats, it is crucial to comprehend the relationship between urban environments and resident fauna (Cavia et al., 2009). This understanding can guide land-use planning and management to ensure biodiversity conservation in cities (Jaramillo and Montoya González, 2018) while maintaining the balance of food webs and controlling populations of exotic prey that are generally very abundant in cities (Faeth et al., 2005). Therefore, it is crucial to document the environmental issues linked to urban expansion, such as the use of chemical compounds for rodent control, and their potential impact on urban biodiversity. This is particularly important in regions like the tropical Andes, which are renowned for their high conservation value due to being one of the world's most significant biodiversity hotspots (Myers et al., 2000), and which also have one of the highest urban development and population densities in Latin America (Rodríguez Eraso et al., 2013).

The urban area of Medellín, located in the north of the tropical Andes in Colombia, hosts a great richness of vertebrates, insects, and plant species (Alcaldía de Medellín et al., 2014). It has a set of local protected areas, water bodies, and other green spaces that are essential for the maintenance of urban flora and fauna (Alcaldía de Medellín et al., 2014). The Medellín Land Use Plan aims to protect this Main Ecological Structure (MES), which is another way of referring to the city´s ecological network. This network encompasses all the fundamental natural elements that shape the environmental supply and connectivity of the territory (Alcaldía de Medellín, 2014). Consequently, MES connects green spaces (i.e. natural habitats) and supports the urban biodiversity (Jaramillo and Montoya González, 2018).

However, in Medellín, interventions have been carried out for several years to prevent the spread of pathogens transmitted by synanthropic rodents (*Rattus* and *Mus* species), such as *Leptospira* spp., with ARs being one of the main control measures (Secretaría de Salud de Medellín, 2022; Alcaldía de Medellín, 2022). Current rodent control management in Medellín is based primarily on the application of ARs in the form of granular baits without the use of bait stations. This poison is applied whenever an increase in rodent activity is detected at a given location. There is no control over the quantities applied and no effective monitoring of rodent populations or potential resistance has been done. Likewise, this chemical-based management has been done without considering the ecological underpinnings, which are crucial to anticipate the potential impacts on diversity and local and regional trophic networks. Hence, to begin to understand, this toxic element impact in the city of Medellin and its relationship with urban biodiversity conservation, this study aimed at three objectives. First, to evaluate the spatial patterns of ARs use in Medellín as a public health rodent control measure to recognize critical risk hotspots sites. Second, to analyze the interaction between ARs deposit sites with the MES and its biodiversity hotspots as a proxy of the potential threat to urban biodiversity. This was also, analyzed taking into consideration the potential predators most likely to be intoxicated indirectly by ARs (i.e. raptors, Accipitriformes and Strigiformes, and mammals of the order Carnivora. Finally, this work assessed the effectiveness and restrictiveness of the regulations on the commercialization and use of these pesticides in Colombia.

2 Materials and methods

2.1 Study site

The locations of ARs were recorded in Medellín, a major urban center in Colombia (Delgado-V., 2007) and home to one of the most significant ecosystems in the region in terms of biodiversity (Cuervo and Delgado-V., 2001). Medellín is situated in the Aburrá Valley in the South-central part of the department of Antioquia, north of the Central Cordillera (6°15'0.622" N, 75°34'13.718" W) (Supplementary Material 1).

2.2 Record compilation and use spatial patterns of anticoagulant rodenticides

To identify the locations and quantify the doses of ARs applied in Medellín, the Secretary of Health of Medellín was requested, in January 2023, to provide information on the sites, doses, active ingredients, methods, and dates of application of ARs in the city during the last seven years. Afterward, using the Geomedellín platform (https://www.medellin.gov.co/geomedellin/), the site locations were geocoded (i.e. stablish geographical coordinates) as they were provided in address format. Then, it was quantified the application of ARs by sites, doses, years, and the approximated cost that the city invested in the application of ARs was also estimated, considering the total dose applied in grams and the average online market value of these pesticides in Colombia for the year 2023.

Subsequently, to identify critical rodenticide risk zones, it was evaluated whether the highest density ARs zones represent critical cluster spots for the city. To do this, a spatial statistical analysis was carried out through the Optimized Hot Spot analysis,using the application sites and the doses applied per site as variables, and the Getis-Ord Gi* statistic from the spatial statistics tool of the ArcGIS 10.8 program (ESRI, 2020). This test allows for the identification of significant spatial clusters of high values, or hot spots, and low values, or cold spots. This significance indicates whether the spatial clustering of observed hot or cold values, in this case of ARs, are more marked than what is expected in a random distribution. The number of application sites and the doses applied per site were used as variables of reference in the analysis.

Furthermore, to evaluate the temporal dynamics of critical rodenticide risk zones, an Emerging Hot Spot Analysis was carried out. This spatial statistical analysis also uses the Getis-Ord Gi* statistic to identify the intensity of AR clusters considering the temporal dimension. Thus, a spatio-temporal cube (i.e. tree space-time dimensions) was created by selecting 90-day intervals and a fixed distance, to assure detecting possible usage patterns for each year and significant AR clusters, for the period from April 2016 to January 2023. As a result, the Emerging Hot Spot Analysis can detect eight specific hot or cold spot trends: new, consecutive, intensifying, persistent, diminishing, sporadic, oscillating, and historical (ESRI, 2020). This analysis was performed using the space time pattern mining tool of the ArcGIS 10.8 program (ESRI, 2020).

In addition, a raster of biodiversity hotspots in the urban area of Medellín previously conducted by the Alcaldía de Medellín (2014), was utilized to quantify the number of ARs application sites that overlapped with the cells representing biodiversity hotspots, in order to ascertain the extent to which poison application sites may be interacting with the sites of higher biodiversity. All analyses were performed using ArcGIS 10.8 software (ESRI, 2020).

2.3 Anticoagulant rodenticides interaction with main ecological structure

The MES according to the Medellín Land Use Plan, ecologically is integrated by three elements: nodes, fragments, and corridors (Ramírez et al., 2020; Supplementary Material 2). Nodes make up the main base of the MES and are the most important areas for biodiversity conservation as they include all the local protected areas. Corridors are green spaces of high significance, as they are the connecting elements between nodes, like riparian and stream pathways. Fragments are usually much smaller green spaces that are functionally not as relevant as corridors, as they lack connectivity with other elements of the MES.

Thus, to assess the risk of exposure of the MES according to the ARs applied in the city, an overlap analysis was carried out to quantify the number of ARs within the MES elements. This was also quantified considering the buffer zone adjacent to the MES, since it houses the minimum physical and ecological conditions to ensure the movement and maintenance of urban biodiversity and its connection to regional areas (AMVA, 2019).

Furthermore, to evaluate the potential risk of AR exposure in the urban area of Medellín, a threat matrix was created. First, the Euclidean distance was estimated for the MES layer and for the sites where ARs had been applied by the Secretary of Health. Then, these distances were reclassified for both layers. In the case of the MES layer, Resolution 2851 of 2019 was employed as a criterion for the reclassification, which delineates the MES buffer zone into four categories based on distances in which green areas outside the MES continue to be permeable for the movement and maintenance of biodiversity as follows: 1. 0 meters (within the MES), 2. green zones between 1 and 36 meters from MES, 3. green zones between 36 and 54 meters from MES and 4. more than 54 meters (outside the buffer zone). Subsequently, for the layer derived from the AR application sites, the categories were selected based on the distance at which a rodent has been shown to be able to move while poisoned with an AR according to Tosh et al. (2012). Distances were classified into four categories: 0 to 50 meters, 51 to 100 meters, 101 to 150 meters and 151 or more meters. Finally, using map algebra, the values obtained between the two layers were averaged and a threat matrix was obtained showing three categories of low, medium and high potential of AR exposure risk, with the areas of greatest threat to urban biodiversity being those in which ARs had been applied within the MES.

2.4 Potential risk of poisoning by predators

To evaluate the potential risk of indirect poisoning by predators in Medellín, three orders of potential rodent predators were selected: Carnivora (Mammalia), Strigiformes and Accipitriformes, considering that they have been previously reported in the study area (Delgado-V. et al., 2005; Delgado-V., 2007; Pulgarín-R, 2021; Barrera-Vargas et al., 2023). For this, local records information of these species was collected using the GBIF database (GBIF.org), for the studied period. Then, to evaluate the potential risk of indirect exposure, the closest distance between species records and ARs was estimated using the near distance analysis of the proximity analysis tool of the ArcGIS 10.8 program (ESRI, 2020). Then, the distances were reclassified into four categories: 0-50, 51-100, 101-150, and 151 or more meters. It is important to note, that when a distance was greater than 151 meters, this represented the lowest threat of exposure, and a distance less than 50 meters, the highest threat of exposure. These categories were also selected taking as a criterion the distance at which a rodent could be able to move while poisoned (Tosh et al., 2012).

2.5 Diagnosis of online commercialization of anticoagulant rodenticides in Colombia

A systematic review of ARs online commercialization in Colombia was carried out in the common Google search engine, to identify the types of rodenticides offered and how detailed the information provided to the final consumers was. This was done by means of keywords such as "sale of rodenticides", "anticoagulant rodenticides", "sale of rat poison", or different combinations of these words. This was implemented between February and April 2023. Then, a database was created with the following information for each product, based on the reported data sheet: trade name, type of bait, active ingredient, price per gram and whether they reported a safety data sheet.

For those products that presented a safety data sheet, it was verified whether they report the following information recommended by the Globally Harmonized System of Classification and Labelling of Chemicals (to which Colombia adhered under the Decree 2041 of 2014): bioaccumulation potential, mobility in soil, persistence, degradability, and reported toxicity to fish, aquatic invertebrates, algae, bacteria, birds, and bees.

2.6 Compliance with regulations related to the commercialization of the anticoagulant rodenticides products offered currently on the online market

Subsequently, the entities in charge of granting sanitary and environmental licenses for the commercialization of pesticides in public health and domestic use in Colombia, i.e. the National Institute for Drug and Food Surveillance (INVIMA) and the National Environmental Licensing Authority (ANLA), were requested to provide a database of all AR products, with the following information: 1. date of issuance of the sanitary and environmental license, 2. whether the product is manufactured, marketed or imported, 3. the active ingredient it contained, and 4. whether it had a pesticide post-consumer return management plan in place. Once all the information was gathered, a diagnosis was made of how many of the AR products currently marketed through online media means comply, partially or totally, with Colombian regulations. Specifically, in terms of 1. having a valid health and environmental license, 2. informing the consumer of the ecotoxicological effects of the product on other organisms and 3. having a post-consumption plan for the product's packaging.

3 Results

The ARs database revealed that a total of 3,282,204 grams of the brodifacoum were applied of in Medellin. The deposits took place between April 2016 and January 2023 in 4,206 application sites, with 85.33% in urban areas and 14.67% in rural areas (Table 1). In 2022, the application of ARs saw a significant increase with 1,412 sites and 911,990 grams being treated, almost triple the number of sites earmarked for the application of this poison between 2019 and 2021 (Supplementary Material 3).

3.1 Spatial patterns of anticoagulant rodenticides

Spatially, most of the ARs locations are widely distributed throughout the urban area in a heterogeneous manner, with a few focal points where many application sites appear to be agglomerated (Figure 1). 43.44% (1559 sites) of these points are found within a biodiversity hotspot (Figure 1).

Based on the Hot Spot Analysis, the central and southwestern zones of Medellín present the biggest risk areas, although there are also some small hotspot areas located at north and northwest of the city; while two significant low-risk areas were identified: one in the northeastern zone and the other in the western part of the city (p-value < 0.05, see Figure 2A). Likewise, based on the of Emerging Hot Spot analysis, it was found that three of the major areas of the city previously identified as hotspots share a consecutive hotspots pattern, meaning that these sectors have had significant historical concentration of ARs for almost five years of the period analyzed (p-value < 0.05; see Figure 2B). New hotspots of ARs concentration can also be observed near consecutive and oscillating points. These means spots that presented a significant ARs concentration between November 2022 and January 2023, that was the last period analyzed. Also, several sporadic hotspots were identified in different sectors of the city, indicating that these areas have been hotspots during some time steps analyzed in the last seven years.

3.2 Anticoagulant rodenticides interaction with main ecological structure

Within the MES, a total of 1,835 application sites were identified, accounting for 51.13% of the total sites in the urban

TABLE 1 Annual anticoagulant rodenticide costs in Medellin, between 2016 and 2023.

Brodifacuom dose (gr)	Number of Sites	Average cost (COP)	Average cost (USD)	Year
113.155	280	$ 21,485,984.56	3,111.6	2016
546.840	716	$ 103,834,526.04	15,038.1	2017
310.872	295	$ 59,028,686.23	8,548.98	2018
383.656	373	$ 72,848,984.94	10,550.54	2019
428.576	514	$ 81,378,439.46	11,785.84	2020
587.725	603	$ 111,597,810.73	16,162.44	2021
911.990	1412	$ 173,169,573.19	25,079.72	2022
5.390	13	$ 10,234,585.90	148.22	2023
3.282.204	**4206**	**$ 633.578.591,03**	**$ 154.952,80**	**Total**

area (see Figure 3). ARs were found in all elements of the MES, with the buffer zone having the highest number of ARs at 43.52%, followed by corridors at 0.54%, fragments at 0.47%, and nodes at 0.23% (refer to Table 2).

Likewise, several areas where biodiversity may be threatened due to indirect exposure to ARs were identified. These areas were classified as low threat (52.5% of total pixels), medium threat (38.6%), and high threat (8.9%) (Figure 4). The metropolitan system of protected areas, specifically the nodes, forms the main basis for the conservation of Medellin's urban biodiversity, mostly present medium to low threat. The periphery of the nodes, and particularly the corridors zones, which are essential for ensuring connectivity between nodes, were the elements of the MES that posed the greatest potential threat to biodiversity (Figure 4).

3.3 Potential risk of poisoning by predators

There were 51 records of mammalian Carnivora within the urban zone, divided between the non-native cat *Felis catus* (38 records), the

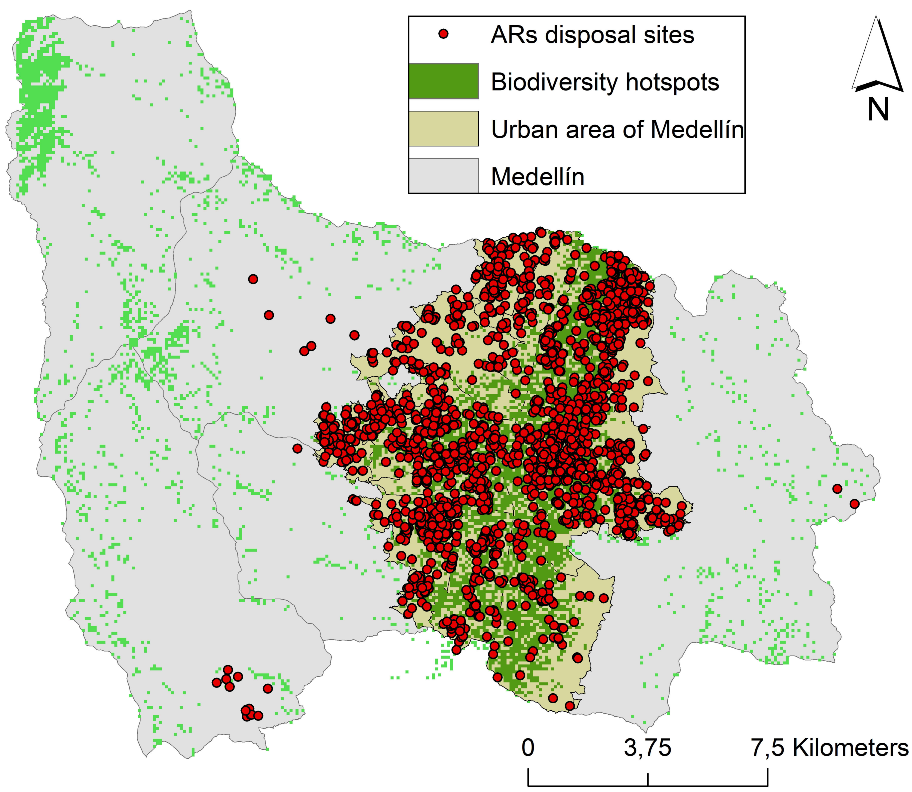

FIGURE 1
Anticoagulant rodenticides spatial distribution along the biodiversity hotspots in the urban area of Medellin.

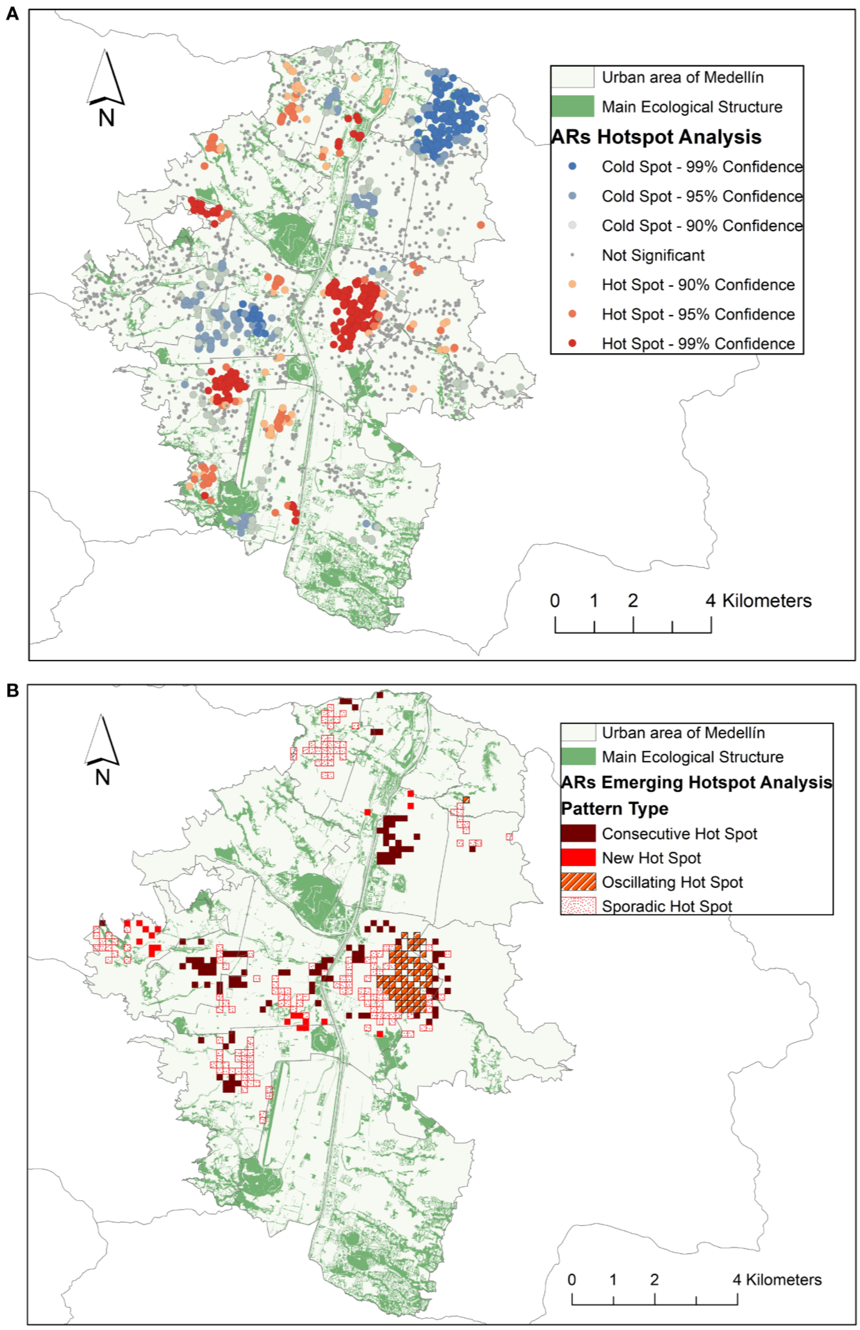

FIGURE 2
(A) Hotspot Analysis of anticoagulant rodenticide application sites in the urban area of Medellín. **(B)** Emerging Hot Spot Analysis of anticoagulant rodenticide application sites in the urban area of Medellín.

crab-eating fox *Cerdocyon thous* (14 records), one record of the ocelot *Leopardus pardalis* and one record of weasel *Neogale frenata* (GBIF.org, 2023a). For birds in Strigiformes, 220 records were obtained, divided into six species of owls (*Asio clamator*, *A. stygius*, *Megascops choliba*, *M. albogularis*, *Pulsatrix perspicillata* and *Ciccaba virgata*) and the barn owl *Tyto alba* (GBIF.org, 2023b). The highest number of records belongs to the tropical screech-owl *M. choliba* with 110 observations, followed by the striped owl *A. clamator* with 21 observations and *A. stygius* with 7 observations.

In the order Accipitriformes, a total of 4,910 records were found for 24 species (11 for the family Accipitridae, four for the family Cathartidae, and one for the family Pandionidae) (GBIF.org, 2023c). Most of the records belong to the black vulture *Coragyps atratus*, followed by the roadside hawk *Rupornis magnirostris* and the turkey vulture *Cathartes aura* with 2,430, 1,667 and 395 observations respectively.

For all three orders, most records were found at a distance greater than 150 meters, showing a low risk of exposure to ARs

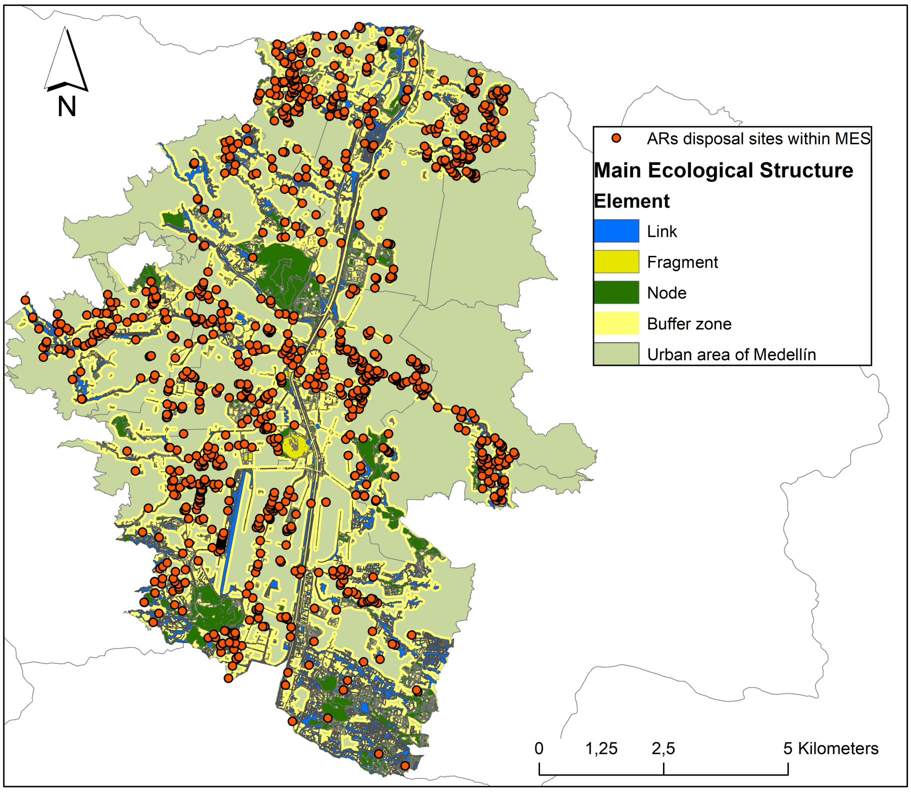

FIGURE 3
Application sites of anticoagulant rodenticides within the Medellín Main Ecological Structure, between April 2016 and January 2023.

(Figure 5). However, when considering the medium, high, and very high threat categories for a poison application site located within 150 meters of a non-target species, nocturnal raptors (Strigiformes) pose the highest risk, with 33.18% of records within this range. In comparison, the distance of records belonging to the orders Accipitriformes and Carnivora poses a much lower risk, with less than 25% of the records classified between medium and very high potential risk of AR exposure (see Figure 5).

TABLE 2 A. Number of sites and percentages where ARs have been placed in urban and rural areas of Medellín. B. Number of sites and percentages where ARs have been placed within the Main Ecological Structure (MES) (Nodes, Corridors, Fragments and the buffer zone).

A. Medellín	ARs application sites	ARs application sites (%)
Urban area	3,589	85.33
Countryside/ rural area	617	14.67
Total	4,206	100
B. Main Ecological Structure		
Corridors	69	0.54
Fragments	20	0.47
Nodes	9	0.23
Buffer zone	1,737	43.52
Total	**1,835**	**51.13**

3.4 Diagnosis of online commercialization of anticoagulant rodenticides in Colombia

In Colombia, 33 brands offer a total of 47 rodenticide products for domestic use through virtual media. Each brand sells between one and four different bait products, which may come in the form of granules, wax blocks, powder, gel, and fresh bait. Out of the total number of products, 25 were anticoagulant rodenticides (7 first-generation and 18 second-generation), being brodifacoum the most heavily marketed active ingredient. Additionally, 8 products contained non-anticoagulant active ingredients (Supplementary Material 4).

Out of the 30 brands that reported rodenticide prices on their websites, the average price per gram was $212.37 pesos for non-anticoagulant rodenticides. For first- and second-generation anticoagulant rodenticides, the prices were $116.68 and $119.71 pesos, respectively (Table 3). Implying that non-ARs are almost twice as expensive as ARs.

Regarding the 32 products that did provide a safety data sheet (SDS), only a small percentage reported ecotoxicological information for certain groups of organisms, being bacteria, bees, and birds the least reported groups, with 89.66% to 96.55% of SDSs

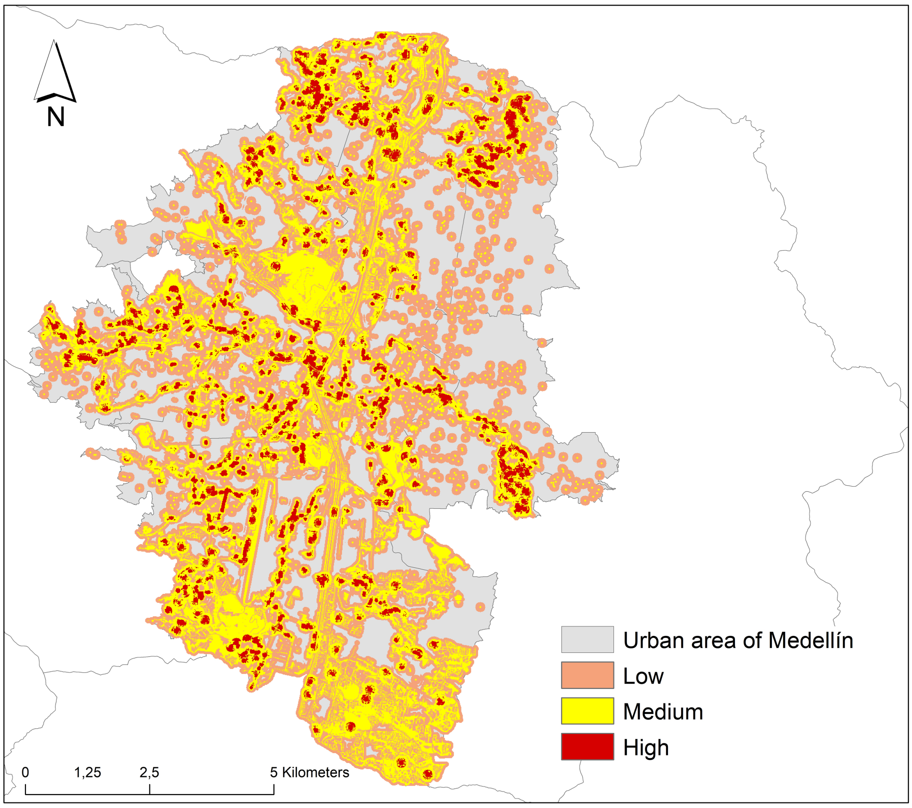

FIGURE 4
Potential risk of exposure for biodiversity to anticoagulant rodenticides in the urban area of Medellín.

not provide information about it (Figure 6A). Likewise, only 41.38% of the products provided information about the persistence and degradability of the rodenticide, 24.14% about the product´s mobility in soil and less than 18% provided information of the bioaccumulation potential (see Figure 6B).

INVIMA's files show that only five rodenticide products for domestic use currently have a sanitary registration in Colombia. One product has a license to import, and four have licenses to produce and sell (Table 4). This represents only 10.63% of the total number of products offered online in the country. Regarding environmental permits issued by the ANLA, 25 out of 47 products found have an environmental license to import and sell rodenticides, which accounts for 53.19% of the products. Only five products have an approved rodenticides post-consumption emergency plan. Thus, only one-tenth

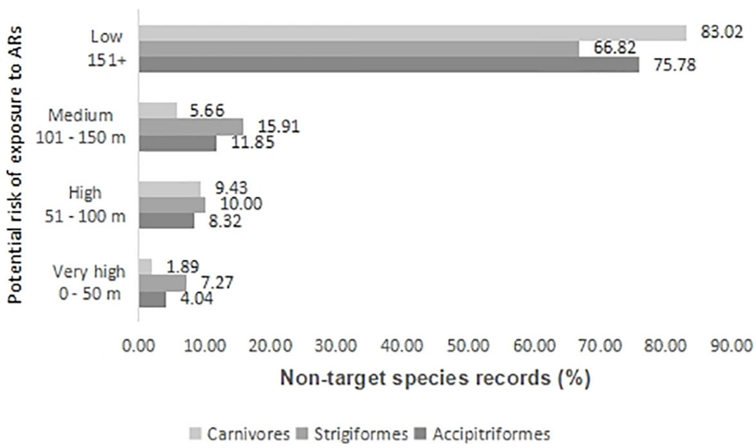

FIGURE 5
Predator groups potential risk of indirect exposure to anticoagulant rodenticides according to the closest distance between the species presence locality and the closest ARs in the urban area of Medellín.

TABLE 3 Average price per gram of 30 commercial brands of rodenticides commercialize in virtual media in Colombia.

Rodenticide type	Average price (COP)/g	Average price (USD)/g	Products
Non-AR	212.37	0.05	8
FGARs	119.71	0.03	7
SGARs	116.68	0.03	15

(Non-AR), non-anticoagulant; (FGARs), first-generation anticoagulant; and (SGArs), second-generation anticoagulant.

of the products currently offered in virtual media comply with this environmental requirement concerning to the final disposal of hazardous waste (refer to Table 4).

4 Discussion

The use of ARs as a control measure for synanthropic rodents in the urban area of Medellín has increased significantly throughout the years, both in terms of number of sites and doses applied. This implies that the city's annual contribution to chemical rodent control seems to be not just ineffective but also increasing exponentially, which is a major concern for urban wildlife conservation, given that the baits are applied outdoors without safety boxes and the active ingredient used, brodifacuom, is one of the most toxic ARs for humans and non-target species (Dutto et al., 2018). Besides, current national legislation do not regulate traceability or control of the density and timing of the application of ARs.

The distribution patterns of ARs in Medellín indicate that specific critical sectors have received regular AR doses over the years. This suggests, as previously demonstrated in other studies (Parsons et al., 2017), that chemical control is not a sustainable solution for controlling rodent infestations. Moreover, a concerning issue is that higher doses are being applied at the same locations, which increases the risk of exposure to non-target species. Thus, the increase in doses may be attributed to two reasons: firstly, rodent populations are becoming more abundant, and secondly,

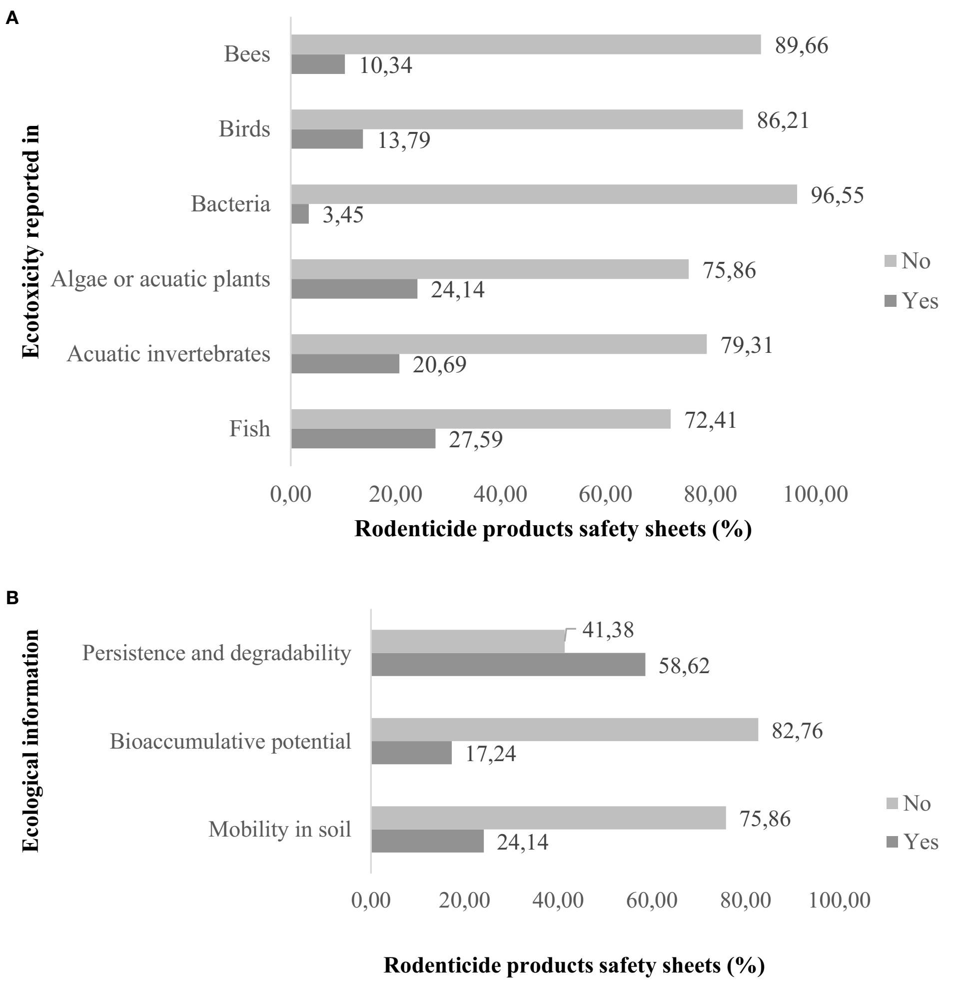

FIGURE 6
(A) Ecotoxicity reports in the safety data sheets of 33 anticoagulant rodenticides marketed online in Colombia for different biological groups. **(B)** Ecological information on persistence and degradability, bioaccumulation potential and mobility in soil in the safety data sheets of 33 anticoagulant rodenticides marketed in Colombia. No (no reported); yes (reported).

TABLE 4 Rodenticide products that comply with Colombian regulations according with three regulatory requirements.

Regulatory requirements to import/ produce/ sell rodenticides in Colombia	Type	Products	Products (%)
Sanitary registry	Import	1	2.13
	Produce and sell	4	8.51
Environmental licence	Import and sell	25	53.19
	Not specified	3	6.38
Disposal program	–	4	8.51

Total of rodenticide products commercialized online in Colombia: 47.

populations are developing greater resistance to second-generation ARs (Ruiz-López et al., 2022). Previous studies conducted in Latin America have shown that ARs are ineffective or only effective for a limited period, if the urban environmental conditions are also adequately managed (Babolin et al., 2016; Pertile et al., 2022).

As the result shows, the rodent control strategy in Medellín fails to consider the proximity of ARs to ecologically important sites for the conservation of urban biodiversity. The MES of Medellín not only represents a physical green structure, but also involves a series of ecological interactions, such as predator-prey relationships, that not only support urban biodiversity, but also provide a link to rural areas. If the MES is not properly managed and the necessary environmental conditions are not provided, its ecological functionality in the long term will be compromised (Cui et al., 2020). The progressive invasion of such a potentially serious toxin in the ecosystem, due to its capacity to bioaccumulate in urban food webs (Hofstadter et al., 2021), even in species that are not the direct predators of synanthropic rodents (Dowding et al., 2010; Elliott et al., 2014), is not congruent with one of the main territorial development objectives of Medellín, which is to conserve biodiversity and the ecosystem services it provides (Alcaldía de Medellín, 2014). Planning urban ecological networks must consider not only the improvement of the quality of life of urban residents and ecologically harmonious urban settlements, but also the protection of urban biodiversity areas (Huang et al., 2021).

Moreover, current control, is not considering the spatial ecology and population dynamics of synanthropic rodents, which has been shown to be of vital importance to monitor and evaluate the effectiveness of the control measures implemented (Byers et al., 2019; Pertile et al., 2022). Likewise, studying rodent populations could allow to identify counterproductive effects of AR application, considering that research has demonstrated that rats exposed to ARs are more likely to contract *Leptospira* sp. than those not exposed to the chemical control, suggesting an increased risk of zoonotic infection transmission to humans and other no target species (Murray and Sánchez, 2021).

As urbanization increases, many raptors and mesocarnivores have been found to consume more synanthropic prey, such as pigeons and rodents (Dykstra, 2018). This may be due to the high abundance of such prey in urban environments throughout the year (Cooke et al., 2018). It has been documented that nocturnal raptors, such as *Asio clamator* and *Megascops choliba*, as well as the Crab-eating fox (*Cerdocyon thous*) feed on introduced and native rodent species in Medellín (Delgado-V., 2002; Delgado-V. et al., 2005; Delgado-V., 2007). Therefore, these species may be one of the most threatened species due to indirect exposure to rat poison.

Exposure to ARs could further increase the pressure on some populations of predators, making it more difficult to survive in anthropized landscapes (Serieys et al., 2018). For example, the active ingredient of ARs currently used in Medellín is brodifacuom, which has been shown to last up to 307 days in a rodent's body (Hindmarch and Elliott, 2018). This could lead to increased bioaccumulation riskin predators or scavengers that repeatedly feed on poisoned prey compared to other rodenticides (Hindmarch and Elliott, 2018). The movement patterns of these predators within the city are currently unknown. Consequently, it is uncertain to determine a more realistic extent of the exposure risk as well as how far this bioaccumulation could be affecting the ecosystems surrounding the city, where these natural predators are present (González-Salgado et al., 2022; Barrera-Vargas et al., 2023).

In addition to, the evaluation of rodenticides sold through online platforms in Colombia reveals a significant discrepancy between legal requirements and actual compliance. Furthermore, it is worth noting that the majority of rodenticides marketed for household use contain brodifacoum, which is one of the most toxic second-generation anticoagulant rodenticides (Erickson and Urban, 2004; EPA, 2008). Additionally, less than 30% of the Safety Data Sheets (SDS) contained information on the potential ecotoxicity of these products on other organisms and less than 50% provided information on persistence, degradability, bioaccumulation potential, and mobility in soil. These obscures the actual panorama of the potential bioaccumulation in different links of food webs, where ARs are a major negative effect (Dutto et al., 2018).

In North America and Europe, rodenticide-related environmental issues have become a major research topic (Lohr, 2018; van den Brink et al., 2018). These regions have also implemented the most restrictive measures on the use of these poisons,in response to recurring problems with poisonings in children and non-target wildlife, including endangered species (Erickson and Urban, 2004).

However, many of the products offered in Colombia, do not provide information on the potential ecotoxicity on other organisms or the environment. This lack of information means that the end-user does not have complete knowledge of the environmental hazards linked to the use of this pesticide.

Regulating the online commercialization of ARs still requires attention to the type of active ingredient and the permitted form of application and disposal for domestic use. Furthermore, there is a need for stricter compliance with current legislation and the formulation of more rigorous standards for rodent control in public health, especially considering that poisoning of non-target species by rodenticides is a latent problem in all parts of the world where it has been studied (Koivisto et al., 2010).

The frequent presence of ARs in Medellín, suggests that greater attention, from the academy to the authorities, concerning environmental monitoring and control is necessary for a pollutant that affects biodiversity, human health and ecosystems. To enable this in Colombia, further ecotoxicological studies are necessary to determine the actual impact of these poisons on urban ecosystems. We hope that this study will be the baseline for the investigation of such unknown and neglected environmental issue in Latin America since there is an urgent need to investigate how prevalent ARs are becoming in urban ecosystems in mega-diverse regions such as the Neotropics.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

MAJ-Q: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. CAD-V: Conceptualization, Formal analysis, Supervision, Writing – review & editing. AA-A: Conceptualization, Formal analysis, Methodology, Supervision, Writing – review & editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. Partial financial support was received from Universidad CES for the publication of this article.

Acknowledgments

We thank the Secretary of Health of Medellín for providing us with all the information related to the city's Integral Rodent Control Plan. We also thank INVIMA and ANLA for providing us with information related to health registrations, environmental licenses, and post-consumption plans for rodenticides in force. This study was conducted as a requirement for obtaining a Master's degree in Biological Sciences at CES University.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2024.1424047/full#supplementary-material

References

Alcaldía de Medellín (2014). *Acuerdo 48 de 2014 - Plan de Ordenamiento Territorial del Municipio de Medellín* (Medellín, Colombia).

Alcaldía de Medellín (2022). 430 puntos de la ciudad han sido intervenidos por la Alcaldía de Medellín para prevenir contagios de enfermedades causadas por roedores. Available online at: https://www.medellin.gov.co/es/sala-de-prensa/noticias/430-puntos-de-la-ciudad-han-sido-intervenidos-por-la-alcaldia-de-medellin-para-prevenir-contagios-de-enfermedades-causadas-por-roedores/ (accessed September 30, 2022).

Alcaldía de Medellín, Secretaría de Medio Ambiente, Parque Explora, Instituto de Investigación de Recursos Biológicos Alexander von Humboldt, Jardín Botánico de Medellín and Parques Nacionales Naturales de Colombia, et al. (2014). *Propuesta para la gestión integral de la biodiversidad y los servicios ecosistémicos en Medellín* (Medellín, Colombia), ISBN: .

AMVA (2019). *Resolución Metropolitana D-2851 de 2019* (Medellín, Colombia).

Babolin, L. D. S, Almeida-Silva, M. J. F., de, Potenza, M. R., Fava, C., Del, Castro, V., Harakava, R., et al (2016). Zoonosis associated to Rattus rattus and the impacts of the public actions to control the species. *Arquivos Do Instituto Biológico* 83(0). doi: 10.1590/1808-1657000832014

Barrera-Vargas, J., Delgado-V, C. A., and Arias-Alzate, A. (2023). Mesocarnivores activity patterns in the Northern Colombian Andes. *Therya* 14, 371–382. doi: 10.12933/therya-23-1243

Byers, K. A., Lee, M. J., Patrick, D. M., and Himsworth, C. G. (2019). Rats about town: A systematic review of rat movement in urban ecosystems. *Front. Ecol. Evol.* 7. doi: 10.3389/fevo.2019.00013

Cavia, R., Cueto, G. R., and Suárez, O. V. (2009). Changes in rodent communities according to the landscape structure in an urban ecosystem. *Landscape Urban Plann.* 90, 11–19. doi: 10.1016/j.landurbplan.2008.10.017

Cooke, R., Hogan, F., Isaac, B., Weaving, M., and White, J. G. (2018). Urbanization and Raptors: Trends and Research Approaches. In: Boal, C. W., and Dykstra, C. R. (eds) *Urban Raptors*. Washington, DC: Island Press. doi: 10.5822/978-1-61091-841-1_5

Cuervo, A. M., and Delgado-V., C. (2001). Adiciones a la avifauna del Valle de Aburrá y comentarios sobre la investigación ornitológica local. *Boletín SAO* XII, 52–65.

Cui, L., Wang, J., Sun, L., and Lv, C. (2020). Construction and optimization of green space ecological networks in urban fringe areas: A case study with the urban fringe area of Tongzhou district in Beijing. *J. Clean. Product.* 276, 124266. doi: 10.1016/j.jclepro.2020.124266

Delgado-V., C. A. (2002). Food habits and habitat of the crab-eating fox Cerdocyon thous in the highlands of eastern Antioquia, Cordillera Central, Colombia. *Mammalia* 66, 599–602. doi: 10.1515/mamm.2002.66.4.599

Delgado-V., C. A. (2007). La dieta del Currucutú Megascops choliba (Strigidae) en la ciudad de Medellín, Colombia. *Boletín SAO* XVII, 111–114.

Delgado-V., C. A., Pulgarín-R., P. C., and Calderón-F., D. (2005). Análisis de egagrópilas del búho rayado (Asio clamator) en La Ciudad de Medellín. *Ornitol. Colombiana* 3, 100–103.

Dowding, C. V., Shore, R. F., Worgan, A., Baker, P. J., and Harris, S. (2010). Accumulation of anticoagulant rodenticides in a non-target insectivore, the European hedgehog (Erinaceus europaeus). *Environ. pollut.* 158, 161–166. doi: 10.1016/j.envpol.2009.07.017

Dutto, M., Di Domenico, D., and Rubbiani, M. (2018). Use of anticoagulant rodenticides in outdoor urban areas: Considerations and proposals for the protection of public health and non-target species. *Annali Di Igiene Medicina Preventiva e Di Comunita* 30, 44–50. doi: 10.7416/ai.2018.2194

Dykstra, C. R. (2018). City lifestyles: behavioral ecology of urban raptors. *Urban Raptors* 18–35, 18-35. doi: 10.5822/978-1-61091-841-1_2

Elliott, J. E., Hindmarch, S., Albert, C. A., Emery, J., Mineau, P., and Maisonneuve, F. (2014). Exposure pathways of anticoagulant rodenticides to nontarget wildlife. *Environ. Monit. Assess.* 186, 895–906. doi: 10.1007/s10661-013-3422-x

Elliott, J. E., Rattner, B. A., Shore, R. F., and van den Brink, N. W. (2016). Paying the pipers: mitigating the impact of anticoagulant rodenticides on predators and scavengers. *BioScience* 66, 401–407. doi: 10.1093/biosci/biw028

EPA (2008). Risk mitigation decision for ten rodenticides.

Erickson, W., and Urban, D. (2004). Potential risks of nine rodenticides to birds and nontarget mammals: a comparative approach.

ESRI (2020). ArcGIS Desktop: Release 10.8. Redlands, CA: Environmental Systems Research Institute.

Faeth, S. H., Warren, P. S., Shochat, E., and Marussich, W. A. (2005). Trophic dynamics in urban communities. *BioScience* 55, 399–407. doi: 10.1641/0006-3568(2005)055[0399:TDIUC]2.0.CO;2

GBIF.org (2023a). doi: 10.15468/dl.2btxca

GBIF.org (2023b). doi: 10.15468/dl.qv2jrr

GBIF.org (2023c). doi: 10.15468/dl.z2wtgg

González-Salgado, C., Burbano-Salazar, J., Sánchez-Londoño, J. D., and Gutierrez-Henao, A. (2022). Presencia del Grisón Galictis vittata (Carnivora, Mustelidae) en el Valle de Aburrá y ampliación de su rango altitudinal. *Mammal. Notes* 8, 327. doi: 10.47603/mano.v8n1.327

Himsworth, C. G., Parsons, K. L., Jardine, C., and Patrick, D. M. (2013). Rats, cities, people, and pathogens: A systematic review and narrative synthesis of literature regarding the ecology of rat-associated zoonoses in urban centers. *Vector-Borne Zoon. Dis.* 13, 349–359. doi: 10.1089/vbz.2012.1195

Hindmarch, S., and Elliott, J. E. (2018). Ecological factors driving uptake of anticoagulant rodenticides in predators. *Anticoagul. Rodenticides Wildl.* 5, 229–258. doi: 10.1007/978-3-319-64377-9_9

Hindmarch, S., Rattner, B. A., and Elliott, J. E. (2019). Use of blood clotting assays to assess potential anticoagulant rodenticide exposure and effects in free-ranging birds of prey. *Sci. Total Environ.* 657, 1205–1216. doi: 10.1016/j.scitotenv.2018.11.485

Hofstadter, D. F., Kryshak, N. F., Gabriel, M. W., Wood, C. M., Wengert, G. M., Dotters, B. P., et al. (2021). High rates of anticoagulant rodenticide exposure in California Barred Owls are associated with the wildland-urban interface. *Ornithol. Appl.* 123, 1-13. doi: 10.1093/ornithapp/duab036

Huang, X., Wang, H., Shan, L., and Xiao, F. (2021). Constructing and optimizing urban ecological network in the context of rapid urbanization for improving landscape connectivity. *Ecol. Indic.* 132, 108319. doi: 10.1016/j.ecolind.2021.108319

Jacob, J., and Buckle, A. (2018). Use of anticoagulant rodenticides in different applications around the world 11–43. doi: 10.1007/978-3-319-64377-9_2

Jaramillo, C. H., and Montoya González, S. (2018). Estado del arte Red Ecológica de Medellín, en el contexto metropolitano.

Koivisto, S., Laakso, S., and Suomalainen, K. (2010). *Literature Review on Residues of Anticoagulant Rodenticides in Non-Target Animals* (Copenhagen, Denmark: Nordic Council of Ministers). doi: 10.6027/tn2010-541

Liu, S., Hou, X., Yin, Y., Cheng, F., Zhang, Y., and Dong, S. (2017). Research progress on landscape ecological networks. *Acta Ecol. Sin.* 37, 1-10. doi: 10.5846/stxb201611172333

Lohr, M. T. (2018). Anticoagulant rodenticide exposure in an Australian predatory bird increases with proximity to developed habitat. *Sci. Total Environ.* 643, 134–144. doi: 10.1016/J.SCITOTENV.2018.06.207

McKinney, M. L. (2002). Urbanization, Biodiversity, and Conservation: The impacts of urbanization on native species are poorly studied, but educating a highly urbanized human population about these impacts can greatly improve species conservation in all ecosystems. *BioScience* 52 (10), 883–890. doi: 10.1641/0006-3568(2002)052[0883:UBAC]2.0.CO;2

Masuda, B. M., Fisher, P., and Jameison, I. G. (2014). Anticoagulant rodenticide brodifacuom detected in dead nestlings of an insectivorous passerine. *New Z. J. Ecol.* 38, 110–115.

Murray, M. H., and Sánchez, C. A. (2021). Urban rat exposure to anticoagulant rodenticides and zoonotic infection risk. *Biol. Lett.* 17, 20210311. doi: 10.1098/rsbl.2021.0311

Murray, M. H., and St. Clair, C. C. (2015). Individual flexibility in nocturnal activity reduces risk of road mortality for an urban carnivore. *Behav. Ecol.* 26, 1520–1527. doi: 10.1093/beheco/arv102

Myers, N., Mittermeier, R. A., Mittermeier, C. G., da Fonseca, G. A. B., and Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature* 403, 853–858. doi: 10.1038/35002501

Namala, S. R., Anusha, B., Mohan Rao, A. M. K., and Sharma, S. N. (2022). Impact of rodent outbreaks in rice paddies on incidence of rodent-borne zoonosis in human populations. *J. Communicable Dis.* 54, 33–38. doi: 10.24321/0019.5138.202268

Nivia, E. (2004). Los plaguicidas en Colombia. *Semillas En La Economía Campesina*. Available online at: https://www.semillas.org.co/es/los-plaguicidas-en-Colombia (accessed October 14, 2022).

Parsons, M. H., Banks, P. B., Deutsch, M. A., Corrigan, R. F., and Munshi-South, J. (2017). Trends in urban rat ecology: a framework to define the prevailing knowledge gaps and incentives for academia, pest management professionals (PMPs) and public health agencies to participate. *J. Urban Ecol.* 3, 1-8. doi: 10.1093/jue/jux005

Pertile, A. C., Lustosa, R., Carvalho-Pereira, T., Pedra, G. G., Panti-May, J. A., Oliveira, U., et al. (2022). Evaluation of the impact of chemical control on the ecology of Rattus norvegicus of an urban community in Salvador, Brazil. *PloS One* 17, e0270568. doi: 10.1371/journal.pone.0270568

Poessel, S. A., Breck, S. W., Fox, K. A., and Gese, E. M. (2015). Anticoagulant rodenticide exposure and toxicosis in coyotes (Canis latrans) in the Denver metropolitan area. *J. Wildl. Dis.* 51, 265–268. doi: 10.7589/2014-04-116

Pulgarín-R, P. (2021). "Aves del Valle de Aburrá," in *Sociedad Antioqueña de Ornitología (SAO) y Área Metropolitana del Valle de Aburrá, 2nd ed.*, vol. 2 . Eds. D. Gardner, I. Bernal, C. Londoño, A. Sanín and M. A. Sáenz (Medellín, Colombia: Ornitología Colombiana), 62–63. Available at: https://asociacionColombianadeornitologia.org/ojs/index.php/roc/article/view/36.

Ramírez, D. C., Ortíz-Yusty, C. E., Velandia Romero, L. A., and Sánchez Castrillón, J. (2020). Análisis de la conectividad ecológica funcional y estructural en el Área Metropolitana del Valle de Aburrá (informe técnico).

Rattner, B. A., Lazarus, R. S., Elliott, J. E., Shore, R. F., and van den Brink, N. (2014). Adverse outcome pathway and risks of anticoagulant rodenticides to predatory wildlife. *Environ. Sci. Technol.* 48, 8433–8445. doi: 10.1021/es501740n

Rattner, B. A., and Mastrota, F. N. (2018). Anticoagulant rodenticide toxicity to non-target wildlife under controlled exposure conditions 45–86). doi: 10.1007/978-3-319-64377-9_3

Riley, S. P. D., Bromley, C., Poppenga, R. H., Uzal, F. A., Whited, L., and Sauvajot, R. M. (2007). Anticoagulant exposure and notoedric mange in bobcats and mountain lions in urban Southern California. *J. Wildl. Manage.* 71, 1874–1884. doi: 10.2193/2005-615

Rodríguez Eraso, N., Armenteras-Pascual, D., and Alumbreros, J. R. (2013). Land use and land cover change in the Colombian Andes: Dynamics and future scenarios. *J. Land Use Sci.* 8, 154–174. doi: 10.1080/1747423X.2011.650228

Rodríguez-Estival, J., and Mateo, R. (2019). Exposure to anthropogenic chemicals in wild carnivores: a silent conservation threat demanding long-term surveillance. *Curr. Opin. Environ. Sci. Health* 11, 21–25. doi: 10.1016/j.coesh.2019.06.002

Ruiz-López, M. J., Barahona, L., Martínez-de la Puente, J., Pepió, M., Valsecchi, A., Peracho, V., et al. (2022). Widespread resistance to anticoagulant rodenticides in Mus musculus domesticus in the city of Barcelona. *Sci. Total Environ.* 845, 157192. doi: 10.1016/j.scitotenv.2022.157192

Santiago-Alarcón, D., and Delgado-V., C. A. (2017). Warning! Urban threats for birds in Latin America. *Avian Ecol. Latin Am. Cityscapes*, 1–173. doi: 10.1007/978-3-319-63475-3

Secretaría de Salud de Medellín (2022). Plan para intervención de sectores críticos con presencia de roedores en áreas públicas de Medellín.

Serieys, L. E. K., Bishop, J., Okes, N., Broadfield, J., Winterton, D. J., Poppenga, R. H., et al. (2019). Widespread anticoagulant poison exposure in predators in a rapidly growing South African city. *Sci. Total Environ.* 666, 581–590. doi: 10.1016/j.scitotenv.2019.02.122

Serieys, L. E. K., Lea, A. J., Epeldegui, M., Armenta, T. C., Moriarty, J., VandeWoude, S., et al. (2018). Urbanization and anticoagulant poisons promote immune dysfunction in bobcats. *Proc. R. Soc. B: Biol. Sci.* 285, 20172533. doi: 10.1098/rspb.2017.2533

Thornton, G. L., Stevens, B., French, S. K., Shirose, L. J., Reggeti, F., Schrier, N., et al. (2022). Anticoagulant rodenticide exposure in raptors from Ontario, Canada. *Environ. Sci. pollut. Res.* 29, 34137–34146. doi: 10.1007/s11356-022-18529-z

Tosh, D. G., McDonald, R. A., Bearhop, S., Llewellyn, N. R., Ian Montgomery, W., and Shore, R. F. (2012). Rodenticide exposure in wood mouse and house mouse populations on farms and potential secondary risk to predators. *Ecotoxicol. (London England)* 21, 1325–1332. doi: 10.1007/S10646-012-0886-3

van den Brink, N. W., Elliott, J., Shore, R., and Rattner, B. (2018). *Anticoagulant Rodenticides and Wildlife*. Available online at: http://www.springer.com/series/7360 (accessed February 6, 2023).

Witmer, G. (2022). Rodents in agriculture: A broad perspective. *Agronomy* 12, 1-6. doi: 10.3390/agronomy12061458