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Review article

Pesticide use in banana plantations in Costa Rica – A review of environmental and human exposure, effects and potential risks

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ABSTRACT

Biodiversity is declining on a global scale. Especially tropical ecosystems, containing most of the planetary biodiversity, are at risk. Agricultural monocrop systems contribute to this decline as they replace original habitats and depend on extensive use of synthetic pesticides that impact ecosystems. In this review we use large-scale banana production for export purposes in Costa Rica as an example for pesticide impacts, as it is in production for over a century and uses pesticides extensively for more than fifty years. We summarise the research on pesticide exposure, effects and risks for aquatic and terrestrial environment, as well as for human health. We show that exposure to pesticides is high and relatively well-studied for aquatic systems and humans, but hardly any data are available for the terrestrial compartment including adjacent non target ecosystems such as rainforest fragments. Ecological effects are demonstrated on an organismic level for various aquatic species and processes but are not available at the population and community level. For human health studies exposure evaluation is crucial and recognised effects include various types of cancer and neurobiological dysfunctions particularly in children. With the many synthetic pesticides involved in banana production, the focus on insecticides, revealing highest aquatic risks, and partly herbicides should be extended to fungicides, which are applied aerially over larger areas. The risk assessment and regulation of pesticides so far relies on temperate models and test species and is therefore likely underestimating the risk of pesticide use in tropical ecosystems, with crops such as banana. We highlight further research approaches to improve risk assessment and, in parallel, urge to follow other strategies to reduce pesticides use and especially hazardous substances.

1. Introduction

Many tropical countries depend on the export of tropical crops, so called cash crops. In Latin America, bananas provide the countries with exchange earnings to maintain development plans and programs. This fruit is one of the world's most important export commodity and food crop (Wilson and Otsuki, 2002; FAO, 2022) and the world's most important "fruit" in the sense of a sweet dessert crop (Bebber, 2022). Banana production involves complex and labour-intensive processing and marketing, which resulted in an oligopolistic industry, being dominated by a few multinational enterprises, that are especially prevalent in Latin America (Wilson and Otsuki, 2002; Zaglul Ruiz, 2022).

To date, no comprehensive synthesis of the published literature is available to summarize the current knowledge on pesticide use in a tropical crop scenario regarding its exposure, effect and risk to aquatic and terrestrial environment as well as human health. In this literature review we use banana production in Costa Rica as an example for pesticide impacts in tropical areas, as it represents an industrialised cropping system with a high pesticide use in a tropical environment of exceptional biodiversity. This review sets the scene by briefly highlighting the history of banana cultivation, biodiversity and pesticide application in banana plantations focusing on Costa Rica. Against this background, we summarise the available knowledge on environmental and human pesticide exposure. Subsequently, we address effects in aquatic and terrestrial ecosystems as well as humans, which is followed by the current environmental risk assessment and the risks for human health of the people working and living in the production area. We close with a number of gaps and recommendations for steps to be taken in the

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context of this review. Although this is not a systematic review, we used elements of this methodology (Tranfield et al., 2003). We conducted a literature search using the ISI Web of Knowledge database as well as Google Scholar with the search terms (Costa Rica) AND (banana) AND (exposure OR effect OR risk OR aquatic OR terrestrial OR human). We carefully evaluated the resulting publications by reading title, abstract and conclusion. Citation tracing was used in key publications and recent papers. While this review lacks the narrow focus and comprehensive searches of a systematic review, our ambition is to be critical, objective and transparent and present the retrieved studies that we believe to be essential, in a concise form.

1.1. *Brief history of banana cultivation in Costa Rica*

Banana as a crop arrived in the Caribbean islands during the 16th century, brought by Spanish conquerors from the Canaries (Soto Ballestero, 2014). In Costa Rica, banana farming was introduced in 1872 in the Caribbean province of Limón, with the fruits being produced for export to the United States (Soto Ballestero, 2014). By 1898, production increased and 2.3 million bunches (~62,100 t) were exported per year. The following year the United Fruit Company (UFC) was created, becoming the biggest in Latin America. In Costa Rica, during the 1930́s, fungal diseases (e.g. *Sigatoka - Pseudocercospora fijiensis)* affected banana and a social movement, led by the Costa Rica communist party, strove for dignified working conditions. These developments resulted in the United Fruit Banana Strike in 1934 (Barraza et al., 2013; Marquardt, 2002). In the Costa Rican Caribbean, banana production was re-boosted during the 1950́s with the arrival of the Standard Fruit Company, as they introduced the Cavendish banana clone resistant to fungal diseases. Later in the 1960́s, the government implemented the Banana Development Plan or “Plan de Fomento Bananero”, in order to promote the participation of nationals in the production and exportation of bananas. Nowadays, according to the Executive Secretary of Sectorial Agricultural Planification (SEPSA, 2018), banana production is almost completely based in the Caribbean slope of the country. As a consequence, the economic structure and labour force at the Caribbean side are recognised as especially vulnerable because of their reliance on a single crop which faces serious threats due to the Tropical Race 4 (TR4) strain of the *Fusarium* fungus (Bebber 2022; IICA, 2021; Russo and Prado, 2006).

1.2. *Current agricultural practice*

Today, Costa Rican banana production relies on the monoculture of Cavendish varieties (mainly Grande Naine) of *Musa acuminata* AAA cultivar (Vargas, 2006). This variety substituted the Gros Michel bananas, which were highly affected by the first strain of the *Fusarium* fungal disease. The country has reached the highest productivity per hectare compared to all other producers, exporting more than 120 million boxes (2.18 million tons) of bananas per year, mostly to Europe (53 %) and the US (32 %) (CORBANA, 2020; Soto Ballestero, 2014). According to SEPSA (2018), banana crop exports accounted for 9.5 % of the cultivated land in Costa Rica (42,921 ha). The earnings of this crop, nearly-one billion US dollars, represent 18.4 % of the gross agricultural product of the country as well as 36.6 % of Costa Rica‘s agricultural exports and the industry has close to 40,000 occupied workers (CORBANA, 2020; SEPSA, 2018), from almost 172,000 people living in the Caribbean region (MTSS, 2022).

The high productivity of the banana crop is enhanced by fertile soils and stable climatic conditions (mean annual temperature of 26.3 °C and mean annual precipitation of 3,500–4,500 mm), which make irrigation unnecessary and are favourable for continuous production resulting in year-round income generation (McClearn et al., 2016). Nevertheless, extreme rainfall, as typical of the Caribbean lowlands, brings its own challenges: the plants have to be protected from the frequent natural flooding. Good soils for banana production should be naturally well-drained, with a ground water table at 1.8 m. Therefore, in the Caribbean, a drainage system is required in order to protect the roots of the banana trees from excessive humidity which would affect productivity (Soto Ballestero, 2014). The drainage system has three levels: tertiary channels, close to plant rows with a depth of about 1.8 m; secondary channels, collecting the water from tertiary channels; and primary major channels dedicated to evacuate the water from the entire farm. These primary channels are interconnected with natural water bodies, such as streams and rivers transporting water downstream (Fig. 1).

1.3. *Biodiversity in the banana plantation region in Costa Rica*

Banana crops are located in the lowlands (0–300 m a.s.l.) of the Caribbean slope of Costa Rica. Due to the isthmian position of the country, the production area is located within highly biodiverse ecosystems where North and South American flora and fauna mix (McClearn et al., 2016). According to Holdridge’s life zones (Holdridge, 1967), the plantations are located in tropical wet, premontane wet, and tropical moist forests, where dense evergreen vegetation once occupied the land. Until the 1950s most of the area was covered with primary and secondary forest (McClearn et al., 2016), however, extensive deforestation (especially during the 1960s to 1980s) has reshaped the landscape. Banana and pineapple plantations are ubiquitous, isolating remaining forest fragments (Fig. 1).

The remaining forests and freshwater ecosystems of the Caribbean lowlands (mostly national parks or biological reserves) host more than 3,000 species (196 families) of vascular plants and are a recognised biodiversity hotspots for orchids (Crain and Fernández, 2020). Additionally, more than 70 fish, 104 amphibian (91 frogs, 10 salamanders and 3 caecilians), 127 reptile (36 lizards, 83 snakes, 6 turtles and 2 crocodilians), 484 bird (in 61 families) and close to 125 mammal species within 30 families were recorded (Bussing, 1998; McClearn et al., 2016). Especially the lowland evergreen forests are extremely rich in species and show the highest species richness for amphibians in Central America (Salazar-Zúñiga et al., 2019). This biodiversity is threatened by land-use change resulting in habitat modification and fragmentation. Furthermore, agriculture and especially the use of pesticides have been identified as a critical factor affecting biodiversity in this area (Castillo et al., 2000; Echeverría-Sáenz et al., 2018a; Salazar-Zúñiga et al., 2019).

In the 1990s, Buck (1992), studied vertebrates associated with banana plantations at the EARTH University (Escuela de Agricultura de la Región Tropical Húmeda) (3376 ha) in the Caribbean lowlands, and compared it to other areas (pastures and protected forest in the campus). He found that species numbers were > 50 % lower inside banana plantations for mammals (6/18 species in banana plantation/pastures and forest of the campus), birds (16/152), amphibians (10/22), reptiles (5/22) and fish (3/25). Bats were the most common group of vertebrates inside the banana plantations. The bats *Carollia perspicillata* and *Glossophaga soricina* were also identified as suitable species for bat pesticide exposure and effects studies in banana plantations due to their wide distribution in the country, their foraging habits and high metabolic rate (Buck, 1992). A recent study confirmed the frequent occurrence of the Pallas’ long-tongued bat *Glossophaga soricina*, one of the most common nectar-feeding bat species in the Neotropics, in banana plantations. These plantations provide a high energy density, however, the lack of protein in form of pollen leads to a simplified and incomplete diet and together with pesticide exposure might negatively affect this species (Alpízar et al., 2020). Another study found higher feeding activity of insectivorous bats in banana plantations compared to forested areas, which suggests that plantations may function as a convenient food source for some bat species even when the abundance of insects might be higher in the forest (Alpízar et al., 2019). Especially open space foraging bat species can use plantations as potential foraging habitat and might take advantage of temporal insect outbreaks, whereas several forest specialist species were never recorded in the plantations. However, bats might be exposed chronically to pesticides residues from emerging

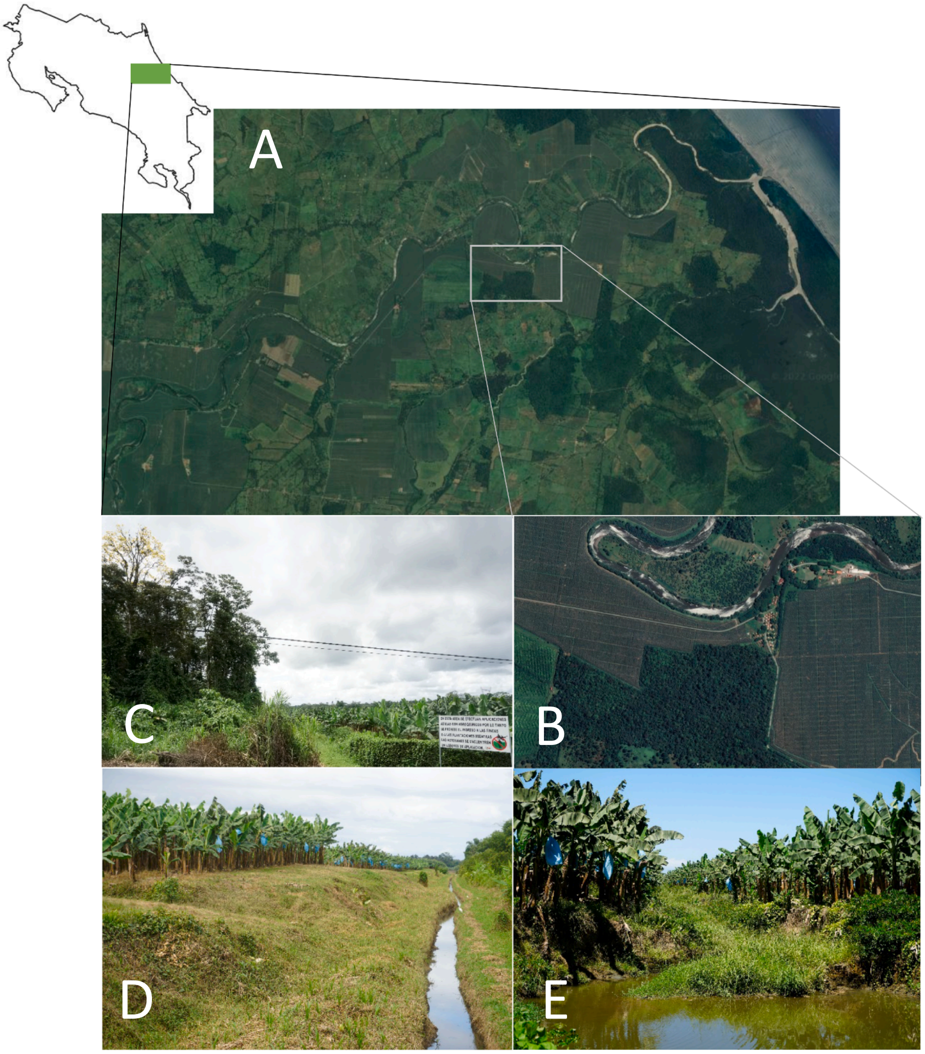

Fig. 1. A. Industrial banana plantations in the Caribbean lowlands of Costa Rica. The lower catchment of Pacuare river is exposed to pesticides from banana plantations (mentioned in text). B. Banana plantations bordering a rainforest fragment and human settlements. (A & B: Google Earth). C. Rainforest fragment next to a conventional banana plantation. D & E Drainage canals in banana plantations. (C, D & E: Carsten A. Brühl).

insects that might lead to sublethal effects affecting foraging (Roodt et al., 2022; Wu et al., 2020). Some species may be more attracted than others to banana plantations. For example, Vaughan et al (2007) described the available vs used habitats for two sloth species in different agricultural landscapes and forests of Guácimo, Limón (Caribbean). The results show that sloths used banana plantations as habitats less than expected (Vaughan et al 2007).

An inventory of the bird community in ten forest fragments in the proximity of banana plantations recorded 194 bird species, suggesting a viable habitat for the conservation of birds (Matlock et al., 2002). However, the avian community present in such forest fragments were characterized by species indicators of disturbed habitats (Matlock and Edwards, 2006). Although the information of birds using the plantations has not been updated in recent years, an older survey reported 53 species with a known high tolerance to disturbance inside the banana plantations, confirming a depauperate avifauna in such habitats (Stiles and Skutch, 1989). In 2007, Harvey and González-Villalobos described differences in bird and bat diversity in forests, agroforestry and monocultures systems, including banana, in indigenous reserves in the South Caribbean. They reported birds showing greater sensitivity compared to bats in community composition to the change in land use, with monocultures showing significant lower abundances and species richness and diversity (Harvey and González Villalobos, 2007). A previous analysis in the same region showed similar results on the species richness and diversity of dung beetles (Harvey et al., 2006).

Fish diversity assessments in Caribbean catchments have identified up to 42 species, distributed in 22 families (ANAI, 2007). The dominant species in the region include the characid *Astyanax aeneus*, several species of cichlids, and a high abundance of snooks or róbalos (Centropomidae), which are relevant for artisanal and sport fishing. More recently, a fish survey was carried out along an elevational gradient of the Pacuare river by Picado Barboza and Umaña Villalobos (2018). They demonstrated a higher diversity and abundance of fish in the lower part of the catchment, which is also the section more exposed to pesticide runoff. This suggests an important risk for fish diversity.

1.4. Pesticide use

With a global economy, tropical countries have specialized in the production of cash crops for export and continue to intensify these efforts. The production of these crops largely depends on pesticides (Donald, 2004). Both the types and amount of pesticides that are being used for banana production for export purposes are of concern. Several pesticides that have been restricted or banned in the EU (e.g., terbuphos, ethoprophos, chlorpyrifos, mancozeb, chlorothalonyl) are extensively used on bananas (Bravo Durán et al., 2013). Despite their well-documented health and environmental hazards, the combination of their effectiveness and their low costs often promote their continued use in banana production in Costa Rica (Córdoba Gamboa et al., 2020). These pesticides can be an essential part of the production of a crop that is sold then in countries where, ironically, they are banned. In addition, the frequency of pesticide applications, and therefore amount, is much higher in tropical regions as compared to regions with a different climate. The warm and moist climate promotes growth of a variety of pests, and year-round applications of pesticides are therefore characteristic. Pesticide use in banana plantation is especially high as they are extremely susceptible to pests (including fungal diseases, weeds, nematodes and insects), largely because of the genetic uniformity of the crop itself, the large extension of the croplands, and to meet stringent cosmetic standards, production goals and phytosanitary requirements of importing countries of the global North (Thrupp, 1990; Vargas, 2006).

In Costa Rica, on the more than 40,000 ha of banana monoculture around 75 kg of pesticide products are being applied per ha and year (Instituto Nacional de Estadística y Censos, 2015; Echeverría-Sáenz et al., 2018b). This is eight to nine times the amount applied on average in crops in Germany (8.8 kg pesticide products /ha /year; Frische et al. (2018)). The high pesticide use in banana over decades is recognised as a prime example of the "pesticide treadmill" – where especially the former application of high amounts of insecticide lead to pest resistance and therefore resurgence and outbreaks (Thrupp, 1990). However, integrated management with implemented biological control introduced in the 1980s changed insecticide inputs to the system significantly.

In 2021, 79 different pesticide molecules are authorised in Costa Rica for application in banana cultivation alone. Those pesticides are available in 818 product formulations (SFE, 2021). Among them are 43 fungicide substances, like mancozeb, chlorothalonil, pyrimethanil and epoxiconazole, applied with light aircrafts, some of them on a weekly basis, to control mainly black Sigatoka (*Mycosphaerella fijiensis*). Currently, a typical fungicide program in a conventional banana plantation as provided by an agricultural advisor includes 52 applications: five triazole (2 × epoxiconazole, 2 × difeconazole and 1 × propriconazole), two fenpropidin, three pyrimethanil, two carboxamide (boscalid and fluapyroxad) and two strobilurin (trifloxystrobin and pyraclostrobin) applications, as well as 36 applications of protectant fungicides on base of mancozeb, leading to a total application volume of more than 67 kg/ha for this fungicide alone. Mancozeb, the central molecule in the current fungicide program, was identified as an endocrine disruptor affecting reproduction, which resulted in a ban in Europe in 2021. Additionally, the fungicides thiabendazole and imazilil are applied post-harvest in fumigation chambers before shipment (Bravo Durán et al., 2013). Furthermore, 12 herbicides, among them diquat and paraquat, both banned since 2007 and 2018 in the EU, respectively, are registered for weed control and are applied under the banana plants mostly by hand. To control insects during culturing of banana saplings six insecticides are registered among them chlorpyrifos, banned in the EU since 2020, especially because of potentially detrimental effects on children's health. Among the seven insecticidal substances for use in impregnated bags to protect the fruits is imidacloprid, which is banned for outdoor use in the EU since 2018 due to high pollinator risks. Additionally, eight nematicides, among them fluopyram which is authorised as a fungicide in the EU, and three soil fumigant substances are registered for use in banana.

In essence, a high variety of pesticides in hundreds of formulations, often banned for health and environmental concerns in the EU, is applied in banana plantations throughout the year at high application rates and frequencies, especially for fungicides and nematicides, as well as by diverse application methods, such as aerial and hand application or impregnated bags. Consequently, we can anticipate a high risk to pesticides and their mixtures and high frequency of exposure for in-field (banana plantations) and surrounding (off-field) non-target (rainforest fragments) environments as well as humans working and living in the area.

2. Exposure

2.1. Environmental pesticide exposure

Until 1997, only a few studies dealt with pesticide presence within tropical aquatic ecosystems of the Central American region, and most of them focused on organochlorine residues (Castillo et al., 1997). However, some pesticides such as ametryn, cadusafos, chlorothalonil, chlorpyrifos, imazalil, propiconazole, terbufos, and thiabendazole, which are still used in banana plantations, were detected in surface waters (Castillo et al., 1999; von Düszeln, 1988), sediments (Castillo et al., 1995; Readman et al., 1992) and even in marine life of the Caribbean Sea (e.g., sea cucumber *Holothuria* sp. (Abarca and Ruepert, 1992). From the year 2000 onwards, more studies acknowledged pesticide pollution from banana plantations. In Costa Rica, several authors studied pesticide residues in packing plant drainages (Castillo et al., 2006), banana plantation drainage canals (Castillo et al., 2000, 2006), natural rivers and lagoons (Arias-Andrés et al., 2018; Castillo et al., 2006; Echeverría-Sáenz et al., 2018a; Rämö et al., 2018), air and dust (Córdoba Gamboa et al., 2020; Daly et al., 2007; Shunthirasingham et al., 2011; Wang et al., 2019) as well as soil (Chaves et al., 2007; Mendez et al., 2018; Shunthirasingham et al., 2011). Table 1 contains an overview of recent (2009 onwards) pesticide concentrations detected in different environmental matrices of the banana growing region in Costa Rica. Pesticides have been frequently analysed and detected in surface waters at a maximum concentration of 40 μg/L as reported for the insecticide diazinon. However, although less data is available for pesticide concentrations in soil and air, elevated concentrations levels of up to 140 ng/g (clorothalonil) and 62 ng/m^3 (terbufos), respectively, have been detected (Table 1).

Table 1 indicates that the frequent and year-round pesticide applications at high rates result in high environmental pesticide concentrations within banana plantations and in adjacent ecosystems. Transport processes during (i.e., spray drift) and after application (runoff, leaching) lead to frequent exposure of aquatic and terrestrial non-target ecosystems. Mendez et al. (2018) state that runoff accounts for almost all of the inputs of epoxiconazole and ethoprophos from the soil into the water compartment, while for diuron, leaching represents the most relevant pathway. Another specific pathway for pesticides from banana plantations to non-target ecosystems are insecticide impregnated bags protecting banana bunches: 90 % of the insecticide chlorpyrifos used to impregnate these plastic bags is lost within 10 days, mostly due to evaporation. It is estimated that by this source alone 22.5 t of chlorpyrifos and its degradation products are released from banana production into the environment (Altabtabaee et al., 2016). The available data indicate that all environmental components in or near banana plantations are exposed, however, pesticide concentrations were most frequently reported for surface waters, while exposure information in other matrices (soil, air) is comparably scarce. At the same time, fungicides are most frequently detected relative to herbicides and insecticides, which may be explained by their recurrent application throughout the year (see above).

The amount and number of pesticides moving from banana plantations into nearby lowland tropical forests is currently unknown (see Fig. 1 for example locations). Especially isolated forest fragments in the proximity of banana plantations could be exposed to pesticides because of the weekly aerial fungicide applications. In support of this assumption, drift from aerial endosulfan spraying in cotton reached 18 % of the field application rate 100 m away from the agricultural land, 5 % at 200 m and 2 % at 500 m distance (Woods et al., 2001). Similarly, Cordova and co-workers used rice plants as biotests for aerial glyphosate applications and estimated 14 % of the field rate reaching 150 m from the edge of the agricultural fields, 13 % at 200 m and 5 % at 400 m (Córdova et al., 2020). Therefore, especially drift from aerially applied pesticides - for banana plantations this considers mainly fungicides - to surrounding forest fragments is very likely to result in a repeated and thus chronic

Table 1
Pesticide concentrations from environmental samples in or near banana plantations of Costa Rica (from 2009 to 2019), including regulatory threshold levels and calculated risk quotients for surface waters (see text for details), (I: insecticide; F: fungicide; H: herbicide).

Active ingredient	Air ^{1}(ng/m^{3}) mean (SD), max.	Soil^{2} (µg/kg) max. - min.	Surface water^{3}(µg/L) mean (SD), max.	Regulatory Threshold Level (µg/L)	Aquatic Risk Quotient based on mean/max. concentration
buprofezin (I)	n.d.		0.06 (0.15), 1.13 *	n.a.	n.a.
carbaryl (I)			0.39 (0.52), 2.2	0.017	**22.9412/129.4118**
carbofuran (I)	n.d.		1.24 (1.73), 5	0.0376	**32.9787/132.9787**
chlorpyrifos (I)	18.2 (6.3), 36.1 ***	5 $^{+}$	0.06 (0.09), 0.73	0.00035	**171.4286/2085.7143**
diazinon ^{a} (I)	0.6 (1.0), 4.0 *		0.37 (3.05), 40 **	0.0021	**176.1905/19047.6190**
dimethoate (I)			0.16 (0.02), 0.2	0.43	0.3721/0.4651
ethoprophos (I)	5.5 (10.9), 60.9 **	~ 2.7 ^{c}	0.19 (0.33), 2.7 *	0.428	0.4439/**6.3084**
fenamiphos (I)	n.d.		0.53 (1.63), 8.3	0.019	**27.8947/436.8421**
terbufos (I)	6.2 (13.7), 61.7		0.10 (0.16), 0.51	0.002	**50/255**
azoxystrobin (F)	n.d.		0.39 (0.43), 2.7 *	2.59	0.1506/**1.0425**
bitertanol (F)	n.d.		0.10 (0.09), 0.29	21	0.0048/0.0138
boscalid (F)			0.07 (0.07), 0.3	27	0.0026/0.0111
chlorothalonil (F)	present, non quantifiable *	140–20 ^{b}	0.15 (0.38), 2.06	0.179	0.8380/**11.5084**
difenoconazole (F)	1.3 (3.4), 21.3		0.20 (0.25), 1.38	7.69	0.0260/0.1792
epoxiconazole (F)	3.1 (4.5), 15.9 *	~ 2 ^{c}	0.22 (0.24), 2 *	n.a.	n.a/n.a
fenpropimorph (F)	2.3 (3.5), 21.0 *		0.06 (0.08), 0.4	21.43	0.0028/0.0190
fluopyram (F)			0.16 (0.176), 0.78	260	0.0006/0.0030
imazalil (F)			0.38 (0.29), 1.01	14.79	0.0257/0.0682
metalaxyl (F)			0.06 (0.06), 0.25	293	0.0002/0.0009
Active ingredient	**Air^{1}(ng/m^{3}) mean (SD), max.**	**Soil ^{2} (µg/kg) max. - min.**	**Surface water^{3}(µg/L) mean (SD), max.**	**Regulatory Threshold Level (µg/L)**	**Aquatic Risk Quotient based on mean/max. concentration**
myclobutanil (F)			0.09 (0.09), 0.6 *	83	0.0011/0.0072
propiconazole (F)	n.d.		0.12 (0.10), 0.44	8.5	0.0141/0.0518
pyrimethanil (F)	5.4 (6.9), 22.2 **		0.10 (0.11), 0.81 *	30.4	0.0033/0.0266
spiroxamine (F)	5.5 (12.1), 61.9		0.03, 0.05 $^{+}$	0.257	0.1946 $^{++}$
tebuconazole (F)	n.d.		0.16 (0.13), 0.6	28.8	0.0056/0.0208
thiabendazole (F)			0.28 (0.27), 1.2	3.1	0.0903/0.3871
triadimefon (F)			0.21(0.17), 0.6	17.3	0.0121/0.0347
triadimenol (F)			0.16 (0.09), 0.31	25	0.0064/0.0124
ametryn (H)			0.31(1.44), 20 **	0.367	0.8446/**54.4959**
atrazine (H)			0.09 $^{+}$	1.1	0.0818 $^{++}$
bentazone (H)			0.15 (0.09), 0.4	623	0.0002/0.0006
bromacil (H)			0.48 (0.37), 1.6	0.68	0.7059/**2.3529**
butachlor (H)			0.04, 0.04 $^{+}$	2.8	0.0143 $^{++}$
diuron (H)		~ 24 ^{c}	0.49 (1.80), 24 **	0.24	**2.0417/100**
hexazinone (H)			0.22 (0.52), 3	0.68	0.3235/**4.4118**
oxyfluorfen (H)			0.02, 0.03 $^{+}$	2	0.0150 $^{++}$
terbuthylazine (H)			0.03, 0.04 $^{+}$	0.32	0.1250 $^{++}$
terbutryn (H)			0.07 (0.07), 0.18	8.2	0.0085/0.0220

bold values indicate RQ >1 (i.e., the mean or max surface water concentration exceeds its RTL);
* detection frequency >25 % of the samples; ** >50 % of the samples; *** >90 % of the samples; n.d.: not detected, n.a.: not available.
[a] not reported to be used on banana; [b] 4-hydroxy-chlorothalonil is the main metabolite found in soil (present even 6 days after application in a dissipation study by Chaves et al. 2007); [c]Model-estimated concentrations in soil, given that predicted concentrations for soils and sediments are as high or higher than peak concentrations in the water (Mendez et al., 2018).
1. Córdoba Gamboa et al. (2020). 2. Chaves et al. (2007); Van Wendel et al. (2012); Mendez et al. (2018).
3. Arias-Andrés et al. (2018); Castillo et al. (2006); Echeverría-Sáenz et al., (2018a); Rämö et al.,(2018); Echeverría-Sáenz et al., (2020); Echeverría-Sáenz et al., (2018b).

exposure over the entire year with significant off-field transport up to several hundred meters. Herbicide and nematicide applications are relevant for the exposure of soil within plantations and may be transported to surrounding terrestrial areas via runoff. A study in German conservation areas situated in agricultural landscapes revealed that a distance of 2 km was relevant for the exposure of flying insects (Brühl et al., 2021), indicating pesticide transport over distances substantially exceeding the reports for spray drift. This biological transport is also likely in a landscape where banana plantations and rainforest fragments compose a matrix used by different kinds of organisms. No data are available for soil and vegetation exposure within banana plantations. Also, for temperate agricultural soils, first data on pesticide residues only emerged recently (Hvězdová et al., 2018; Pelosi et al., 2021; Sabzevari & Hofman, 2021; Silva et al., 2019). Related to soil health allowing sustainable use for future generations (Tahat et al., 2020) monitoring of pesticide exposure of the agricultural soils themselves deserves further attention.

In recent years it became clear that not only habitats adjacent to banana plantations are exposed to pesticides. Pesticides were recorded in mountain areas, some of them even under protection, a few 100 km away from banana plantations. This was shown for the insecticide endosulfan, before it was banned in Costa Rica (Shunthirasingham et al., 2011) as well as current use pesticides (Daly et al., 2007; Wang et al., 2019). Specifically, elevated concentrations of the fungicide chlorothalonil and the herbicide dacthal used in banana production as well as the insecticide metabolite endosulfan sulfate were detected on volcanoes in the Central Valley, lying downwind of extensive banana plantations of the Caribbean lowland. These observations point to a shift in relevance of the different pesticide transport processes in tropical relative to temperate regions. Especially higher temperatures may favour volatilization in the tropics. In combination with deposition and reduced breakdown of pesticides in remote and cool montane areas this led to detectable concentrations of a number of pesticides in forest mist and even phytotelmata of bromeliads (Shunthirasingham et al., 2011).

2.2. Human exposure

Exposure to pesticides is especially high in workers involved in the spray procedures and handling of pesticides as well as their families living in the area. In the Caribbean lowlands many villages and schools are situated near banana plantations. For example, in Matina County, 18 out of 33 primary schools (55 %) are situated less than 200 m, and ten (30 %) at even less than 100 m from banana plantations. The Infants Environmental Health (ISA) cohort study enrolled 451 pregnant women from villages close to or in banana plantation (van Wendel de Joode et al., 2014). Among these women, urinary concentrations of the main metabolite of the aerially applied fungicide mancozeb, were detected in 100 % of samples and concentrations were more than five times higher than those reported for other general populations and inversely associated with residential distance to banana plantations. In addition, urinary pesticide metabolite concentrations of the fungicides pyrimethanil, thiabendazole and the insecticide chlorpyrifos were detected among these pregnant women (0.56 (368.55); 0.11 (339.00); 1.75 (62.96) median and (maximum) concentrations in ng/mL respectively) (Mora et al., 2020). Another study revealed that aerial mancozeb spraying leads to higher urinary metabolite concentrations in children than other application strategies, possibly due to inhalation, exposure through skin or ingestion (van Wendel de Joode et al., 2016). Depending on the type of pesticide and its physical- chemical properties, different exposure routes are of importance. In the banana growing area exposure through inhalation to not only single pesticides but mixtures is likely. In fact, nine different pesticides used on banana plantations were detected in passive air monitors at 12 schools in Matina county on four occasions (Córdoba Gamboa et al., 2020). Six out of these pesticides were fungicides, two nematicides and one insecticide (chlorpyrifos). The insecticide chlorpyrifos was detected in 98 % of all samples and concentrations were higher in schools closer than 100 m to plantations, yet it was still detected at one school more than 1000 m away. In a houses study in the Talamanca area, chlorpyrifos was recorded in mattresses (2 out of 10), indoor dust (3 out of 12), outdoor soil (1 out of 2), all relevant for contact exposure, surface water (2 out of 4), but not in drinking water (0/5), as well as in all of the 12 hand and foot wash samples obtained among children living near banana plantations (Van Wendel et al., 2012). Ultimately, these studies indicate that drift from pesticides applied in banana plantations results in exposure of families living nearby.

3. Effects

3.1. Effects in the aquatic environment

Pesticides pose a threat for the integrity of aquatic ecosystems worldwide, leading to changes in biodiversity and ecosystem functioning (Beketov et al., 2013). Whether and to which extent the impact of pesticides in tropical aquatic ecosystems deviates from impacts observed in temperate regions has been discussed for several decades (Castillo et al., 1997; Rico et al., 2011). These potential differences may arise from climate related parameters, sensitivity of organisms or agricultural practices (Daam and van den Brink, 2010). The latter aspect is considered as the most relevant, driven by the high frequency of applications and amounts of pesticides applied (Daam and van den Brink, 2010). Regarding comparative sensitivity of tropical species, studies are scarce. In the case of Costa Rica, native species of cladocerans *(Daphnia ambigua and Simicephalus serrulatus)* showed a sensitivity 20 times higher to ethoprophos as compared to the standard test species *Daphnia magna* (Arias-Andrés et al., 2014).

In line with this theoretical approach a range of field studies documented adverse impacts of agricultural practices in tropical aquatic ecosystems (e.g., Damanik-Ambarita et al. (2016)). In streams within the agricultural landscape of Panama, Cornejo et al. (2020) reported a lower leaf litter decomposition with increasing but unspecified agricultural activity within the catchment. This effect was related to a shift in the leaf consuming invertebrate community composition driven by sediment and pesticide input. Similarly, in Costa Rican streams the macroinvertebrate community composition was negatively affected by pesticides originating from banana (Castillo et al., 2006; Echeverría-Sáenz et al., 2018a) and pineapple plantations (Echeverría-Sáenz et al., 2012). Moreover, Svensson et al. (2018) documented a consistent reduction of diversity and poorer scores in macroinvertebrate biodiversity indexes at sites within a short distance downstream from banana plantations relative to upstream sections. Along these lines, the concentration of pesticides in caiman blood samples decreased with distance from banana plantations, which was reflected in their body condition and thus health (Grant et al., 2013). The impact on caiman health can either be a consequence of direct effects of pesticides on the exposed individuals or indirect through changes in the availability and quality of their prey, namely fish. Indeed, fish mortalities have been reported in streams draining banana plantations (Castillo et al., 2000). These observations have been linked to runoff events shortly after application of nematicides, including neurotoxic organophosphates like ethoprophos, fenamiphos and terbufos, that are highly toxic for fish (Forth, 2001). However, in most of the reported cases, no clear relationship between environmental pesticide concentrations and the effect in aquatic biota, such as fish kills, has been established (Polidoro and Morra, 2016). This could be attributed to the methodological limitations related to capturing the peak concentrations of pesticides or the still existing lack of knowledge of biota responses to repeated exposures to pesticide mixtures (Stehle et al., 2013). Additionally, concentrations of some insecticides such as pyrethroids are difficult to detect and are therefore underestimated in their effects in fish kills (Rämö et al., 2018).

When effects other than acute mortalities have been assessed, biomarker responses have indicated signs of neurotoxicity, such as inhibition of cholinesterase activity; biotransformation (induction of glutathione S-transferase activity) and oxidative stress (increased lipid peroxidation) in fish affected by runoff from banana plantations. Correlations have been established between residues of individual pesticides or groups and the biochemical responses in fish (Mena et al., 2022, 2014). Regarding mixtures, the local fish *Parachromis dovii* was exposed to fractions of the median lethal concentrations of two pesticides (chlorpyrifos and difenoconazole), individually and in mixture. Cholinesterase (ChE) inhibition was observed after the exposure to an environmentally relevant concentration (5 μg/L range) of chlorpyrifos; however, in the mixture with difenoconazole, no significant ChE inhibition occurred but theinduction of the biotranformation phase I enzyme, Ethoxyresorufin-O-deethylase (EROD), was observed (Jiménez et al., 2021). Further, the responses of two different fish species (*P. dovii* and *Poecilia gillii*) were compared after a short exposure to the same mixture of chlorpyrifos-difenoconazole. In this case,*P. gillii* had significant induction of phase I biotransformation (Cyp1A induction and increased EROD activity), ChE inhibition, and behavioral changes while *P. dovii* only showed Cyp1A induction (Redondo-López et al., 2022). This demonstrates the complexity of the interaction of such contamination with the metabolism of the recipient biota and how the effects of pollution can differ among species from the same trophic level. Sandoval-Herrera et al. (2019) found that the exposure of the local fish *Astyanax aeneus* to a fraction of the median lethal concentration of ethoprophos, caused the expected inhibition of cholinesterase activity and this biochemical effect was correlated with a delayed escape from predation. These are examples of how the permanent presence of pesticides from banana plantations can affect the physiology and behaviour of fish and some of these effects can be linked to higher ecological adverse outcomes (Hellou, 2011; Peterson et al., 2017).

Amphibians were assessed by Méndez et al. (2016; 2022) addressing the toxicity of chlorothalonil, that is transported from banana plantations towards higher elevations, to tadpoles of Costa Rican frog species recorded there. Chlorothalonil was highly toxic for three species and caused different sub-lethal effects, including induction of biotransformation and changes in the development of the tadpoles. The high toxicity of chlorothalonil, as well as the nematicides terbufos and ethoprophos was also reported for tadpoles of the red-eyed tree frog (*Agalychnis callidryas*) (Ghose et al., 2014).

Consequently, the aquatic organisms studied in the watersheds impacted by banana plantations suggest a range of effects from sublethal and suborganismic to ecosystem processes. The chronic exposure to pesticide mixtures needs further research also under tropical conditions, especially when it comes to effects on population, community and ecosystem level. These insights will significantly boost pesticide risk assessment in this climatic zone.

3.2. *Effects in the terrestrial environment*

Studies on direct pesticide effects on the terrestrial environment are scarce and often based on comparisons of organic versus conventional plantations, that differ not only in pesticide use but also in varieties planted, fertiliser input and a number of other parameters. A field study comparing organic and conventional banana plantations revealed higher numbers of macroinvertebrates and a higher biodiversity in the soil of plantations under organic management (Castillo et al., 2002). However, comparisons between plantations with high and low pesticide input did not show any difference in microbial communities (Vargas, 2006). Sanderson Bellamy et al. (2018) studied the impact of banana production on terrestrial insect communities. By assessing the insect diversity and functional roles present in transects along farms with different management regimes (conventional, conventional with lower pesticide input, and organic) they observed a reduction in both variables related to more intensive management characterised by increasing pesticide applications.

Parasitic Hymenoptera play an important role in biological control of insect pests in banana plantations and especially Lepidoptera like e.g., the banana stalk borer, *Castniomera humboldti* (Harrison, 1963). An inventory showed highest parasitoid abundance and species richness in low-input banana plantations and lowest values for conventional systems where especially nematicide and insecticide applications had a strong negative impact (Matlock and de La Cruz, 2002). Biological control even in conventional plantations might currently still be in place but historic outbreaks caution against heavy use of insecticides and nematicides.

Salas-Rojas et al. (2006), studied bird and amphibian diversity within one organic and one conventional banana plantation in Costa Rica in 2001. They documented 69 bird species and 13 amphibians in the organic banana farm, while the conventional farm had 29 bird species and 4 amphibians. Although based on restricted sample size, the authors attribute the difference to enhanced floral composition, which favours availability of food, refuge, reproduction sites and rest areas. Furthermore, insecticide use in the conventional farm may have altered the abundance and structure of insect communities that are important dietary items for specialist species of birds or amphibians, inducing shifts to more generalistic species. In a similar approach, Bach (2000) studied the diversity, abundance and distribution of amphibians in three banana farms (one organic, two conventional). In the organic banana plantation, a higher abundance (71 ind.) and higher species richness (13 spp.) than in the conventional was recorded. Eight amphibian species were only recorded at the organic farm. The least biodiverse plantation (with only 13 ind. /3 spp.) was also the largest (8 times the area of the organic) and oldest. Direct toxicity of pesticides to amphibians and birds might also affect their populations in banana plantation areas. Especially fungicides, which are applied weekly in conventional banana plantations, proved to be acutely toxic for temperate amphibians (Adams et al., 2021; Brühl et al., 2013). So far studies on the sensitivity of terrestrial stages of tropical amphibian species in banana plantations are lacking. For reptiles, only the pit viper (Terciopelo) *Bothrops asper*, that is commonly found in banana plantations, was studied. The snakes showed elevated biomarker levels related to detoxification, which may be associated with pesticide contamination (Arguedas et al., 2019).

Compared to aquatic studies, no pesticide measurements are available to characterise exposure in all terrestrial studies, which is especially important for field investigations supporting conclusions and potentially decision making. Additionally, indirect effects that are affecting food chains, as for example a decline of insect biomass that affects insectivorous bats and birds feeding their offspring, are so far not addressed at all.

3.3. *Human health effects*

Human health effects can range from acute poisoning to the development of cancer and/or neurological development. The world health organisation (WHO) estimated 3 million acute poisonings resulting in 220,000 deaths worldwide, mostly in developing countries. In Central American countries 30,000 poisonings were estimated to be caused by low levels of worker and community awareness as well as the import and use of banned or restricted pesticides, among others (Ngowi et al., 2007). For Costa Rica 296 annual fatalities due to pesticide poisoning are estimated (Boedeker et al. 2020).

Health effects on banana plantation workers have been reported for decades. In 1942, manual spray workers complained to the national physician president of Costa Rica that “headaches, night coughs and bad eyes are all common among us” (Marquardt, 2002). Massive use of Bordeaux Mixture, which is based on copper, to control *Sigatoka* in the 1960s led to incidences of a lung disease, that first was diagnosed as tuberculosis but later seen as copper build-up in the lungs of spraying workers (Marquardt, 2002). In the 1970s the nematicide DBCP (1,2-dibromo-3-chloropropane), that was applied as granules in industrial banana plantations, caused the sterilization of 1,500 workers. The effects included psychological trauma as well as permanent infertility (Thrupp 1991). Human health effects of pesticides used in banana plantations include fatal incidences among workers and their families. A detailed study of 15 poisonings with paraquat showed that the herbicide may cause fatal poisonings by intentional ingestion of small amounts to commit suicide but also by unintentional dermal absorption of diluted paraquat, and possibly by inhalation (Wesseling et al., 1997).

In an analysis of the cancer registry of Costa Rica from 1981 to 1993, high incidences of cancer of respiratory organs as well as ovary and prostate were recorded in the banana producing Caribbean region, which are not mirrored in other rural areas in Costa Rica (Wesseling et al., 1999). A retrospective study evaluating the cancer record of Costa Rica indicated elevated incidences of melanoma, penile and cervix cancer and leukaemia in the human population there and have been linked to the high pesticide use (Wesseling et al., 1996).

Pesticide effects were studied in parallel to exposure in the Talamanca region in children living near banana plantations. Exposure was determined by analysing urinary metabolites of the fungicide mancozeb and the insecticides chlorpyrifos and pyrethroids (van Wendel de Joode et al., 2016). Metabolites of chlorpyriphos were associated with poorer working memory, poorer visual motor coordination, inattention, poorer verbal learning outcomes and other symptoms and the pyrethroid metabolites with poorer processing speed. The study indicated the exposure and neurodevelopmental effects for children living in the banana growing area, however also mothers in pregnancy are exposed (see above) and prenatal development might be affected.

Human health effects are diagnosed for workers and their families in the banana plantation area for the last decades. With new pesticide compounds being used in the banana plantations a continuous monitoring of health effects in the Caribbean rural areas is necessary.

4. Risk assessment

4.1. Environmental risk assessment and pesticide regulation

The present regulatory Environmental Risk Assessment (ERA) procedure (laid down in Regulation R-635-2001) used for the authorization of pesticides in Costa Rica generally follows those in the US (US U.S. Environmental Protection Agency, 2021) and the EU (European Food Safety Authority Panel on, 2013).

For the aquatic risk assessment, the estimated exposure is compared to the outcome of an effect assessment using the Risk Quotient (RQ) method as in the US ((US U.S. Environmental Protection Agency, 2021); see below). The pesticide exposure assessment for surface waters in Costa Rica is currently conducted using the EU standardized “forum for the coordination of pesticide fate models and their use” (FOCUS) exposure modelling approach (2015). The outcome of the FOCUS models are Predicted Environmental Concentrations (PEC). In Costa Rica and the EU, PECs are calculated using FOCUS steps 1 to 4, where higher steps are less conservative but assumed to be more realistic compared with lower PECs. The higher FOCUS steps 3 and 4 are based on 10 different scenarios representative of the different climatic, agricultural and landscape characteristics in the EU. However, recent studies showed that in particular FOCUS steps 3 and 4 to be not sufficiently protective when compared to actual pesticide field concentrations in agricultural surface waters (Knäbel et al., 2014, 2012). Additionally, there is currently no FOCUS step 3 and step 4 scenario available, which reflects the specific conditions of tropical Costa Rican agri-environmental settings. This accounts also for the aerial application of pesticides as pesticide applications by aircraft are only allowed in very specific conditions in some EU member states and is therefore not considered in FOCUS. Further, there is no specific crop scenario for bananas available in FOCUS. It follows that the regulatory exposure assessment in Costa Rica is based on improper exposure modelling scenarios developed for temperate agricultural settings, that do not reflect the specific agri-environmental (e.g., climate, landscape, soil, crop) conditions in tropical ecosystems.

The regulatory effect assessment for aquatic organisms is based on endpoints of acute and chronic toxicity tests (e.g., L(E)C50, NOEC) using standard test species (i.e., daphnia, algae, fish species according to OECD and OCSPP guidelines). To evaluate the risk, the RQ method is used comparing effects (e.g., LC50) to the estimated exposure (i.e., PECs) (MINAE, 2020). RQs are then compared to a predefined level of concern (LOC, i.e., 100 for acute toxicity, 10 for chronic toxicity and plants) to ensure that unacceptable risks are unlikely. No higher tier effect studies, such as Species Sensitivity Distributions (SSD) or mesocosms are currently considered for the regulatory ERA in Costa Rica, which is in sharp contrast to ERA procedures in the EU and the US (European Food Safety Authority Panel on, 2013; U.S. Environmental Protection Agency, 2021). Moreover, no toxicity information for tropical or indigenous species, if available at all, are considered.

To assess the risks for aquatic organisms based on field data in the present study, we used water-phase concentrations that were reported for 39 pesticide compounds (incl. 2 metabolites) since 2009 in watersheds of banana plantations in Costa Rica (Table 1). We conducted a retrospective risk assessment based on the RQ method, i.e., the mean or maximum water-phase concentration for a given pesticide was divided by its regulatory threshold level (RTL). To calculate these RTL, the respective LOC was used as an assessment factor applied to acute effect concentrations for aquatic invertebrates, fish and plants in accordance with current regulatory risk assessment methods employed in Costa Rica ((MINAE, 2020), see above). Effect data was retrieved from the USEPA ECOTOX Knowledgebase (U.S. Environmental Protection Agency, 2022), applying validity criteria as described in Petschick et al. (2019). Data was evaluated using R (version 4.2.2, 64-bit, R core Team, 2022). RTLs were available for 35 out of the 39 pesticide compounds with surface water concentrations and were compared to the measured field concentrations (i.e., n = 1,980 concentrations).

Approximately 25 % of all measured field concentrations exceed their respective RTL in Costa Rican surface waters (i.e., 488 out of 1,980 concentrations). Exceedances are highest in the group of insecticides (i.e., 72.07 % of insecticide concentrations (351 out of 487)), second highest in the group of herbicides (i.e., 21.79 % of herbicide concentrations (126 out of 578)) and lowest for the group of fungicides with only 1.20 % of fungicideconcentrations exceeding the respective RTL (11 out of 915 concentrations, see Fig. 2). Our data show that particularly insecticide concentrations reveal high environmental risks in surface waters associated with banana plantations. Further risk assessment results (Table 1) show mean concentrations of 7 (20 %) out of the 35 pesticides to exceed the RTL. Notably, 6 out of the 7 RTL exceedances of mean concentrations were related to insecticides, whereas hardly any RTL exceedance occurred for herbicides and fungicides (see also Fig. 2). For fungicides this is due to the test organisms involved in testing for risk assessment and pesticide regulation that include fish, algae and aquatic invertebrates but not yet any aquatic fungi (Zubrod et al., 2019). More information on toxicity of fungicides to aquatic fungi is necessary and especially chronic effects on aquatic litter decomposition (Cornejo et al. 2021) deserver further attention in the tropics to adopt the local risk assessment accordingly. For maximum water-phase concentrations, risk assessment results show RTL exceedances for 13 (37.1 %) out of the 35 pesticides detected in surface waters in banana plantations in Costa Rica. RTL exceedances were found for maximum concentrations of insecticides (n = 7 compounds), fungicides (n = 2 compounds) and herbicides (n = 4 compounds). Highest RTL exceedances up to a factor of 19,047 were found for the insecticides diazinon and chlorpyrifos, indicating a high risk for aquatic biota in banana plantation watersheds. It is noteworthy that in all these studies pesticides mixtures of several active ingredients with different modes of action and toxicities were frequently recorded, and consequently the risks for aquatic biota could be even higher than indicated by RTL-exceedances for individual compounds only.

The results of this risk analysis are similar to an early study, where acute and chronic aquatic risks of a range of pesticides applied in banana plantations were documented (Castillo et al., 2000). Studies using effect data from SSDs including native Costa Rican species showed risks above accepted levels for individual herbicides and insecticides (Arias-Andrés et al., 2018). A risk analysis in the watershed of the Madre de Dios River based on water samples collected over two years indicated risks to algae and invertebrates, with risks decreasing with increasing distance from

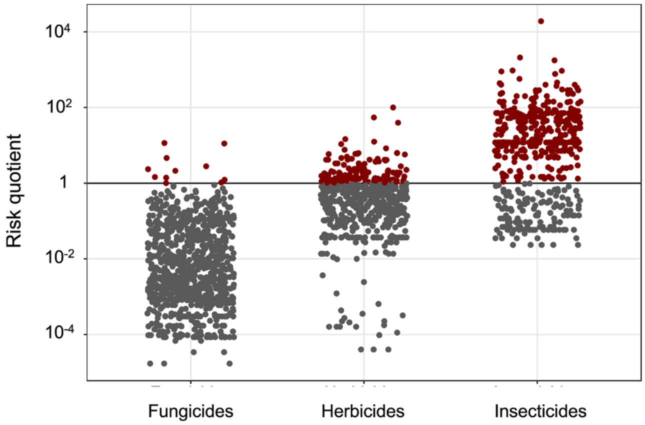

Fig. 2. Distribution of log10-transformed risk quotients (RQ) per pesticide group (based on 915, 578, and 487 surface water concentrations in Costa Rican banana plantations for fungicides, herbicides and insecticides, respectively). Red dots indicate surface water concentrations exceeding respective regulatory threshold levels (RTL, i.e., RQ > 1). See text for details. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

banana plantations (Rämö et al., 2018). A risk analysis showed that five active substances (diazinon, mancozeb, chlorothalonil, terbutylazine and ethoprophos) contribute to more than 75 % of the aquatic ecotoxicity and yet represent less than 40 % of the amount used, calling for an evaluation of potential replacement by other substances (Humbert et al., 2007).

The ERA for terrestrial organisms in Costa Rica is performed for birds and mammals, bees and earthworms and follows European guidelines (European Food Safety Authority, 2014, 2009; SANCO, 2002). Especially the conditions in tropical soil like higher humidity, lower clay content, acidity, deficiency in organic carbon and increased anion exchange capacity might lead to different fate of pesticides and therefore differ from temperate conditions (Daam et al., 2019). The risk to non-target arthropods including insects other than bees and plants is so far not assessed in regulatory procedures.

Additionally, the current approach, which is entirely based on temperate standard test species, may therefore potentially underestimates effects for tropical indigenous and potentially more sensitive species in Costa Rica (Arias-Andrés et al., 2018). Further on, the current risk assessment approach does not consider potential effects on ecosystem functioning and processes. Especially fungicides, affecting ecosystem processes and food webs already at the microbial level (Bundschuh et al., 2021), deserve more attention as they are heavily used in banana cultivation, occur widely, can be highly toxic to a broad range of organisms and are so far understudied in their potential risk (Zubrod et al., 2019). The protectiveness of assessment factors also remains unknown, considering the high biodiversity of the ecosystems to be protected, the year-round application of pesticides and the specific tropical conditions.

In conclusion it seems likely that the current regulatory ERA schemes conducted for pesticide authorisation in Costa Rica might not fully protect tropical biodiversity and ecosystems. The specific conditions and peculiarities of tropical agroecosystems in Costa Rica such as banana plantations, aerial applications, high rainfall amounts and temperature, high biodiversity and different soil properties are not reflected in the current risk assessment procedures. Additionally, fundamental flaws in the current EU risk assessment, which include the lack of consideration of exposure to multiple pesticides, indirect food web effects as well as the evaluation of effects on in-field biodiversity leading to a regulatory system that is not sufficiently protective, especially for the terrestrial environment (Brühl and Zaller, 2019) is also valid for the regulation in Costa Rica. Unacceptable effects on ecosystems and the biodiversity resulting from pesticide applications in Costa Rica can thus not be excluded.

4.2. Human risk

Health risks identified for the population living and working in the banana area include acute poisonings, skin inflammation, respiratory problems, cancer, neurobehavioral changes and male sterility (Barraza et al., 2011). Children are especially vulnerable and developmental effects are likely, given the high number of pesticides used in the banana plantations, including endocrine disruptors (Matisova and Hrouzková, 2012) and fungicides like mancozeb that are applied aerially. The risks of endocrine effects are particularly high for pregnant women exposed to the fungicides mancozeb and pyrimethanil, pyrethroid insecticides as well as chlorpyrifos (Vargas et al., 2022). Findings from the ISA study suggest that current regulations concerning aerial pesticide spraying activities in banana plantations do not protect pregnant women and foetuses from exposure to mancozeb. Risks for children are estimated as high, because even mild maternal alterations may affect foetal neurological development (van Wendel de Joode et al., 2014).

5. Conclusion

Conventional industrial banana plantations require the use of many pesticides in high quantities leading to the highest pesticide inputs worldwide. Especially black sigatoka limits the implementation of organic production without synthetic foliar fungicides to drier climates like Colombia or the Dominican Republic, the latter producing more than half of the organic bananas consumed as fruits world-wide (Bebber 2022). In Costa Rica, organic banana is grown for pulp production for baby food for decades. Production is comparably low with 12 t /ha compared to 70 t/ha in conventional plantations, however additional fruit and fibre is produced in these agroforest systems (Deugd, 2001). The Voluntary Certification Schemes that are in place such as for example Rainforest Alliance, Fair Trade or Gap are differing in their approach to pesticide use and might refer to recently proposed guidelines for selection of lower risk pesticides (Jepson et al., 2020).

Exposure of humans and the environment is especially high for fungicides as they are applied by aircraft and at high frequencies. Additionally, herbicides and nematicides are applied over the plantation areas and insecticides are used for specific treatments of the developing fruit and plants. The current understanding of the fate of pesticides under tropical climatic conditions and specific soil properties and resulting ecosystem exposure differ from temperate regions. However only scenarios developed for temperate regions in Europe are used in regulatory exposure assessment in Costa Rica and other tropical countries, potentially underestimating exposure of surrounding aquatic and terrestrial ecosystems. Our review shows, besides high concentrations currently reported for surface waters, that especially terrestrial exposure is highly understudied in tropical crops like banana, with virtually no data on mixture exposure on soils and vegetation, either within the plantations or due to transport processes in e.g., neighbouring rainforest fragments. Effects and risks of pesticide exposure on tropical organisms are also most likely underestimated as a higher tropical biodiversity might also include more sensitive species, which, however, are not tested for and included in pesticide authorization. So far only few native species were studied for their sensitivity towards pesticides, most of them of the aquatic environment. Importantly, ecotoxicity information for tropical and indigenous species is overall lacking in the environmental risk assessments. In conclusion, the current ERA implemented in the regulation of pesticides, could not be protective enough for tropical crops like banana in Costa Rica. It seems very unlikely that the banana industry is able to switch on a large scale to organic cultivation in the next decade and therefore pesticides will continue to be used. However, as Costa Rica is using EU guidelines for pesticide regulation, the country might also be interested in following the EU farm to fork and biodiversity strategy aim "to reduce by 50 % the use and risk of chemical pesticides by 2030 and to reduce by 50 % the use of more hazardous pesticides by 2030" (EU Comission, 2022), especially in a crop that is exported also to the EU in large quantities. Also, the Montreal Convention on Biodiversity meeting in December 2022 sets a global target to "reduce by half both excess nutrients and the overall risk posed by pesticides and highly hazardous chemicals" by 2030 (CBD 2022).

To reduce pesticide risks and to identify the most harmful substances for humans and the environment, detailed studies on exposure, effect and development of risk assessment approaches are needed. Additionally, tropical and native species need more attention in toxicity testing and effect assessment. Tropical species might be more sensitive to pesticides, but the higher productivity of tropical systems might lead to lower effects on population levels in the field due to faster recovery than assumed in temperate systems. Therefore, especially field studies that focus on population and community level responses towards pesticide mixtures are needed to develop a better understanding of pesticide risks for tropical biodiversity in agricultural landscapes intermixed with natural and semi-natural habitats. Studies on human health effects as well as effects on non-target aquatic and terrestrial organisms and follow-up risk assessments, can potentially identify high risk pesticides that then could be identified for substitution by less harmful pesticides. An especially worrying case is the continuing use of pesticides that are already banned in the US and EU. Tropical countries should follow this ban based on the overwhelming scientific evidence composed.

To reduce human health and environmental risks, a true safe use approach for pesticides in developing tropical countries should consider first whether there is a real need for a certain pesticide, by examining pests and the substation options with less dangerous alternatives. Regulatory authorities in these countries also need the capacity and support to develop and conduct local risk assessments. It also seems necessary to implement pesticide monitoring, especially as many of the factors in tropical systems (e.g., sensitivity of local species, local climatic and soil conditions) are not well understood (Wesseling et al., 2003).

Research results of pesticide exposure and risks in the Caribbean lowlands of Costa Rica, where banana plantations have been in place for decades and pesticides use is high, can be transferred to other tropical areas with banana or other industrialised crops. With the recognised declines of biodiversity, also related to pesticide use, and hotspots of biodiversity remaining in tropical areas, we consider research on the role of pesticides there especially important to be able to correctly estimate the risk of pesticide use and implement protective management options.

CRediT authorship contribution statement

Carsten A. Brühl: Supervision, Conceptualization, Project administration, Funding acquisition, Writing – original draft, Writing – review & editing. **Maria Arias Andres:** Writing – original draft, Writing – review & editing. **Silvia Echeverría-Sáenz:** Project administration, Funding acquisition, Data curation, Writing – original draft, Writing – review & editing. **Mirco Bundschuh:** Writing – original draft, Writing – review & editing. **Anja Knäbel:** Writing – original draft, Writing – review & editing. **Freylan Mena:** Writing – original draft, Writing – review & editing. **Lara L. Petschick:** Formal analysis, Data curation, Writing – original draft, Writing – review & editing. **Clemens Ruepert:** Writing – original draft, Writing – review & editing. **Sebastian Stehle:** Formal analysis, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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