Impact of pesticides in the amazon basin: a multidisciplinary review

Pablo Ochoa[1*]; Maria Gabriella da Silva Araújo[2]; Ana Claudia Batista[2]; Fátima A. Arcanjo[3]; Mario Rique Fernandes[4]; Ulysses Madureira Maia[5]; Isabela Maria Souza Silva[2]

[1] Departamento de Ciências Biológicas e Agrárias, Universidade Técnica Particular de Loja (UTPL), Equador – paochoa@utpl.edu.ec

[2] Laboratório de Ecologia Isotópica – Centro de Energia Nuclear na Agricultura, Universidade de São Paulo (CENA/USP), Brasil – gabriella.araujo@usp.br, anaclaudiabatista89@gmail.com, isabela_souza@usp.br

[3] Laboratório de Biodiversidade e Restauração de Ecossistemas, Departamento de Biologia Animal e Vegetal, Universidade Estadual de Londrina (LABRE-UEL), Brasil – fatimaa.arcanjo@gmail.com

[4] Núcleo de Estudos da Amazônia Indígena, Universidade Federal do Amazonas (Neai/UFAM) – riquemario@gmail.com

[5] Instituto Tecnológico Vale, Belém, Brasil – ulymm86@hotmail.com

*Corresponding author: Pablo Ochoa – paochoa@utpl.edu.ec

ABSTRACT

Pesticides are chemical substances used in agriculture to control pests and diseases in crops. However, their excessive and unregulated use can have severe repercussions on both human health and the environment. This review examines the utilization of pesticides in the Amazon basin, considering their socioeconomic impact on public health, regional biodiversity, and the availability of soil and water resources. For this purpose, the Scopus and SciELO scientific databases were consulted to gather relevant literature, including publications from various countries within the basin. The temporal distribution of information was also analysed. The findings reveal a significant increase in scientific research conducted in recent decades regarding pesticide usage in the Amazon basin. The study describes the impact regarding the loss of natural forest and the expansion of agricultural and livestock frontiers, especially in recent years. These practices have resulted in serious health issues, particularly among local and indigenous populations. Furthermore, there has been a decline in regional biodiversity, impacting crucial animal species that contribute to ecological balance by providing ecosystem services such as pollination and seed dispersal. Lastly, a case study is presented that showcases a successful agroecological model, emphasizing the urgent need for control measures to reduce pesticide usage throughout the entire Amazon basin. Such measures are vital for safeguarding human health and the environment. This demands the implementation of measures and policies that promote sustainable approaches by farmers and raise public awareness about the risks associated with indiscriminate pesticide use and responsible food consumption.

Keywords: deforestation, monocultures, pesticides use, human and environmental health, bioeconomy, Amazon basin.

Introduction

The Amazon basin is renowned for its rich biodiversity, hosting thousands of species of flora and fauna (Nobre *et al.* 2021). Furthermore, it is one of the three main centers of deep atmospheric convection, situated within the equatorial convergence zone (Reis *et al.* 2022). Despite its global significance, deforestation increased by approximately 30% between 2018 and 2019. In the year 2020, there was a resurgence of severe forest fires, which experts attribute mainly to factors such as land grabbing, the expansion of agricultural frontiers, pressure from international markets, inadequate public policies, and insufficient regulations for climate change mitigation and adaptation (de Araújo Mascarenhas *et al.* 2020).

Agricultural production has significantly increased in this basin since the advent of the "Green Revolution" (Júnior *et al.* 2022). This revolution resulted in a shift from diversified production systems to monocultures that require intensive use of chemical fertilizers and pesticides (Marin *et al.* 2022). These chemicals are currently considered "essential" for conventional and intensive agricultural practices. However, despite their importance in controlling weeds, pests, and diseases, their usage has significant adverse effects on human health and ecosystems (Arévalo-Jaramillo *et al.* 2019; Silva *et al.* 2019).

Some countries within the Amazon basin have laws that regulates the registration of pesticides, mainly concerning the active ingredients of the product, the demarcation of sites and cultivation areas where they will be used, the quantity and frequency of use, the timing of application, storage practices, and the proper disposal of waste and packaging (Júnior *et al.* 2022). However, it is not known how these laws support the commitment of the countries within the basin in issues such as responsible food production and consumption (Ochoa-Cueva *et al.* 2022), which is one of the Sustainable Development Goals (SDGs) of the United Nations (UN) (http://www.un.org/sustainabledevelopment/sustainabledevelopment-goals).

In Brazil, the country with the largest area of the Amazon basin , the use of pesticides has increased significantly over the past two decades. The quantity of active ingredients utilized rose from approximately 150,000 tons in the year 2000 to over 600,000 tons in 2019 (IBAMA 2020). Therefore, it is necessary to review the scientific publications on pesticides that have been conducted in all countries within the Amazon basin. Lastly, it is important to describe a success story from the basin that can be replicated by other communities, locations, or farms. Such a review would be immensely valuable for researchers, decision-makers, regulatory bodies, as well as local and regional governments operating within the Amazon basin. For this purpose, it is necessary to develop agreements and policies that contribute to the reduction of pesticide use and encourage the development of alternatives that are in harmony with the environment.

Material and methods

To carry out this systematic review, we used the method proposed by Page *et al.* (2021), called PRISMA (Preferred Reporting Items for Systematic and Meta-Analyses). This review was based on the collection of scientific articles that are available in the Scopus and SciELO repositories. The keywords for the search were: "pesticides" AND "Amazon"; and "Agrochemicals" AND "Amazon", respectively. We carried out the last search revision before data analysis in January 2023.

Study area

The Amazon River basin encompasses one of the most biodiverse regions on Earth, with eight recognized endemic zones (Rodrigues-Alcântara 2013). The Amazon Forest itself is the largest in the world, covering an approximate area of seven million square kilometers, stretching from the Andes Mountains to the Atlantic coast (Nobre *et al.* 2021). Moreover, the Amazon basin has diverse land cover and use (Figure 1), which have undergone significant changes over the years. While the natural forest cover remains dominant in the region, Brazil, the country with the highest deforestation rate, had an estimated loss of around 45 million hectares (Mha) of native forest between 1985 and 2021, amounting to nearly 12% of its total forest area. Conversely, agricultural land use has increased substantially during the same period, experiencing a growth of almost 244% (MapBiomas). The distribution of agricultural land use is concentrated in the eastern Amazon but is gradually expanding towards the interior (Figure 1; study area with the map of land cover and land use in the Amazon basin).

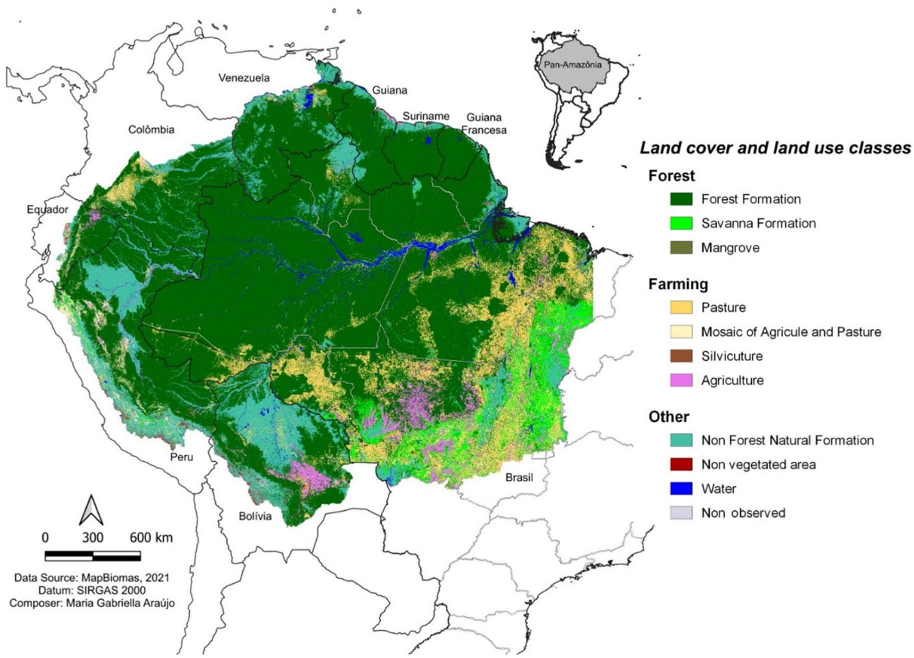

Figure 1 Study area with the land coverage and usage map of the Amazon basin.

Data selection and analysis

The articles selected for further analysis met the following criteria: 1) studies with the main theme of pesticides; 2) the research was carried out in the Amazon basin; 3) published in indexed journals. These three criteria were used to evaluate, initially, the title, abstract and document type (article, review, conference, or book chapter); to subsequently review the complete document of the investigations whose information was not consistent in the sections above.

For the analysis of the data from the selected and reviewed articles, a database was generated with information such as: a) Publication Year; b) Document Type (article, review, book chapter and congress article); c) Country of the Amazon basin in which the research was carried out, and d) specific issues related to the pesticides impacts. These issues were categorized based on the sustainability attributes, which are conceptually divided into economic, environmental, and sociocultural dimensions (Reid *et al.* 2005). Thus, five different subthemes were obtained: Bioeconomy, Deforestation and Biodiversity Loss, Human Health, Social Impact, and Water-Soil (Resources).

The R language was used for the analysis of the database in version 4.2.2. for Windows. For data tabulation, the "dplyr" and "reshape2" packages were used, and for generating graphs, “ggplot2” and “cowplot” were utilized (Team Core, R.).

Results and discussion

Publication trends over time

According to the results obtained for the Amazon basin, the first published reports on the topic of pesticide use began in the 1980s. A study conducted by Brinkman (1983) describes the nutrient imbalance between natural areas and agricultural systems with human interference. From the databases, about 100 articles were reviewed to analyze the historical trend of publications, taking care to identify the records that appear in both databases.

Figure 2 shows the temporal distribution of scientific articles on synthetic pesticides and their impacts in the Amazon basin. Initially, articles from the 1980s that address the characterization or description of the issue are recorded, but over time, the topics diversified and were published exponentially up to the current decade of 2020. Over 85% of the studies recorded in the databases were published in the last 15 years.

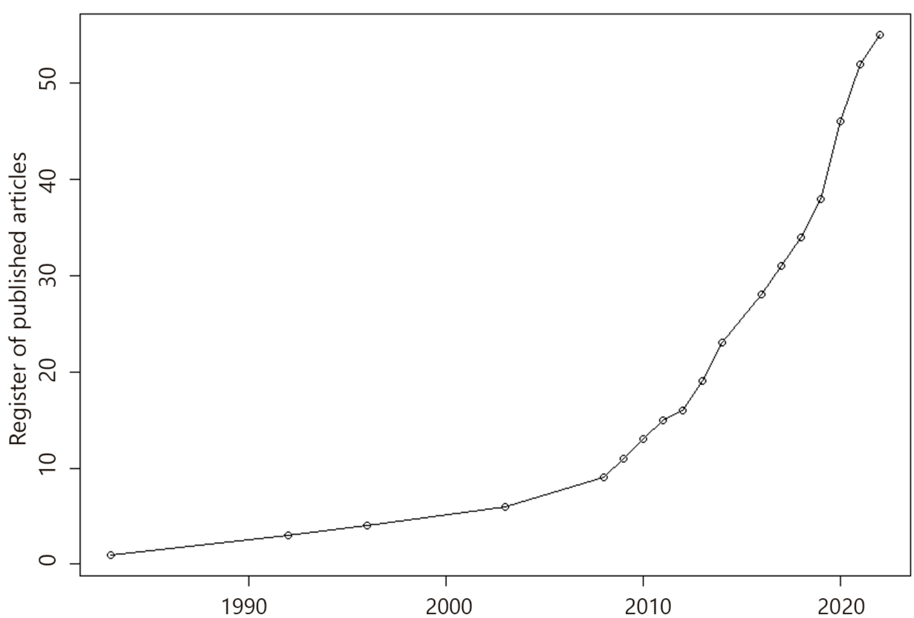

Figure 2 Temporal distribution of scientific articles on pesticide use in the Amazon basin.

Analyzing the data collected, it can be affirmed that research on the impact of synthetic pesticides in the Amazon basin is currently limited and unpublished, compared to the global context. When reviewing the same databases with the same general topic (pesticides), it was found that studies have been available since the 1940s, and these records exceed one hundred thousand articles. For that reason, despite the worldwide importance of this subject, the scientific capacity installed within the Amazon basin remains limited in comparison to the publication efforts of other regions.

Another important issue to highlight is the difficulty of access to the Amazon rainforest, which initially hindered the fragmentation of the natural forest and the expansion of the agricultural frontier. However, more recent studies, such as the one by Araújo Mascarenhas *et al.* (2020), mention that the use of herbicides and the implementation of intensive agricultural techniques are common practices nowadays in the Amazon, favoring river, aerial, and land-based navigation, but with strong negative impacts on human health and the environment. Vasco *et al.* (2021) mentioned that there have been more research efforts aimed at understanding the factors that drive deforestation in the Amazon, rather than understanding why the Amazonian population uses chemical fertilizers and pesticides for their agricultural production.

Trends of publications by country within the Amazon basin

As shown in Figure 3, the country with the greatest scientific production about pesticides is Brazil, accounting for 81.5%, followed by Ecuador with 11.8%. Interestingly, these countries show a significant difference in their Amazonian territorial extent. The record of publications from the other countries that share the Amazon basin is very low, at 1.3%. Figure 3 also shows studies developed in more than one country that is part of the basin, named “Regional.” It is worth noting that Guyana, Suriname, and Venezuela, the remaining three countries in the basin, did not report any articles on pesticides in the reviewed databases.

This analysis reveals a lack of understanding regarding the number of published articles, their temporal distribution, and their correlation with the respective government policies implemented in each country. Furthermore, it raises questions about whether these policies have facilitated or hindered efforts in publishing, as discussed in the previous section.

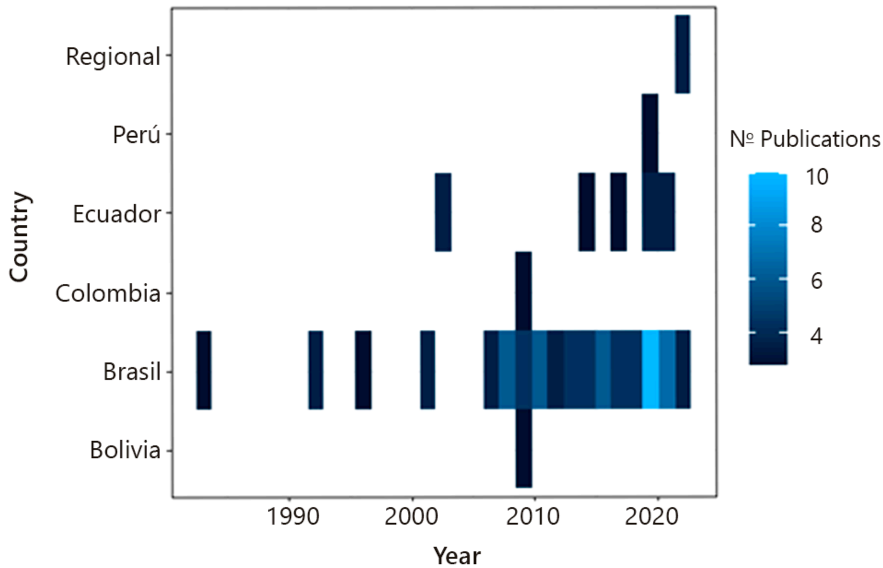

Figure 3 Temporal distribution of articles published by countries within the Amazon basin.

Trends in publications by topic

Figure 4 describes the themes in which the impacts generated by pesticide use on sustainability attributes were classified, which can affect economic, environmental, and/or sociocultural aspects. A detailed analysis of these five themes follows.

Water / soil (resources)

These two natural resources are the most frequent subject of study when investigating the impact of synthetic pesticides on the environment (Ochoa-Cueva *et al.* 2022). The review of this specific topic represents more than 30% of all the topics under analysis. Most of these studies have been conducted in Brazil with few exceptions, including a book chapter and an article covering the entire South American region. However, the first recorded research dates back to the mid-1990s with a foundational study conducted by Louter *et al.* (1996). The study's objective was to identify microcontaminants in samples of surface waters.

Subsequent studies were carried out with different approaches, building upon what was described by Winemiller *et al.* (2008), who examined the diversity and ecology of fish in tropical stream rivers, primarily focusing on sustainable food production and consumption to conserve tropical biodiversity. In the same year, Römbke *et al.* (2008) assessed the risks of pesticides in soils of central Amazonia, comparing them with temperate zones to ascertain potential effects on soil and biodiversity in the region. Studies conducted by Copatti *et al.* (2009), Pessoa *et al.* (2010), and Rico *et al.* (2011) centered their research on the water quality used for agricultural production, with Rico *et al.* (2011) specifically evaluating the toxic effects of pesticides on endemic freshwater fishes and invertebrates.

Later studies analyzed the impact of pesticides on soil quality. Mussy *et al.* (2013) identified microorganisms resistant to one of the most commonly used herbicides for weed and leafy grass control (2,4-D). Meanwhile, Mendez *et al.* (2016) and Rodrigues *et al.* (2017) studied the dynamics of Dichloro-Diphenyl-Trichloroethane (DDT) in soil and sediments in a tropical floodplain and in Belém, respectively. Both studies in the Amazon basin found traces of DDT despite its prohibition. Other research establishes comparisons between areas with natural cover and areas with palm oil production, demonstrating impacts on aquatic insect populations in these Amazonian streams (Shimano & Juen 2016).

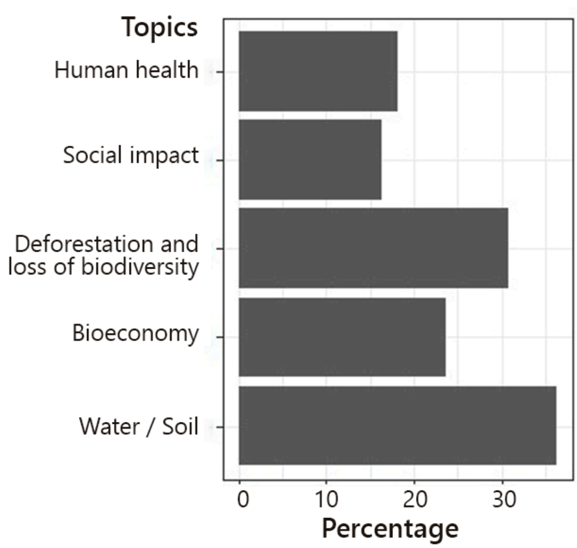

Figure 4 Publication trend of articles categorized by topics.

In the analysis of the last five years, publications are related to the deposition of pesticides in water and sediments (Neves *et al.* 2018; Viana *et al.* 2019). All the subsequent studies are recorded in this database and pertain to the assessment of ecological or environmental risks (Guarda *et al.* 2020; Rico *et al.* 2022; Val *et al.* 2022; Viana *et al.* 2020). This is a current trend detected for the entire region, and the ultimate goal of these studies is to establish a local, national, or with the support of international organizations, global regulatory framework (Daam 2023).

Deforestation and biodiversity loss

The expansion of agricultural frontiers is one of the main causes of deforestation in the Amazon rainforest, which covers approximately 7,000,000 km2 and harbors around 25% of global biodiversity (Nobre *et al.* 2021). It is precisely this vast territorial dimension combined with an inefficient state in managing its natural resources that made the Amazon basin attractive to many agribusiness entrepreneurs (Neves *et al.* 2018).

When discussing the Amazon, it is important to highlight that soy cultivation and livestock are the predominant activities in agribusiness. Synthetic pesticides play a crucial role in controlling weeds, pests, and diseases for the success of these practices. In addressing this issue, it is important to mention that Brazil has Law No. 7802, dated July 11, 1989, which regulates the initial phase of production, their use, and the final disposal of the packaging of these chemical products (Römbke *et al.* 2008; Waichman *et al.* 2007). However, despite this legislation, the intensive and widespread use and management of pesticides persist. Alternatives such as mitigation measures or integrated pest management (IPM) are minimal or nearly non-existent when compared to the availability of chemical solutions in the market (Waichman 2012). Unfortunately, this law has become ineffective in the Brazilian Amazon since 2018, as agribusiness has expanded exponentially without adequate regulatory or environmental oversight (Júnior *et al.* 2022; Lermen *et al.* 2018).

According to a study conducted by Kleanindustries in 2020, pesticides have been released into the Amazon rainforest via aerial means in an attempt to evade supervision by the Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA). Aerial fumigation with synthetic pesticides is used to cover hard-to-reach areas. As mentioned earlier, this practice has been employed since 2018, and this form of deforestation through tree poisoning is slower than clear-cutting or fires. Unfortunately, this tactic has gained strength due to its limited detection by real-time satellite imagery. According to Gonzales (2022), glyphosate and 2,4-D are the most commonly used pesticides to poison trees in natural areas. After their death, these trees are mechanically removed, facilitating the subsequent dispersion of seeds for agricultural crop establishment.

Glyphosate, carbosulfan, and 2,4-D were the pesticides used in the Vietnam War, where cases of congenital malformations are still reported. According to Agência Brasil, these pesticides have been found in clearings in the region of the deforestation arc, where the agricultural frontier advances towards the Amazon rainforest. Over 30,000 hectares of forest have already been cleared using chemicals to poison the trees. According to Ibama (2018), the crisis in the Amazon continues to escalate.

Despite numerous studies on pesticide use, or agrochemicals as they are commonly referred to in the agro-industrial sector to appear less offensive to foreign markets, their intensive use continues to persist as mentioned earlier. Although the international market demands measures to reduce or mitigate environmental impact, these are slow and ineffective (Marin *et al.* 2022).

The depicted in Figure 1 is the area designated for agricultural use. Only between 2000 and 2020, agricultural production in the Amazon saw a 327.3% increase, totaling 11.4 million hectares of harvested area, equivalent to approximately R$ 57.3 billion. The state of Mato Grosso alone accounts for nearly 70% of this total. Despite this, it is believed that Brazil requires more arable land to meet the demands of both local and export markets. Therefore, Martinelli *et al.* (2016) argue that it is necessary to reconsider the current agricultural and livestock model, as clearing the jungle for expansion is no longer a viable option. Cattle ranching areas in the Brazilian Amazon are often associated with illegal deforestation, where false land titles make regulation more challenging (Ribeiro 2020).

According to professionals from the Mamirauá Sustainable Development Institute: "Livestock farming itself is not the issue, but rather the production methods, which can be either beneficial or harmful." Expressions or positions like these weaken the arguments and efforts to combat deforestation in the Amazon rainforest, favoring the expansion of soy and livestock farming. Similar perspectives may exist within the academic and research institutes (Júnior *et al.* 2022). Therefore, it is crucial to disseminate studies that highlight the importance of land restoration, Good Agricultural Production Practices (GAPP), and Integrated Pest Management (IPM) as more sustainable alternatives.

Urgent action is needed to prohibit or limit the use of chemical pesticides in agricultural production, while suggesting the use of organic products to boost the region's bioeconomy. It is also crucial to have an effective state in combating deforestation in the Amazon, with robust control and oversight agencies, particularly concerning aerial pesticide spraying methods over the forest. This requires investments in technologies such as remote sensing and drones, necessary to enhance control and monitoring efforts.

Social impact

The issue of social impact can be approached from various areas, including the economic sector. However, given the specific concern related to the bio-economy, it will be examined from the perspective of ecosystem services. These goods and services are also obtained by humans from ecosystems, including supporting, provisioning, and cultural services (Reid *et al.* 2005). Pollination and seed dispersal fall under the category of supporting and provisioning services. Therefore, the analysis of these environmental services is crucial for ensuring human health and well-being, as well as for maintaining the balance and survival of numerous species on the planet.

Regarding the central theme of this review - pesticides - these can have a significant impact on certain ecosystem services. For instance, in relation to pollination, the use of certain pesticides has been linked to the decrease in bee populations (Sánchez-Bayo *et al.* 2016), having a negative impact on the health and behavior of these insects (Zhao *et al.* 2022), and diminishing their ability to forage, learn, and remember (Siviter *et al.* 2018). Colin *et al.* (2019) suggests that pesticide products such as neonicotinoids, even at sublethal doses, can promote the spread of diseases among bees. Beyond directly killing bees, pesticide exposure can also impact the overall health of beehives (Gill *et al.* 2012). Consequently, this affects the productivity of crops that rely on pollination services. In the Amazon region, bees play a crucial role in pollinating most of the plants that produce edible fruits (Paz *et al.* 2021). Therefore, the uncontrolled use of pesticides would have severe implications for the socioeconomic aspects and food security, particularly for the local communities in the Amazon basin.

Another important provisioning and cultural ecosystem service for biodiversity maintenance is seed dispersal, primarily carried out by birds and bats. They even facilitate the regeneration of degraded areas with this seed dispersal (Athiê & Dias 2016). On the other hand, the exposure of birds and bats to pesticide spraying can compromise their health directly or indirectly, through the consumption of food, water, or the destruction of their habitat (Oliveira *et al.* 2020).

The main effects of pesticide contamination on birds include the loss of safe habitats, changes in their habits or behaviors, particularly in feeding patterns, and a decline in their population due to reproductive disruptions, which may ultimately lead to local extinction (Arya *et al.* 2019). Conversely, bats that feed on insects are considered more susceptible to pesticides as they are at the top of the food chain (de Oliveira & Aguiar 2015). Insectivorous bats play a crucial role in controlling insect populations, including disease vectors such as dengue, leishmaniasis, and malaria, as well as agricultural pests (Oliveira *et al.* 2020). Thus, the biological control of pests, which is also a regulatory ecosystem service, is affected by the use of pesticides. Bats observed foraging in organically cultivated areas exhibited longer feeding times and greater species diversity compared to those found near chemically treated crops (Barré *et al.* 2018). These impacts on bats can significantly reduce the survival capacity of their populations, resulting in substantial losses not only in terms of ecological conservation efforts but also in socio-economic aspects.

Human health

In this matter of human health, several aspects need to be analyzed. One of them is the health of local populations, who are directly affected by the applications of pesticides for agricultural production in fields near their residences. At the same time, in many cases, these very local communities are the first to take action to protect the environment through their practices of sustainable management. Indigenous peoples, in particular, possess ancestral knowledge and hold deep respect for "Mother Earth," which provides them with a holistic view of their environment. This perspective enables them to provide multiple ecosystem services for the benefit of humanity as a whole (Ribeiro & de Sá Neto 2019).

However, despite their contributions, ancestral communities and indigenous peoples face various challenges, such as marginalization and negative impacts generated by society. They also confront destructive policies related to the encroachment on their territories (Oliveira *et al.* 2018). Pesticide contamination and intoxications are the main threats to municipalities, along with mining, which generates territorial conflicts due to its usage and gold-digging (Lima *et al.* 2022; Pignati *et al.* 2021; Ribeiro & de Sá Neto 2019).

As mentioned earlier, Brazil has a long history of pesticide use, which is reflected in current practices and observed harmful effects, especially among indigenous populations (Ribeiro & de Sá Neto 2019). Although it is impossible to disregard this historical problem, it is crucial to address recent cases of pesticide intoxication in Amazonian populations, often justified as mere accidental events (Oliveira *et al.* 2018). As mentioned, the majority of reported cases of intoxications involving indigenous peoples are concentrated in areas near the agricultural frontier, mainly in the southern Legal Amazon, specifically in the northern region of the state of Mato Grosso. This area has witnessed the widespread implementation and imposition of large-scale agro-industrial practices (Pìnheiro *et al.* 2022). Mato Grosso is one of the main contributors to deforestation in the Amazon region, and it also hosts numerous indigenous groups whose territories are increasingly invaded by the expansion of monocultures. This is an exemplary case of the environmental degradation that the agribusiness model can lead to if it continues to expand to other Amazonian states (Bombardi 2017; Oliveira *et al.* 2018).

Given the extent of problems resulting from the expansion of the agricultural frontier in the Amazon, it is crucial to comprehend the socio-environmental impacts that this expansion brings, especially in the context of indigenous communities. In this regard, representatives from organizations such as the Indigenous Amazon Operation (OPAN) have redirected their efforts towards a deeper understanding of the indigenous perspective on the effects of pesticide contamination, as seen in the case of the indigenous communities in the Juruena River basin hydrographic region, located in the northwest of the state of Mato Grosso (Oliveira *et al.* 2018). Indigenous communities like Paresi, Rikbaktsa, Manoki, Myky, and Nambikwara highlight the intrinsic relationship between pesticides, loss of biodiversity, and food insecurity, which poses a threat to the sustainability of their territories. It's noteworthy that indigenous perspectives on pollution and observed landscape changes differ from the dominant discourse in specialized academic fields.

From the perspective of indigenous knowledge, "attention is not only focused on the harm suffered by the human species, but rather on the concern for the well-being of various living beings that are also at risk of contamination." In indigenous narratives, this concern is reflected by highlighting the contamination of specific beings considered as rights-holders (Regina 2021). Furthermore, the way contamination occurs differs among various beings, both human and non-human. This underscores the intimate relationship between bodies and the territory they inhabit. The author further argues that the reciprocal nature of this relationship is evident, whether they are humans, fish, land animals, plants, or other beings (Regina 2021).

Another reference that illustrates the indigenous perspective on the impacts of agribusiness in Mato Grosso's territories is the short film "Para onde foram as andorinhas?" (available on YouTube), produced by the Socio-Environmental Institute and the Catitu Institute, in the Xingu Indigenous Park (PIX). The short film shows that in the last 30 years, 42% of the forests surrounding PIX have been deforested to make way for soy and corn monocultures. PIX is home to approximately 6,500 indigenous people from 16 different communities who rely on the forest for food, ritual materials, medicinal resources, and construction materials for their homes. The Xingu indigenous people have also observed the spread of forest fires and how the fruits from their fields rot before reaching maturity.

In Brazil, however, there is a lack of data or reports about pesticide poisoning in traditional populations. Incidents of poisoning in towns and villages are either unknown or not included in the government's official statistics (Marques *et al.* 2022). This limited availability of information hinders a comprehensive understanding of the issue and poses a significant obstacle to the development of public health policies that could protect local communities (Ochoa-Cueva *et al.* 2022). Consequently, addressing this issue at all possible scales becomes a challenge.

The adverse effects of pesticides on individuals living in areas near monoculture plantations remain a major challenge for public health. It is important to consider the historical context of pesticide spraying in regions close to local Amazonian populations and its detrimental health effects. It is also essential to examine how external and transnational agribusinesses promote the use of these chemical products for agricultural production, even within indigenous communities (Leite 2007). This latter aspect will be further addressed in the topic of bioeconomy, described below in more detail.

Bioeconomy

Concerning the field of bioeconomy, we have identified scientific publications, of which 70% originate from Brazil, 23% from Ecuador, and 7% from Peru. Publication records were discovered in only one article each during the 1980s, 1990s, and 2010s. Consequently, more than 50% of the publications on this subject have been documented in the last three years.

The Brazilian economy heavily relies on the agricultural sector (Ribeiro 2020), making the country one of the world's largest consumers of pesticides, second only to the United States (FAO 2022). Schiesari *et al.* (2013) emphasize that in the Amazon region, the lack of technical assistance leads to the improper use of these chemical products, resulting in overdosing or underdosing. Both short-term and long-term practices contribute to increased contamination of natural resources due to product ineffectiveness, leading to more frequent applications that directly and indirectly affect the population's health.

Given this reality, it is crucial to strategically change the dynamics of agricultural development in the region towards a more sustainable model that encompasses economic, social, and environmental aspects (Arvor et al. 2017;

Martinelli *et al.* 2010). Therefore, it is essential to promote and replicate successful cases of sustainable agriculture that have managed to eliminate or replace the use of these synthetic inputs with alternatives that are not harmful to the environment and human health. This is exemplified in Durofil *et al.* (2021) and Spletozer *et al.* (2021), which demonstrate that some Amazonian plants, such as *piperaceae*, have the potential to be employed as natural insecticides.

Impacts on the bioeconomy of Amazonian communities (Guaraná)

In the context of the bioeconomy related to agricultural production in the Amazon region, a native crop known as guaraná [*Paulinia cupana* var. *sorbilis* (*Martius*) *Ducke*] can be highlighted. Originally classified as a vine, it assumes a shrub-like form when cultivated in open environments. Brazil is the only country that commercially produces guaraná on a significant scale.

According to the Brazilian Institute of Geography and Statistics (IBGE 2021), the production of guaraná in 2021 amounted to approximately 2,732 tons. This was cultivated across an area of about 10,099 hectares, resulting in an average yield of 271 kg/ha. The total revenue generated from guaraná production was R$ 39,857,000.00. Among the states in Brazil, Bahia leads in terms of production, with around 1,831 tons and an average yield of 321 kg/ha. Amazonas follows with a production of 643 tons and an average yield of 160 kg/ha.

In this state, particularly in the city of Maués, a significant portion of guaraná production is carried out by family farmers. The Sateré Mawé indigenous people, who consider themselves the descendants of this plant, refer to it as 'Waraná,' a term that eventually evolved into its commercial name. They were the first to cultivate guaraná, utilizing it for medicinal, nutritional, spiritual, and ritual purposes. This ethnic group firmly believed that the fruit embodies the profound spiritual power of knowledge and wisdom inherent in the « Wará » . Guaraná holds profound significance for the local population in this municipality, serving as a symbol of their history and culture, while also playing a pivotal role in the local economy and, in turn, fostering social progress (Beaufort *et al.* 2008; Figueroa 2016; IDESAM 2018).

Currently, guaraná production primarily caters to the demand in the pharmaceutical industry for medicinal purposes and in the soft drink industry, where it is used as a main extract in beverages. The guaraná market has expanded, and in order to meet the strong demand, it became necessary to increase production. As a result, the traditional agricultural systems that used to cultivate guaraná shifted towards predominantly monoculture practices (Filoche & Pinton 2014).

To achieve higher productivity, reduced losses, and enhanced resistance, the Brazilian Company for Agricultural Research (EMBRAPA) has been conducting genetic improvement and studying matrix plants since 1976. This has led to the development of genetically improved and studied "clone seedlings" that form the basis of the monoculture system (Atroch *et al.* 2012).

To induce rooting of these clone seedlings, phytohormones are applied, with indole-3-butyric acid being the most commonly used. The substrate for cultivation consists of a mixture of forest soil, sand and simple superphosphate. Water, urea, and potassium chloride are typically used for seedling fertilization. Despite the resistance of these clones, there is still a risk of diseases such as anthracnose (*Colletotrichum gloeosporioides* (*Penz*.) Penz. and Sacc.) and pests like thrips (*Liothrips adisi*), which can affect the plants at various stages of growth. To mitigate infestations, agrochemicals such as acephate and deltamethrin, classified as insecticides, and fungicides like azoxystrobin, difenoconazole, methyl thiophanate, tebuconazole, and flutriafol are used (Pereira 2005).

According to Pereira *et al.* (2018), the application of cloned matrices in this "novel" production system has caused some small-scale producers to become dependent on agrochemicals and other inputs, resulting in increased production costs and rendering it economically unviable. A survey conducted by the Institute for Conservation and Sustainable Development of the Amazon - IDESAM (2018) reveals that 69% of producers in the region establish their guaraná plantations using clones, of which 25 to 30% employ chemical fertilization, while others adhere to traditional practices and apply organic fertilizers such as black earth, twigs, branches, dry leaves, and pruning remnants. Clones that do not receive adequate care, often due to the producers' lack of financial resources, become more susceptible to pest and disease infestations, which adversely affect the final production output.

In addition to economic problems, the use of agrochemicals has a direct impact on the populations of *Apidae* family, particularly the species *Meliponia seminigra*, *Xylocopa muscaria*, and *Apis mellifera*, which are considered the primary pollinators of guaraná (Gondim 1984; Lima & Rocha 2012). Nevertheless, dedicated studies that examine the behavior of bees in reaction to the pesticides employed in guaraná cultivation are imperative. It is also known that adopting agricultural practices that support pollinators, such as reducing pesticide usage, especially during flowering, and preserving nearby forests to create a favorable environment for nesting and the availability of floral resources for bees, is crucial for improving production (Wintermantel *et al.* 2022).

In line with the adoption of Sustainable Agroecological Models (SAM), the farmers from the communities along the Urupadi River have made the decision to revive the traditional approach to guaraná cultivation. They have replaced the use of clones with seedlings, often referred to as "offshoots" and obtained from the original liana plants known as "wild guarana" found in their natural state within the forest. The collection of forest seedlings is carried out in areas that harbor a diverse gene pool of wild guaraná. These seedlings are then planted in conjunction with existing trees, including fruit trees and other naturally occurring species.

This agroecosystem approach establishes an environment for the guaraná crop that closely mirrors its natural habitat. Therefore, the replication of the natural environment is likely to contribute to the natural regulation of pests and diseases. As a result, the cultivated area is transformed into a forest agroecosystem that benefits from natural fertilization sources (Aguiar *et al.* 2021).

In 2015, to strengthen the market, the producers of the Urupadi River formed the "Association of Family Farmers of Alto Urupadi" (AAFAU). This association gathered approximately 50 families engaged in sustainable guaraná cultivation through family farming. The association holds the ECOCERT seal (Guaraná Organic Conformity Certificates), which not only guarantees a 100% organic production but also highlights the product's value and the producers, ensuring equitable pricing for both domestic and international sales (Trindade *et al.* 2021).

The SAM approach, where its members actively participate in forest preservation and conservation, has proven to be successful. In addition to selling roasted guaraná beans, the association offers secondary products such as organic guaraná powder and a snack drink made from guaraná. In 2017, the producers of this association obtained the registration as a "Social Control Organization" (OCS), which allows them to sell their products directly in fairs, markets, or to the government (Pereira *et al.* 2020).

At present, AAFAU markets its products through both physical retail outlets and its website's online store. As a result, more and more guaraná producers are joining the movement and utilizing wild guaraná as their main product. It is essential to emphasize that these producers abstain from the use of pesticides, aiming to achieve a production that is more in balance with the environment.

Upon completing the review of scientific literature on the subject, a lack of comparative studies on productivity between the guaraná clone and wild guaraná has been observed. Although extensive research has been carried out on the guaraná clone, the study of wild guaraná in its current state represents a relatively recent area of investigation. This temporal discrepancy underscores the need for further studies to evaluate and compare the productivity of these two varieties. Additionally, it is crucial to conduct research that acknowledges the value of organic and family-based guaraná production, and other wild crops from the Amazon, taking into account not only economic aspects, but also the preservation and perpetuation of local culture.

Conclusions

This study makes a temporal review of the publications indexed in scientific databases on agrochemicals for the entire Amazon basin. It shows the beginning and the number of publications for decades of the different countries that compose it. It also describes how the different approaches to pesticide studies have been distributed, revealing possible biases and gaps in knowledge in the detailed data.

The use of pesticides and the expansion of the agricultural frontier are related and multifaceted issues that involve different sectors, with the economic aspect towards a global market being the one that currently prevails. Consequently, there is a pressing need to expand research efforts on all the issues addressed, but particularly on the adverse effects on human and environmental health (biotic and abiotic parts) of the Amazon.

It is also important to emphasize the need to describe sustainable production alternatives for the region. A potential solution includes taking advantage of the agricultural production of wild species with organic production and the transformation of these natural products with the same members of the local communities, activating the bioeconomy and social impact. Numerous case studies, such as the one on guaraná in this review, demonstrate the feasibility of replicating similar approaches in different communities, crops, and countries that make up the Amazon basin.

Although scientific research on pesticides has increased exponentially in the last 15 years, there is still a need to improve public policies and collaboration between the 8 countries that make up the basin. International links between universities and research institutes will allow the establishment of collaborative networks that will promote future research for the benefit of the sustainable management of the Amazon's natural resources.

Acknowledgments – The authors express their gratitude to the São Paulo Research Foundation (FAPESP) for supporting the development of the first edition of the São Paulo School of Advanced Science (ESPCA) "Inclusive and Sustainable Amazon," FAPESP 2022/06028-3. Our special thanks to the professors who participated in ESPCA, provided comments, and offered suggestions to enhance this review.

Author Contributions – All authors equally contributed to the conceptualization, methodology, and drafting of the initial and final versions of the text.

Conflict of Interest – The authors declare that they have no conflicts of interest related to the publication of this manuscript.

Ethics – This study does not involve human subjects and/or clinical trials that should be approved by the Institutional Ethics Committee

References

AGUIAR, O. D. C. M., DA SILVA LOPES, S. K., CASCAES, S. F., TRINDADE, L. L. L., DONEGÁ, M. V. B., RABELO, N. P., DA SILVA, S. C. P., PEREIRA, C. F., DE SOUZA, L. A. N., & FRAXE, T. D. J. P. (2021). Sistema agrícola tradicional e certificação orgânica: o caso dos guaranazais nativos das comunidades tradicionais do Alto Urupadí, Maués (AM). **In**: **Carla da Silva Sousa, Sayonara Cotrim Sabioni, Francisco de Sousa Lima.(Org.). Agroecologia: Métodos E Técnicas Para Uma Agricultura Sustentável. 1ed. Guarujá: Editora Científica Digital**, **2**, 80-100. https://doi.org/10.37885/210203245

ARÉVALO-JARAMILLO, P., IDROBO, A., SALCEDO, L., CABRERA, A., VINTIMILLA, A., CARRIÓN, M., & BAILON-MOSCOSO, N. (2019). Biochemical and genotoxic effects in women exposed to pesticides in Southern Ecuador. **Environmental Science and Pollution Research**, **26**(24), 24911-24921. https://doi.org/10.1007/s11356-019-05725-7

ARVOR, D., TRITSCH, I., BARCELLOS, C., JÉGOU, N., & DUBREUIL, V. (2017). Land use sustainability on the South-Eastern Amazon agricultural frontier: Recent progress and the challenges ahead. **Applied geography**, **80**, 86-97.

ARYA, A. K., SINGH, A., & BHATT, D. (2019). Pesticide applications in agriculture and their effects on birds: an overview. **Contaminants in agriculture and environment: health risks and remediation**, 5(10), 130-137.

ATHIÊ, S., & DIAS, M. (2016). Use of perches and seed dispersal by birds in an abandoned pasture in the Porto Ferreira state park, southeastern Brazil. **Brazilian Journal of Biology**, **76**, 80-92.

ATROCH, A. L., NASCIMENTO-FILHO, F. J. D., ANGELO, P. D. S., FREITAS, D. V. D., SOUSA, N. R. D., RESENDE, M. D., & CLEMENT, C. (2012). Domestication and breeding of the guaraná tree. **Domestication and Breeding: Amazonian Species, Federal University of Viçosa, Viçosa**, 333-360.

BARRÉ, K., LE VIOL, I., JULLIARD, R., CHIRON, F., & KERBIRIOU, C. (2018). Tillage and herbicide reduction mitigate the gap between conventional and organic farming effects on foraging activity of insectivorous bats. **Ecology and Evolution**, **8**(3), 1496-1506.

BEAUFORT, B., WOLF, S., & MARY, R. (2008). **Le guarana, trésor des indiens Sateré Mawé: mythes fondateurs, biodiversité, commerce équitable**. Y. Michel.

BOMBARDI, L. M. (2017). **Geografia do uso de agrotóxicos no Brasil e conexões com a União Europeia**. São Paulo.

BRINKMAN, W. (1983). Nutrient balance of a central Amazonian rainforest: comparison of natural and man-managed systems. **Hydrology of Humid Tropical Regions IAHS Publication**(140).

COLIN, T. O., MEIKLE, W. G., WU, X., & BARRON, A. B. (2019). Traces of a neonicotinoid induce precocious foraging and reduce foraging performance in honey bees. **Environmental Science & Technology**, **53**(14), 8252-8261.

COPATTI, C. E., GARCIA, L. D. O., & BALDISSEROTTO, B. (2009). Uma importante revisão sobre o impacto de agroquímicos da cultura de arroz em peixes. **Biota Neotropica**, **9**.

DAAM, M. A. (2022). Towards a tiered regulatory framework for the prospective aquatic effect assessment of pesticides in (Neo) tropical areas. **Integrated environmental assessment and management**.

DE ARAÚJO MASCARENHAS, G. M., DE ARAÚJO, L. M., & TIETZMANN, J. A. (2020). Agrotóxicos, dominação e fronteiras: significação, relação e perspectivas sobre o pacote tecnológico agrícola e a Amazônia brasileira. **Revista Brasileira de Políticas Públicas**, **10**(3).

DE OLIVEIRA, H. F. M., & AGUIAR, L. M. S. (2015). The response of bats (Mammalia: Chiroptera) to an incidental fire on a gallery forest at a neotropical savanna [Article]. **Biota Neotropica**, **15**(4), Article e0091. https://doi.org/10.1590/1676-0611-BN-2015-0091

DUROFIL, A., RADICE, M., BLANCO-SALAS, J., & RUIZ-TÉLLEZ, T. (2021). Piper aduncum essential oil: a promising insecticide, acaricide and antiparasitic. A review. **Parasite**, **28**, 42. https://doi.org/10.1051/parasite/2021040 (L'huile essentielle de Piper aduncum: un insecticide, acaricide et antiparasitaire prometteur. Une synthèse.)

FAO. (2022). Pesticides use, pesticides trade and pesticides indicators – Global, regional and country trends, 1990–2020. **FAOSTAT Analytical Briefs, no. 46.** https://doi.org/https://doi.org/10.4060/cc0918en

FIGUEROA, A. L. G. (2016). Guaraná, a máquina do tempo dos Sateré-Mawé. **Boletim do Museu Paraense Emílio Goeldi. Ciências Humanas**, **11**.

FILOCHE, G., & PINTON, F. (2014). Who Owns Guaraná? Legal Strategies, Development Policies and Agricultural Practices in Brazilian Amazonia. **Journal of Agrarian Change**, **14**(3), 380-399.

GILL, R. J., RAMOS-RODRIGUEZ, O., & RAINE, N. E. (2012). Combined pesticide exposure severely affects individual-and colony-level traits in bees. **Nature**, **491**(7422), 105-108.

GONDIM, C. J. E. (1984). Alguns aspectos da biologia reprodutiva do guaranazeiro (Paullinia cupana var. sorbilis (Mart.) Ducke - Sapindaceae. **Acta Amazonica**, **14**.

GONZALES, J. (2022). **Chemical defoliants sprayed on Amazon rainforest to facilitate deforestation in Brazil.** Retrieved February 14, 2023 from https://news.mongabay.com/2022/01/pesticides-released-into-brazils-amazon-to-degrade-rainforest-and=-facilitate-deforestation/#:~:text-Glyphosate%2C%20carbosulfan%20(prohibited%20on%20aerial,of%20Deforestation%20(the%20Legal%20Amazon

GUARDA, P. M., PONTES, A. M. S., DOMICIANO, R. D. S., GUALBERTO, L. D. S., MENDES, D. B., GUARDA, E. A., & DA SILVA, J. E. C. (2020). Assessment of Ecological Risk and Environmental Behavior of Pesticides in Environmental Compartments of the Formoso River in Tocantins, Brazil. **Archives of Environmental Contamination and Toxicology**, **79**(4), 524-536. https://doi.org/10.1007/s00244-020-00770-7

IBAMA. (2018). **Instrução Normativa Nº 27, De Dezembro de 2018. Ministério do Meio Ambiente Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais e Renováveis.** Retrieved 21 de Janeiro de 2023 from www.ibama.gov.br/component/legislacao/?view=legislacao&force=1&legislacao=138813

IBAMA. (2020). **Consumo de agrotóxicos e afins (2000 - 2019).** Retrieved 14 de Fev. 2023 from http://www.ibama.gov.br/phocadownload/qualidadeambiental/relatorios/2019/grafico_do_historico_de_comercializacao_2000-2019.pdf.

IBGE. (2021). **Produção do guaraná.** INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA. Disponível em: https://www.ibge.gov.br/explica/producao-agropecuaria/guarana/am

IDESAM. (2018). INSTITUTO DE CONSERVAÇÃO E DESENVOLVIMENTO SUSTENTÁVEL DA AMAZÔNIA. A cadeia de valor do guaraná de Maués. **Ana Carolina Bastida da Silva, Eric Marotta Brosler, Laís Bentes de Almeida, Marina Yasbek Reia, Ramon Weinz Morato**, 82 p. il. Color. ISBN:978-85-64371-34-7.

JÚNIOR, J. M. V., VARGAS, L. P., & BET, V. T. (2022). Flexibilização dos agrotóxicos no Brasil: a expansão dos registros e do consumo. **Iniciação Científica Cesumar**, **24**(1), 1-22.

LEITE, M. S. (2007). **Transformação e persistência: antropologia da alimentação e nutrição em uma sociedade indígena amazônica**. Editora Fiocruz.

LERMEN, J., BERNIERI, T., RODRIGUES, I. S., SUYENAGA, E. S., & ARDENGHI, P. G. (2018). Pesticide exposure and health conditions among orange growers in Southern Brazil. **Journal of Environmental Science and Health, Part B**, **53**(4), 215-221.

LIMA, F. A. N. D. S., CORRÊA, M. L. M., & GUGELMIN, S. A. (2022). Territórios indígenas e determinação socioambiental da saúde: discutindo exposições por agrotóxicos. **Saúde em Debate**, **46**, 28-44.

LIMA, M. C. D., & ROCHA, S. D. A. (2012). Efeitos dos agrotóxicos sobre as abelhas silvestres no Brasil. **Brasília**, **IBAMA**(Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis).

LOUTER, A. J. H., VAN BEEKVELT, C. A., CID MONTANES, P., SLOBODNIK, J., VREULS, J. J., & BRINKMAN, U. A. T. (1996). Analysis of microcontaminants in aqueous samples by fully automated on-line solid-phase extraction-gas chromatography-mass selective detection. **Journal of Chromatography A**, **725**(1), 67-83. https://doi.org/https://doi.org/10.1016/0021-9673(95)00979-5

MARIN, F. R., ZANON, A. J., MONZON, J. P., ANDRADE, J. F., SILVA, E. H. F. M., RICHTER, G. L., ANTOLIN, L. A. S., RIBEIRO, B. S. M. R., RIBAS, G. G., BATTISTI, R., HEINEMANN, A. B., & GRASSINI, P. (2022). Protecting the Amazon forest and reducing global warming via agricultural intensification. **Nature Sustainability**, **5**(12), 1018-1026. https://doi.org/10.1038/s41893-022-00968-8

MARQUES, N. R., DE LIMA, I. C. M., LOPES, A. C., DE ALCÂNTARA MENDES, R., FAIAL, K. R. F., MOTA, A. M., & MIRANDA, F. P.-J. (2022). Neurological Evaluation in Quilombolas Individuals Exposed to Organophosphorus Pesticides in the Brazilian Amazon Population. **International Journal of Advanced Engineering Research and Science**, **9**, 7.

MARTINELLI, L. A., COLETTA, L. D., LINS, S. R. M., MARDEGAN, S. F., & DE CASTRO VICTORIA, D. (2016). Brazilian Agriculture and Its Sustainability. In G. Steier & K. K. Patel (Eds.), **International Food Law and Policy** (pp. 767-792). Springer International Publishing. https://doi.org/10.1007/978-3-319-07542-6_32

MARTINELLI, L. A., NAYLOR, R., VITOUSEK, P. M., & MOUTINHO, P. (2010). Agriculture in Brazil: impacts, costs, and opportunities for a sustainable future. **Current Opinion in Environmental Sustainability**, **2**(5), 431-438. https://doi.org/https://doi.org/10.1016/j.cosust.2010.09.008

MENDEZ, A., NG, C. A., TORRES, J. P. M., BASTOS, W., BOGDAL, C., DOS REIS, G. A., & HUNGERBUEHLER, K. (2016). Modeling the dynamics of DDT in a remote tropical floodplain: indications of post-ban use? **Environmental Science and Pollution Research**, **23**(11), 10317-10334. https://doi.org/10.1007/s11356-015-5641-x

MUSSY, M. H., BRUCHA, G., REIS, M. G., USHIMARU, P. I., YAMASHITA, M., & BASTOS, W. R. (2013). Identification of microorganisms resistant to the herbicide 2, 4-dichlorophenoxyacetic acid (2, 4-D) in soils of Rondonia, Brazil. **Interciencia**, **38**(5), 353-357.

NEVES, P., COLABUONO, F., FERREIRA, P., KAWAKAMI, S., TANIGUCHI, S., FIGUEIRA, R., MAHIQUES, M., MONTONE, R., & BÍCEGO, M. (2018). Depositional history of polychlorinated biphenyls (PCBs), organochlorine pesticides (OCPs) and polycyclic aromatic hydrocarbons (PAHs) in an Amazon estuary during the last century. **Science of the Total Environment**, **615**, 1262-1270.

NOBRE, C., ENCALADA, A., ANDERSON, E., & NEVES, E. G. (2021). Science panel for the Amazon: Amazon Assessment Report 2021: executive summary.

OCHOA-CUEVA, P. A., ARTEAGA, J., ARÉVALO, A. P., & KOLOK, A. S. (2022). A potential pesticides exposure index (PPEI) for developing countries: Applied in a transboundary basin. **Integr Environ Assess Manag**, **18**(1), 187-197. https://doi.org/10.1002/ieam.4470

OLIVEIRA, J., DESTRO, A., FREITAS, M., & OLIVEIRA, L. (2020). How do pesticides affect bats?–A brief review of recent publications. **Brazilian Journal of Biology**, **81**, 499-507.

OLIVEIRA, L. K. D., PIGNATI, W., PIGNATTI, M. G., BESERRA, L., & LEÃO, L. H. D. C. (2018). Processo sócio-sanitário-ambiental da poluição por agrotóxicos na bacia dos rios Juruena, Tapajós e Amazonas em Mato Grosso, Brasil. **Saúde e Sociedade**, **27**, 573-587.

PAGE, M. J., MCKENZIE, J. E., BOSSUYT, P. M., BOUTRON, I., HOFFMANN, T. C., MULROW, C. D., SHAMSEER, L., TETZLAFF, J. M., AKL, E. A., BRENNAN, S. E., CHOU, R., GLANVILLE, J., GRIMSHAW, J. M., HRÓBJARTSSON, A., LALU, M. M., LI, T., LODER, E. W., MAYO-WILSON, E., MCDONALD, S., . . . MOHER, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. **International Journal of Surgery**, **88**, 105906. https://doi.org/https://doi.org/10.1016/j.ijsu.2021.105906

PAZ, F. S., PINTO, C. E., DE BRITO, R. M., IMPERATRIZ-FONSECA, V. L., & GIANNINI, T. C. (2021). Edible fruit plant species in the Amazon forest rely mostly on bees and beetles as pollinators. **Journal of economic entomology**, **114**(2), 710-722.

PEREIRA, C. F., DA SILVA, S. C. P., DONEGÁ, M. V. B., FRAXE, T. D. J. P., DA SILVA LOPES, S. K., CASCAES, S. F., AGUIAR, O. D. C. M., JUNIOR, S. V. C., TRINDADE, L. L. L., & PEREIRA, J. V. R. G. (2020). Certificação Orgânica de Cultivos de Guaraná Originários de Sementes Nativas pelas Comunidades Tradicionais do Alto Urupadí, Maués, AM. **Cadernos de Agroecologia**, **15**(4).

PEREIRA, C. F., SALDARRIAGA, G. M., SANTIAGO, J. L., FRAXE, T. D. J. P., & CASTRO, A. P. D. (2018). Organização de controle social da produção agroecológica do guaraná selvagem (Paullinia cupana Khunt.): experiência da Associação dos Agricultores Familiares do Alto Urupadi, no município de Maués–Amazonas. **Cadernos de Agroecologia**, **13**(1).

PEREIRA, J. C. (2005). Cultura do guaranazeiro no Amazonas (4. Edição). **Embrapa Amazônia Ocidental** 40 p. ISSN 1679-8880

PESSOA, M. C. P. Y., FIGUEIREDO, R. D. O., DE QUEIROZ, S. C. N., GOMES, M. A. F., SOARES PEREIRA, A., CARVALHO, E. J. M., FERRACINI, V. L., SOUZA, M. D. D., LIMA, L. M., & CRUZ, F. M. (2010). CMLS94 Trends on Water Risk Contamination by Pesticide at Two Field Crops over Areas of Aquifers at Amazon and Southeast Regions, Brazil.

PIGNATI, W. A., CORRÊA, M., & LEÃO, L. (2021). Desastres sócio-sanitário-ambientais do agronegócio e resistências agroecológicas no Brasil. **São Paulo: Outras Expressões**, **15**, 364.

PÌNHEIRO, C. D. P. D. S., SILVA, L. C., MATLABA, V. J., & GIANNINI, T. C. (2022). Agribusiness and environmental conservation in tropical forests in the eastern Amazon. **Sustainable Production and Consumption**, **33**, 863-874. https://doi.org/https://doi.org/10.1016/j.spc.2022.08.015

POSSAMAI, R., & SERIGATI, F. (2022). A relevância do bioma Amazônia para a produção agrícola. **AgroANALYSIS**, **42**(2), 16-18.

REGINA, A. W. (2021). Como os indígenas percebem a contaminação por agrotóxicos. **Cuiabá: OPAN**, 23. https://amazonianativa.org.br/wp-content/uploads/2022/10/Como-os-indigenas-percebem-a-contaminacao-por-agrotoxicos.pdf

REID, W. V., MOONEY, H. A., CROPPER, A., CAPISTRANO, D., CARPENTER, S. R., CHOPRA, K., DASGUPTA, P., DIETZ, T., DURAIAPPAH, A. K., & HASSAN, R. (2005). **Ecosystems and human well-being-Synthesis: A report of the Millennium Ecosystem Assessment**. Island Press.

REIS, L. S., BOULOUBASSI, I., MENDEZ-MILLAN, M., GUIMARÃES, J. T. F., DE ARAÚJO ROMEIRO, L., SAHOO, P. K., & PESSENDA, L. C. R. (2022). Hydroclimate and vegetation changes in southeastern Amazonia over the past ∼25,000 years. **Quaternary Science Reviews**, **284**, 107466. https://doi.org/https://doi.org/10.1016/j.quascirev.2022.107466

RIBEIRO, H. M., & DE SÁ NETO, C. E. (2019). Meios de extermínio na sociedade de risco: A pulverização de agrotóxicos em terras indígenas brasileiras. **Revista Jurídica Luso-Brasileira (RJLB)**, **5**.

RIBEIRO, M. F. (2020). **Desmatamento zero: modelo sustentável inova a criação de gado na Amazônia.** Retrieved 14 de fev. 2023 from https://brasil.mongabay.com/2020/04/desmatamento--zero-modelo-sustentavel-inova-a-criacao-de-gado-na-amazonia/#:~:text=A%20cria%C3%A7%C3%A3o%20de%20gado%20na%20Amaz%C3%B4nia%2C%20contudo%2C%20est%C3%A1%20quase%20sempre,Quase%20tudo%20ilegal>

RICO, A., DE OLIVEIRA, R., SILVA DE SOUZA NUNES, G., RIZZI, C., VILLA, S., DE CAROLI VIZIOLI, B., MONTAGNER, C. C., & WAICHMAN, A. V. (2022). Ecological risk assessment of pesticides in urban streams of the Brazilian Amazon. **Chemosphere**, **291**, 132821. https://doi.org/https://doi.org/10.1016/j.chemosphere.2021.132821

RICO, A., WAICHMAN, A. V., GEBER-CORRÊA, R., & VAN DEN BRINK, P. J. (2011). Effects of malathion and carbendazim on Amazonian freshwater organisms: comparison of tropical and temperate species sensitivity distributions. **Ecotoxicology**, **20**(4), 625-634. https://doi.org/10.1007/s10646-011-0601-9

RODRIGUES-ALCÂNTARA, C. (2013). **Amazon: Biodiversity Conservation, Economic Development, and Human Impact**. Nova Publishers.

RODRIGUES, A. O., DE SOUZA, L. C., DA SILVA ROCHA, C. C., DA COSTA, A. C. G., & DE ALCÂNTARA MENDES, R. (2017). Assessment of DDT and Metabolites in Soil and Sediment of Potentially Contaminated Areas of Belém, Amazon Region, Brazil. **Bulletin of Environmental Contamination and Toxicology**, **99**(1), 125-130. https://doi.org/10.1007/s00128-017-2090-x

RÖMBKE, J., WAICHMAN, A. V., & GARCIA, M. V. (2008). Risk assessment of pesticides for soils of the Central Amazon, Brazil: comparing outcomes with temperate and tropical data. **Integrated environmental assessment and management**, **4**(1), 94-104.

SÁNCHEZ-BAYO, F., GOULSON, D., PENNACCHIO, F., NAZZI, F., GOKA, K., & DESNEUX, N. (2016). Are bee diseases linked to pesticides?—A brief review. **Environment international**, **89**, 7-11.

SCHIESARI, L., WAICHMAN, A., BROCK, T., ADAMS, C., & GRILLITSCH, B. (2013). Pesticide use and biodiversity conservation in the Amazonian agricultural frontier. **Philosophical Transactions of the Royal Society B: Biological Sciences**, **368**(1619), 20120378.

SHIMANO, Y., & JUEN, L. (2016). How oil palm cultivation is affecting mayfly assemblages in Amazon streams [10.1051/limn/2016004]. **Ann. Limnol. - Int. J. Lim.**, **52**, 35-45. https://doi.org/10.1051/limn/2016004

SILVA, G. S. D., MATOS, L. V. D., FREITAS, J. O. D. S., CAMPOS, D. F. D., & ALMEIDA E VAL, V. M. F. D. (2019). Gene expression, genotoxicity, and physiological responses in an Amazonian fish, Colossoma macropomum (CUVIER 1818), exposed to Roundup® and subsequent acute hypoxia. **Comparative biochemistry and physiology. Toxicology & pharmacology : CBP**, **222**, 49-58. https://doi.org/10.1016/j.cbpc.2019.04.010

SIVITER, H., KORICHEVA, J., BROWN, M. J., & LEADBEATER, E. (2018). Quantifying the impact of pesticides on learning and memory in bees. **Journal of Applied Ecology**, **55**(6), 2812-2821.

SPLETOZER, A. G., SANTOS, C. R. D., SANCHES, L. A., & GARLET, J. (2021). Plantas com potencial inseticida: enfoque em espécies amazônicas. **Ciência Florestal**, **31**.

TRINDADE, L. L. L., CASCAES, S. F., PINHEIRO, N. R., PEREIRA, J. V. R. G., DA SILVA LOPES, S. K., & DONEGÁ, M. V. B. (2021). Extensão universitária e certificação orgânica: o caso das comunidades tradicionais no alto rio Urupadí, Maués-AM University extension and organic certification: the case of traditional communities in the Urupadí upper river, Maués-AM. **Brazilian Journal of Development**, **7**(12), 115030-115054.

VAL, A. L., DUARTE, R. M., CAMPOS, D., & DE ALMEIDA-VAL, V. M. F. (2022). Environmental stressors in Amazonian riverine systems.

VASCO, C., TORRES, B., JÁCOME, E., TORRES, A., ECHE, D., & VELASCO, C. (2021). Use of chemical fertilizers and pesticides in frontier areas: A case study in the Northern Ecuadorian Amazon. **Land Use Policy**, **107**, 105490. https://doi.org/https://doi.org/10.1016/j.landusepol.2021.105490

VIANA, J. L. M., DINIZ, M. D. S., SANTOS, S. R. V. D., VERBINNEN, R. T., ALMEIDA, M. A. P., & FRANCO, T. C. R. D. S. (2020). Antifouling biocides as a continuous threat to the aquatic environment: Sources, temporal trends and ecological risk assessment in an impacted region of Brazil. **Science of the Total Environment**, **730**, 139026. https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.139026

VIANA, J. L. M., DOS SANTOS, S. R. V., DOS SANTOS FRANCO, T. C. R., & ALMEIDA, M. A. P. (2019). Occurrence and partitioning of antifouling booster biocides in sediments and porewaters from Brazilian Northeast. **Environmental Pollution**, **255**, 112988. https://doi.org/https://doi.org/10.1016/j.envpol.2019.112988

WAICHMAN, A. V. (2012). A problemática do uso de agrotóxicos no Brasil: a necessidade de construção de uma visão compartilhada por todos os atores sociais. **Revista Brasileira de Saúde Ocupacional**, **37**, 42-47.

WAICHMAN, A. V., EVE, E., & DA SILVA NINA, N. C. (2007). Do farmers understand the information displayed on pesticide product labels? A key question to reduce pesticides exposure and risk of poisoning in the Brazilian Amazon. **Crop Protection**, **26**(4), 576-583.

WINEMILLER, K. O., AGOSTINHO, A. A., & CARAMASCHI, É. P. (2008). 5 - Fish Ecology in Tropical Streams. In D. Dudgeon (Ed.), **Tropical Stream Ecology** (pp. 107-III). Academic Press. https://doi.org/https://doi.org/10.1016/B978-012088449-0.50007-8

WINTERMANTEL, D., PEREIRA-PEIXOTO, M.-H., WARTH, N., MELCHER, K., FALLER, M., FEURER, J., ALLAN, M. J., DEAN, R., TAMBURINI, G., KNAUER, A. C., SCHWARZ, J. M., ALBRECHT, M., & KLEIN, A.-M. (2022). Flowering resources modulate the sensitivity of bumblebees to a common fungicide. **Science of the Total Environment**, **829**, 154450. https://doi.org/https://doi.org/10.1016/j.scitotenv.2022.154450

ZHAO, H., LI, G., CUI, X., WANG, H., LIU, Z., YANG, Y., & XU, B. (2022). Review on effects of some insecticides on honey bee health. **Pesticide Biochemistry and Physiology**, 105219.

About the authors

Ana Claudia Batista is a Forest Engineer who graduated from the State University of Pará (UEPA), with a Master's degree in Science (Wood Technology) from the Luiz de Queiroz College of Agriculture (ESALQ/USP). Currently, she is a Ph.D. candidate at the Nuclear Energy Center in Agriculture (CENA/USP). https://orcid.org/0000-0001-8226-7996

Fátima Aparecida Arcanjo is a Biologist, who graduated from the State University of Londrina (UEL), with a Master's and PhD in Biological Sciences with an emphasis on Biodiversity and Conservation in Fragmented Habitats/UEL. Currently, she is conducting postdoctoral research at the State University of Londrina. https://orcid.org/0000-0002-9107-6339

Isabela Maria Souza Silva is a Forest Engineer who graduated from the State University of Amazonas (UEA), holding a master's degree from the National Institute of Amazonian Research (INPA). Currently, she is a doctoral student at the Center for Nuclear Energy in Agriculture of the University of São Paulo (CENA/USP). https://orcid.org/0000-0001-7311-359X

Maria Gabriella da Silva Araújo holds a Bachelor's degree in environmental engineering from the Federal Rural University of the Amazon (UFRA), a master's degree in Sciences with a concentration in Applied Ecology from the University of São Paulo (USP), and is currently a doctoral student in the Interunit Applied Ecology program (ESALQ-CENA/USP). https://orcid.org/0000-0003-1366-9929

Mario Rique Fernandes holds a degree in Ecology, a Master's degree in Sustainable Development, and a PhD in Social Anthropology. He is a member of the Nucleus for Studies on the Indigenous Amazon (NEAI/UFAM) and a consultant to the Scientific Committee of the Amazon Cooperation Treaty Organization (ACTO). https://orcid.org/0000-0002-1891-2943

Pablo Ochoa Cueva is an Environmental Management Engineer from the Private Technical University of Loja - UTPL. He has a doctorate in Agricultural Sciences and Technologies, Natural Resources, and Rural Development from the Universities of Córdoba and Málaga. He is currently a tenured professor at UTPL in face-to-face and distance modalities. https://orcid.org/0000-0003-2230-1026.

Ulysses Madureira Maia is a Biologist who graduated from the Universidade do Estado do Rio Grande do Norte (UERN). He holds a master's degree in Animal Science from the Universidade Federal Rural do Semi Árido (UFERSA) and a PhD in Zoology from the Universidade Federal do Pará (UFPA). https://orcid.org/0000-0003-0940-9331