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**Nutritional, ecological and economical importance of Amazon fish: old
challenges and new perspectives**

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1. Abstract

Amazon has the largest freshwater biodiversity in the world. Its aquatic biota, especially fish, have been serving as the main source of protein for the indigenous populations since before colonial times, expanding it to the riverine population as the area grew. Fish are known for being a valuable source of nutrients, they have protein of high biological value, rich in unsaturated fatty acids, aiding in the prevention and low incidence of cardiovascular, neurological and autoimmune diseases, and a great source of mineral salt, like iron, sodium, copper, zinc and magnesium, helping prevent chronic diseases. In the Amazonian ecosystem, aside from being a nutrition source, providing food security and nutritional quality to vulnerable populations, it also plays an important role in the local economy, steadily increasing to a national and international level, providing a valuable source of income to artisanal small-scale fishers, who have limited access to other options. However, diverse anthropogenic actions have been threatening the balance established by these populations, from implementation of large-scale projects that promotes habitat disruption and population displacement, contamination of heavy metals and pesticides by industries and expansion of agricultural activities, with mercury contamination from gold mining at a focus as its health effects are already seen in some communities, to climate change effects worsening due to deforestation and longer drought periods and overfishing issues. The health of Amazonian fish and, consequently, of the populations that depend on its consumption face different risks from different sources, challenging the long-term sustainability of this unique ecosystem. Urgent actions, with input and contribution from local communities, are needed to preserve Amazonian aquatic biota, its habitats and subsequently, the livelihoods of its traditional populations. This study review characterized the importance, as well as the invisibility, of Amazonian fish and local populations and the risks to its preservation and conservation.

2. Aim of thesis

Despite the ecological and commercial importance of Amazonian fish, the recurring and increasing threats to the numbers and to the health of the Amazonian aquatic biota poses a serious risk to thousands of people that depend on this ecosystem as a form of food security, nutritional quality and source of income. Therefore, this review thesis aimed at characterizing the significance of Amazonian fish to local riverine populations, contamination and hygiene issues that challenge fish health, and consequently, human health, anthropogenic activities that promote depletion of resources, and lastly, future perspectives.

3. Introduction

The Amazon is the largest rainforest on Earth, it covers about 40% of South America, stretching across eight countries: Bolivia, Peru, Ecuador, Colombia, Venezuela, Guyana, Suriname and Brazil, with the latter containing more than half of the rainforest, which covers nine states of the country, including its biggest state that is named after the rainforest, the Amazonas, and consequently, Brazil also has more than half of the Amazon River basin, with around four million square meters of the second largest river in the world within its borders. The Amazon River basin discharge is the largest in the conworld, at around 215 thousand cubic meters per second, representing one-fifth of the entire freshwater volume on the surface of the planet, and at Manaus, the largest city on the river, there is an unique phenomenon called 'Meeting of Waters', the confluence of Solimões river and Rio Negro, in which both rivers flow for 30km before fully mixing (Fig 1.), due to great difference in speed, temperature and quantity of sediments dissolved in the water between the two rivers, and to match its vast size and uniqueness, it has an equally great, endemic fauna and flora, being the richest ecosystem on earth (Dagosto & Pinna, 2019).

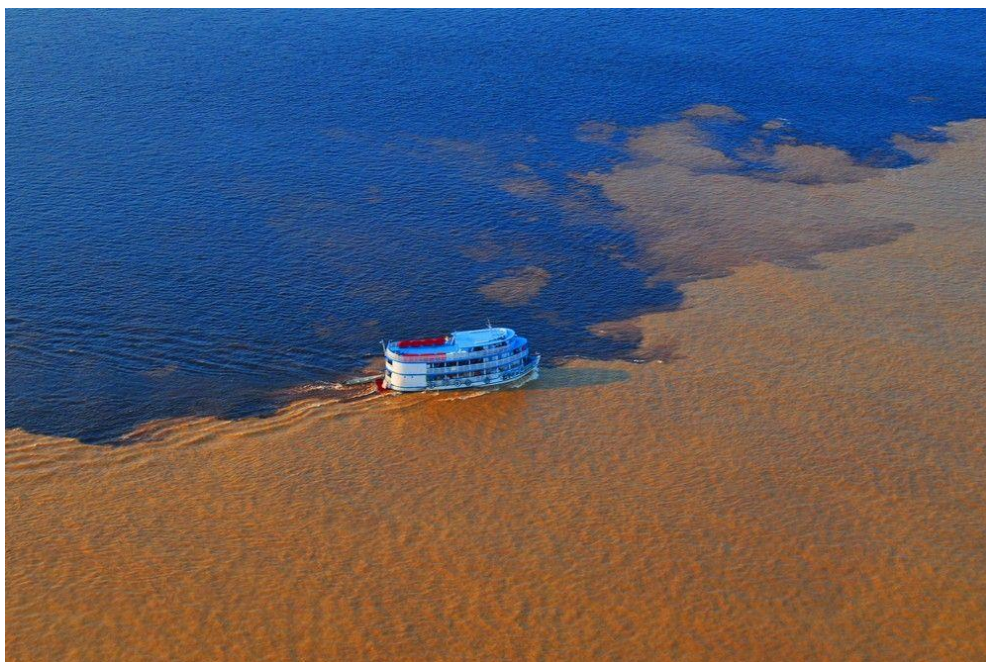


*Figure 1. Meeting of the Waters, confluence between Solimões river and Rio Negro.
Source: Portal Amazônia*

Historically, the rivers had a fundamental role in the occupation and colonization of the Amazon as the path by which started the exploration, seen in the concentration of population along the margins, however, aside from still being the main pathway for the majority of the local population, the rivers also provide the main protein source for the inhabitants of the region, fish (Santos et al., 2009). Within its great biodiversity, fish are among the faunal elements whose number of species is up to two thousand, with about 1696 being endemic ones, with such diversity maintaining the cultural, ecological, nutritional and economic aspects of many Amazonian livelihoods, with subsistence fishing practiced by the riverine and indigenous populations, one of their main food sources, however, despite its significant importance, there is still a lack of a summarized and synthesized framework about the true extent of this diversity and its geographical distribution (Dagosto & Pinna, 2019). The lack of this knowledge contributes to the difficulties of maintaining sustainable aquaculture and fishery management.

Aquatic systems across the world have been increasingly gaining recognition and importance as they offer clear solutions, with overall low environmental impact, to improve food security and nutrition, reduce poverty and enhance socioeconomic development, especially for riverine and coastal communities. In 2022, the total aquaculture and fishery production reached 223.2 million tons, a record, being

projected to expand by another 15% by 2030 to be able to meet the increasing demand, showcasing the rising significance of fishing and fish farming in both national and global scenarios (FAO, 2022). In 2023, Brazil produced 887 thousand tons of farmed fish, an increase of 3,1% of the previous year and the highest production to date, with tilapia representing more than half, this increase in supply is related to rise in national demand, with an average of 4,35kg of fish per year per person (Associação Brasileira da Piscicultura, 2024). While the national average is still far from the annual per capita consumption of, at least, 12kg, recommended by World Health Organization (WHO, 2003), for the Amazonian population, this number surpasses national and even international levels with countries like Iceland and Maldives, which have the highest consumption, consuming around 80kg of aquatic food per capita per year (FAO, 2022), while in the Amazonian region, particularly in the rural area, as fish represent a major part of their diet and in many cases, the main source of protein, the consumption is at an average of 95kg per capita per year (Mikkola, 2024).

Following its colonization and occupation, the main population in the Brazilian Amazon is consistent of indigenous people, with still few uncontacted and isolated groups, and descendants of indigenous groups and Portuguese colonizers called 'caboclos', with many living by the main river channels or by lakes in the interior of floodplains, thus, could also be referred to as 'ribeirinhos', being in charge of a great part of inland small-scale fishing (Begossi et al., 2019). Local organization varies from village to village and if the community is inside a protected area and the presence of religious or grassroots groups, both movements contributing to the development of social capital and promotion of organization, as well as the fight towards local rights and conservation, consequently, facilitating the implementation of official management for fisheries, establishing techniques, like lake rotation (Lopes et al., 2019). The establishment of such methods showcase just how their livelihoods and well-being are closely related to the fisheries systems and local biodiversity, with a dependency on the water cycle of the Amazonian ecosystem, providing, more than just a source of income, food security and nutritional quality (Doria et al., 2018; Begossi et al., 2019). As fish consumption is recognized as beneficial for human health, having significant nutritional quality, especially when compared to other foods from different animal sources, they are rich in liposoluble vitamins A and D, calcium, phosphorus, iron and other minerals, as well as having high quantities of long-chain polyunsaturated fatty acids, being

associated with reduced risk of cardiovascular disease and optimization of the nervous system development of children and teenagers (Lobato & Rosa, 2020).

Many factors affect the management of Amazon fisheries, they also suffer from a general lack of proper funding, infrastructure and specialized personnel, challenging the usual management measures commonly applied in fisheries from other tropical regions, not to mention that most of the knowledge about these fisheries come from localized studies that are limited in both space and time, making it so this problem is able to be tackled only by governmental cooperation with local communities (Lopes et al., 2019). In addition to the management problem, different types of challenges impact aquaculture and fishery production, these can include technological development, market demand, consumer preferences, availability of resources, climate change and a handful of environmental issues. Many of those pose an even bigger threat to their long-term sustainability when combined with lack of management capabilities. Due to the Amazon's abundance in a variety of resources, large infrastructural development projects have been continuously aggravating the situation. Among them, there are hydroelectric dams, which have recognized impacts on not only riverine geomorphology and flow regime but also in the migration patterns and habitat of fish, expansion on the agricultural industry, through pollution of soil and stream with pesticides and by illegal deforestation and land grabbing, mining activities that contribute to further pollution of streams and subsequently, the aquatic biota, with mercury contamination, constructions of roads, piers and hydro ways that are accompany the construction of these projects, and lastly, oil exploration at the mouth of the Amazon river that is being pushed for approval by the current Brazilian president (Doria et al., 2017; Lopes et al., 2019).

Besides the implementation of large-scale projects, Amazonian freshwater fisheries already have a historic of overexploitation, with *Arapaima gigas*, popularly called pirarucu (Fig. 2), one of the first Amazonian fish species to show indications of overfishing back in the 1980s, due to being considered the largest freshwater scaled fish reaching between two to three meters of length and weighing between 100 to 200 kilograms and is relatively easy to find as it is a obligate air breathing species (Lopes et al., 2019). Ever since then, a community-based collaborative program was created to hinder overexploitation and promote recovery of the population, where local fishers restricted access of lakes near their communities to large commercial fishing boats, a

program recognized as a fishery management tool by government agencies in 1993, that together with NGOs and local communities, determined lakes used by commercial fishing boats and locally protected and subsistence lakes, where they safeguard pirarucu populations 30-times larger than other unprotected lakes of same size (Campos-Silva et al., 2017). Moreover, in February of this year, the Brazilian Institute of Environment and Renewable Natural Resources, referred to as IBAMA in Brazilian Portuguese, established a program exclusively for the sustainable management of pirarucu, aiming to strengthen and improve the already existing method and institutionalize the tracking system for better monitoring and control (IBAMA, 2025). Although, as of now, pirarucu has legally implemented strategies to ensure its preservation, it is not the only species to suffer from overfishing, other examples include *Brachyplatystoma rousseauxii* (dourada) and *Colossoma macropomum* (tambaqui), the latter having a great economic significance as one of the most commercialized species.



Figure 2. *Arapaima gigas* (pirarucu). Source: Portal Amazônia.

Furthermore, considering the variety of factors, directly or indirectly, impacting fishing resources, it is essential to bring light to the health risks that come along, both for the fish and those who consume it. Due to the expansion of agricultural activities and the growth in urban centers that come along with it, Amazonian River streams have increasingly been suffering from pesticide pollution and degradation of water quality. It has been shown, through various studies, the health impacts different pesticides have on fish's health, including gills and liver impairment, inhibition of brain cholinergic activity, histopathological and DNA damages and increase in the expression of *tp53* (Souza et al., 2023; Braz-Mota et al., 2015; Mela et al., 2013; Santos et al., 2012), thus,

promoting human contamination through ingestion of contaminated fish, leading to acute and chronic intoxication. Likewise, because of improper waste management from mining areas and effluents from industries, contamination by heavy metals, especially mercury used in gold mining, has been steadily rising, and differently from pesticides, heavy metals affect the whole trophic chain through bioaccumulation and biomagnification, producing oxidative stress, neurotoxic effects, histopathological lesions, metabolic and ionoregulatory disturbances (Crémazy et al., 2016; Braz-Mota et al., 2018; Monteiro et al., 2009), posing a serious risk for human consumption.

Contamination of heavy metals in fish expose humans to the risk of acute and chronic intoxication, with serious health consequences. Human exposure to different metallic xenobiotics have been associated with issues in the respiratory system, through development of bronchial asthma, fibrosis and in more severe cases, lung cancer, in the reproductive system through reduction in sperm count, reduced fertility, spontaneous abortions and stillbirths, in the liver by malfunctioning of the kidney, cirrhosis and non-alcoholic fatty liver disease, it also impairs proper development of the nervous system in children, causing cognitive motor disturbances as well as endocrine disruptions, and at a molecular level, causes oxidative stress in different enzymes, leading to damage in cell membrane, cell function and in the DNA (Souza-Arroyo et al., 2022; Pokhrel et al., 2022, Collin et al., 2022; Abdul et al., 215, Charkiewicz et al., 2025).

4. Methodology

The study, with a qualitative and quantitative approach, used bibliographic and documental research retrieved from online databases and platforms of scientific and statistical content as a method of research. Articles without date limitation, available in PubMed, Web of Science, Science Direct and Google Scholar databases, which reported on Amazonian fish, their nutritional value, hygiene problems, heavy metal and pesticide contamination, human health risks through fish consumption, cold chain management of small-scale fisheries and environmental problems that threaten fish biodiversity, through a series of combinations of various search terms, key words included 'Amazonian fish', 'mercury', 'fatty acid content', 'pesticide contamination', 'heavy metal contamination', 'health effects on fish', 'human health risks', 'hygiene' and

'exposure through fish consumption'. Additional articles were further identified by hand-searching references lists of included papers.

5. Economy, ecology and importance of Amazon fish

5.1. Ecological and Economical Importance

Brazil is the second largest aquaculture producer in the Latin America regions, with a production of more than 600 thousand tons in 2019 and 80% of the total being from freshwater aquaculture, with the majority coming from artisanal fisheries, and most of the production supplied by the Amazon basin (FAO, 2020). Amazonian rivers are seasonal ecosystems with productivity increasing during the periodic floodings, which connect the main river to the floodplains, home to many fish species, such as the endangered *Arapaima gigas* (Pirarucu) one of the most commercially common species (Capitani et al., 2021). The floodplain lakes are essential to the productivity of fisheries as they are the refuge, nursing, breeding and feeding grounds to fish populations, being positively related to fish biomass and the main contributor to sustain commercial and artisanal fisheries within the Amazon Basin (Barros et al., 2020). Within the basin, there are 2716 species, a difference of 53,97% from the Congo basin, the second in species number, housing the most diverse regional collection of freshwater fishes in the world (Dagosta & De Pinna, 2019). Together with Amazonian large territory, this diversity helps to maintain economic, cultural and ecological characteristics of Amazonian livelihoods, with local riverine and indigenous populations depending on subsistence fishing (Begossi et al., 2019).

Overall, most of the total fish landings, around 60%, come from artisanal fisheries, representing more than 90% of employment in the capture sector, though the quantity is even higher if only the inland fisheries are considered (FAO, 2020). Despite its importance in the local Amazon basin economy, with estimations of around 3.5 million people involved directly or indirectly, fisheries still only represent 0.5% of Brazil's Gross Domestic Product (GDP) (Mikkola, 2024). Small-scale fisheries (SSFs) are most common in the Amazon, it ensures income for local vulnerable populations, playing a pivotal role in their livelihoods, representing a crucial source of employment, animal protein and culture for both coastal and riverine communities (Jimenez et al., 2019). However, with the technological advances and growth of the population, there has been an increasing interest in fish and fishery products, increasing commercial fishing,

as from the economical point of view, the profits are almost immediate in natural productions, and from the nutritional point of view, it is an important protein source, rich in omega-3 fatty acids (Costa et al., 2020; Cunha et al., 2017).

Aside from fishing for food, ornamental fishing has been steadily presenting itself as a source of income for fisheries. In the Manaus area alone, the capital of the biggest Brazilian state, there are sixteen ornamental fish companies, with catching happening mainly in the middle of Rio Negro, responsible for about 90% of the exports, generating jobs and promoting the economy of nearby municipalities and while the Brazilian Amazonian market pales in comparison with Peru and Colombia, which have less restriction and less bureaucratic systems, it is responsible for the livelihood of a number of fishing communities (Mikkola, 2024). However, the biggest growth in the fishing sector in recent years has been commercial fishing. Technological development, increased population in the basin and its subsequent concentration in urban centers, caused the process of expansion and intensification, changing the profile of commercial fishers, which, in the past, for many used to be a seasonal activity with capture of a limited number of species, now it is practiced all year round with a focus in supplying the urban consumers and exportation to other regions of Brazil (Almeida et al., 2001).

Differently from the fishers in riverine and indigenous communities, whose fishing is mostly turned to their families and local markets, the commercial fisher supplies high-volume markets and have enough resources to capture fish species that have a lower catch per cost benefit (Junk et al., 2007). Commercial fishing has two strategies, one with small boats and another that uses larger ones. Small boats are aimed at supplying local urban markets and have a capacity of storage for less than four tons, with their fishing occurring in floodplain lakes and catching a large variety of fish species and while they have a lower ratio of kg/fisher/day, they represent most of the commercial fleet and have greater economic returns. As for larger boats, they focus on a few species of migratory catfish to provide processing plants, which have a lower price per kilogram but are more abundant and carry out their fishing in the river channels (Almeida et al., 2010). However, while great effort has been made to report and manage commercial fisheries, they only represent a small portion of total fish catch on the Amazon, as small-scale fishers are still responsible for most of the regional catch despite their small capacity.

Although SSFs are predominant, with most of the fish caught being for direct human consumption with lower costs and little discards when compared to large-scale commercial fisheries, they remain mostly underreported and unstudied, with the fish being sold through an informal network of intermediaries, supplying regional and national markets (Begossi et al., 2019). Despite being the main mean of subsistence, monitoring the activity within the basin is difficult, the fisheries are complex and there are severe deficiencies in the political-administrative sector, being ignored by the political and social organization in charge of executing the socioeconomic planning of the region, with a lack of data regarding historical series of catches and fishing efforts, along with diverse aspects causing pressure on the fish assemblage, with negative influence on fish diversity and yield (Pereira et al., 2023). Besides the lack of information regarding the cold chain of SSFs, very little is known about the biology, ecology and exploitation of the fishes, which are the only source of protein for many communities, challenging the evaluation of the true extent of sustainability and resilience of these fisheries (Silvano & Hallwass, 2020).

5.2. Nutritional Value

Despite the challenges to its sustainability, fish from aquaculture and fisheries in the Amazon still provide a valuable source of nutrient for humans. The World Health Organization classifies a healthy diet as a diet that aids in protecting against all forms of malnutrition as well as noncommunicable diseases (NCDs), which include diabetes, heart diseases, stroke and cancer (WHO, 2020). It also suggests that, while the exact composition of a diversified and balanced healthy diet will vary according to individual characteristics and cultural context, the basic principles should stay the same, including the preference for unsaturated fats over saturated ones (WHO, 2020). Additionally, with lipids being responsible for various biological functions and having a significant role in cell membrane formation, lipid-based nutrient supplementation (LPS) has been used as a strategy to prevent and reduce micronutrient deficiency in children in vulnerable places, with aquaculture being a potential source for the LPS (Correia et al., 2024).

However, despite the immense richness of amazonian fishes, estimated to be between 1.500 and 3.000 species, only a small fraction is commercially explored, with a preference for consumption of only about 100 species, of which 90% are concentrated

on about a dozen species, with special mentions to the tambaqui, jaraqui, matrinxã, curitamã, pacu and tucunaré (Santos et al., 2009). The local population overall avoids eating non-scales fish, such as *Pseudoplatystoma fasciatum* (surubim) and *Pimelodus* spp. (mandi), during illness, menstruation, puerperium and in case of injuries or wounds to the body, due to deeply ingrained food taboos, considering them as greasy and 'reimoso', a term to describe food considered unsafe for people going through physical limitations, with the habit of recommending herbivorous fish or invertebrate eaters, such as pacu or tucunaré, when someone is ill (Correia et al., 2020; Begossi et al., 2004). With fish meat having low saturated fats and being a great source of essential fatty acid, such as the docosahexaenoic acid (DHA, 22:6), eicosapentaenoic acid (EPA, 20:5), both omega-3 fatty acids, and arachidonic acid (AA, 20:4), an omega-6 fatty acid, they have been correlated to the prevention and low incidence of many diseases, including cardiovascular, neurological and autoimmune ones (Correia et al., 2020; Oliveira et al., 2024). As seen in Table 1, a summary gathered from different references, the fatty acids profile also varies between muscles and liver, as liver contains a high lipid content being a great source of oil, coincidentally, following popular belief, *B. vaillantii*, commonly piramutuba, a non-scale fish has the highest percentage of saturated fats, well known for increasing low-density protein (LDL) cholesterol, a strong risk factor for cardiovascular diseases (Briggs et al., 2017).

		Saturated fats (%)	Monounsaturated (%)	Polyunsaturated (%)	Source
Muscle of		43.87±0.4	30.71±0.38	15.21±0.79	Amaral <i>et al.</i> 2024
<i>Brachyplatystoma</i> <i>vaillantii</i> (Piramatuba, non- scale)					
Muscle of		17.33±0.88	16.67±0.74	23.13±2.49	Amaral <i>et al.</i> 2024
<i>Macrodon</i> <i>ancylodon</i> (Pescada-gó, scaled)					
Muscle of		36.10±0.55	41.22±0.49	15.08±0.62	Amaral <i>et al.</i> 2024
<i>Prochilodus</i> <i>nigricans</i> (Curimatã, scaled)					
Liver of <i>B. vaillantii</i>		43.25 ± 0.61	18.6 ± 0.3	20.26±1.62	Amaral <i>et al.</i> 2024
Liver of <i>M. ancylodon</i>		34.16±1.77	37.32±0.88	23.89±1.53	Amaral <i>et al.</i> 2024
Liver of <i>P. nigricans</i>		38.46±0.68	40.67±1.7	16.25±0.78	Amaral <i>et al.</i> 2024
Roes of		43.76	5.63	49.69	Oliveira <i>et al.</i> 2024
<i>Colossoma</i> <i>macropomum</i> (Tambaqui, scaled)					
<i>Brycon cephalus</i> (Matrinxã, scaled)		17.01±1.39	24.29±0.69	58.70±1.41	Rodrigues <i>et al.</i> 2017
<i>Prochilodus lineatus</i>		23.99±0.56	22.45±1.51	53.56±1.17	Rodrigues <i>et al.</i> 2017

(Curimatá,
scaled)

<i>Leporinus friderici</i> (Piau, scaled)	21±0.62	28.09±0.97	50.91±0.73	Rodrigues <i>et al.</i> 2017
<i>Cichla ocellaris</i> (Tucunaré, scaled)	17.45±0.83	26.11±0.75	56.44±1.15	Rodrigues <i>et al.</i> 2017
<i>Pseudoplatystoma</i> <i>corruscans</i> (Pintado, non- scale)	24.80±0.39	22.97±0.90	52.23±0.64	Rodrigues <i>et al.</i> 2017

Table 1. Total fatty acid content (%) of 9 different fish species

In contrast, *P. nigricans* (curimatã) muscle and the liver of *M. ancylodon* (pescada-gó) have the highest content of monounsaturated and polyunsaturated fats, being regarded as good nutritional sources. Higher quantities of fatty acids were found in the livers compared to the muscle, as it is an organ with high lipid content, being a great source of oil, despite not being consumed (Amaral et al., 2024). Roes of *C. macropomum*, a co-product of fish processing from the most cultivated native fish in Rondônia state, also presented high content of polyunsaturated fatty acids (Oliveira et al., 2024). Among the species studied by Rodrigues *et al.* (2017), *B. cephalus* and *C. ocellaris* presented the highest PUFA content, with a superior nutritional quality index when compared to other ones. Regardless, all the evaluated species present good PUFAs quantities and nutritional quality indices well within the recommended standard, indicating that consumption would positively contribute to human health.

Their fatty acids composition is not consistent, it relates to life cycle, diet, temperature and seasonality of flooding periods (Petenuci et al., 2016). Throughout the year, river waters levels fluctuate significantly, creating transient habitats available to the aquatic fauna during the flood periods that disappear during the drought ones (Petenuci et al., 2021). Saturated fatty acids tend to be lower in flood periods than in drought ones, as it is mainly used as source or storage of energy because of its high caloric content (Souza et al., 2020). With the diet of the fishes themselves differing from living plants, planktons and debris to non-fish animals, blood, other fish or both animals and plants, with the feeding characteristics also changing as it depends on the seasonal dynamics

of the Amazon River, the chemical composition of the Amazonian fishes can differ (Correia et al., 2020).

Inhamus *et al.* (2009) found increased levels of PUFAs in *Cichla* sp., a piscivorous species, during floodings, a period when there is higher energy intake, seen by the lower total lipid content. In Petenuci *et al.* studies (2016), the five fish species analyzed had 8.6% lower, on average, SFA content in flood periods than in drought ones, with *Brachyplatystoma flavicans* (dourada) and *B. filamentosum* (piraíba), both are no-scale fish, presenting the highest values in both periods, likely, due to their diet as both are piscivorous fish and tend to need more energy to search for food and while PUFA content also increased during floodings, in contrast, it was a frugivorous species, *C. macropomum*, who presented the highest PUFA content. These results coincide with Souza *et al.* (2020) research, in which during flood periods, the SFA content had a decrease in 5.8%, with higher values in predatory fish, and increased values of PUFA in five species, with the highest being in *Hypophthalmus edentatus*, an omnivorous species. The species in both studies are ones who have an advantage in feeding during floods, due to the abundance of food, they spend less energy, when compared to carnivorous or piscivorous species, which need to swim great distances to find food, with the situation reversing in dry periods.

Changes in lipid composition were highly related to the quality of fish feeding habits, in accordance with the capacity of their biosynthetic tissue to attend to the fish individual needs. (Correia et al, 2020). Almeida *et al.* (2009) reported lowers EPA and DHA levels in farmed matrinxã and captured matrinxã in the wet season than those captured in dry season, period in which they feed mostly on insects, smaller fish, mollusks and crustaceans, rich sources of PUFA. For *B. microlepis* and *B. orbignyanus* captured from the wild, arachidonic acid (AA), EPA and DHA levels were higher than those cultured in fish farms (Moreira et al., 2001). In Correia *et al.* (2020) findings, linoleic acid, precursor for AA, and linolenic acid, precursor for DHA and EPA, were present in the muscle tissue of the nine species studied, particularly in carnivorous and piscivorous fish in dry seasons.

In addition to their fatty acid profile, they are also an essential source of nutrients due to the presence of proteins of high biological value and mineral salts, such as iron, sodium, copper, zinc and magnesium, helping prevent chronic diseases (Amaral et al.,

2024). Martin *et al.* (2017) reported that potassium, recommended to reduce blood pressure, was the most present mineral in all pirarucu muscle zones, with the ventral zone having 25% more mineral content when compared to other muscle zones. In contrast, Amaral *et al.* (2024) research showed sodium with the highest content in piramutaba, pescada-gó and curimatã, especially in flood seasons, however, levels of zinc surpassed the recommended daily intake set by the National Sanitary Surveillance (Brazil, 2005), which is 7mg/day, but not the one set by WHO of 14mg/day.

As for proteins, they have innumerable biological functions and metabolic processes essential for human life, composed of chains of amino acids, which are not all synthesized by the body, therefore, it must be supplied through food (Dias et al, 2019). Barai *et al.* (2022) reported, in the centesimal composition, around 22% for *A. ocellatus* and 19% in *P. castelnaeana*, both in dry season, and 18% for *L. friderici* in flood season, while in Silva *et al.* (2020) studies, residues of tambatinga, a hybrid of *C. macropomum* and *Piaractus brachypomus*, had around 39% of protein. Similar results were shown by Dias *et al.* (2019), with *Plagioscion squamosissimus* (corvina) protein content being 15.99g/100g, and by Cavenaghi-Altemio *et al.*, 2024, with the Amazon hybrid sorubim having a content of almost 19% of protein. Pirarucu presented all the essential amino acids, except tryptophan, having the highest quantity of lysine, an amino acid frequently used as reference in the synthesis of muscle proteins and the starter in the digestive process (Martin et al., 2017). The same was true for pescada-gó; for curimatã, it was histidine, precursor of histamine, and for piramutaba, it was phenylalanine, necessary in the biosynthesis of proteins (Amaral et al., 2024). Considering the variation among species, fish possess good protein content, along with a digestibility of 95%, comparable to other sources of animal origin, and a high biological value both in quantitative and qualitative terms (Sartori & Amancio, 2012).

6. Safety issues and challenges of Amazonian fish

6.1. Fish Health Risks

High deforestation rates, population growth and disorderly urbanization have put Amazon through intense anthropic pressures. Recent law projects have increased the threats to the Amazonian aquatic fauna and flora by reducing the restrictions on environmental licenses for new infrastructure projects (PL #3729/2004), weakening existing regulations in the use and sale of pesticides (PL #6299/2002), including ones

prohibited in European Union, and other bills that propose implementation of mining activities and exploitation of water resources in indigenous and protected areas (Abessa et al., 2019; Braz-Mota et al., 2024). These factors exponentially increase the exposure of Amazonian fish to direct and indirect threats to its growth and survival, including exposure to toxic xenobiotics that damage their respiratory functions by reduction of oxygen uptake and an increase in oxygen demand to maintain vital cellular processes (Braz-Mota et al., 2015).

Pesticides

In fish farming ponds, it has been common the use of pesticides to control aquatic weeds, with many compounds being highly soluble, meaning ease in absorption and increase in contamination on non-target species, such as fish, amphibians, turtles and invertebrates (Braz-Mota et al., 2024). In streams around urban and peri-urban areas, it is possible to identify 11 compounds including fungicides, insecticides and herbicides, with eight of them (carbofuran, imidacloprid, chlorpyrifos, chlorpyrifos-methyl, fipronil, diuron, metolachlor, ametrine, atrazine, simazine, hexazinone, tebuthiuron and carbendazim) being currently banned in Europe as they are environmental and/or human health hazards (Rico et al., 2022). Agricultural activities in the Legal Amazon region have grown significantly in the past decades, becoming one of the leading agricultural frontiers in the country, especially for soy production, and with it, pesticide use. In 2023, 755.489 tons of pesticides were sold in Brazil, with 217.435 (almost 30%) being sold in the nine states that comprise the Brazilian Amazon region, with an increase in the purchase of class I and class II products, categorized as extremely dangerous and highly dangerous to the environment, respectively (IBAMA, 2023). Additionally, there is a lack of education and adequate training of small farmers, giving rise to the disorderly and incorrect use of pesticides, with higher than recommended doses, not enough interval between applications and packages discarded inappropriately (Rico et al., 2022). These facts, along with the high rainfall rates in the region, contribute to the dispersion of these xenobiotics into freshwater ecosystems.

Some pesticides, such as glyphosate, malathion and deltamethrin are known to cause imbalances in biotransformation mechanisms and increase activation of antioxidant enzymes in fish, leading to a higher production of reactive oxygen species (ROS) and promoting lipid and protein oxidation (Braz-Mot et al., 2024). It is also noteworthy that

glyphosate, an herbicide used to control weeds in Amazonian fish farms and first place in the list of ten active ingredients most sold in Brazil, is banned or partially banned in places such as European Union and Mexico with studies reporting the increase in toxicological risks to aquatic biota (Sinhorin et al., 2014, Braz-Mota, et al., 2015). Glyphosate not only has great solubility, remaining around 60 days in surface waters, but it is also commonly mixed with the surfactant polyethoxylated (POE), which affects membrane transport, facilitating permeability and increasing the absorption of glyphosate salts by the aquatic fauna (Braz-Mota et al., 2015). Fish tend to absorb it by gills and through dietary routes in all stages of life, causing biochemical, physiological, morphological, neurological and genotoxic effects.

Ames *et al.* (2022) showed how exposure to glyphosate in different stages of the lifecycle affect zebrafish, with it being able to impact the fish's morphology in embryonic and larval stages, causing locomotor difficulties, as well as increasing mortality, decreasing heart rate and accelerating hatching, while adult specimens showed high quantity of ROS in the gills, and increased lipid peroxidation markers in brain, liver and muscle. These results coincide with Sinhorin *et al.* (2014), who reported a decrease in important antioxidant enzymes, superoxide dismutase (SOD) and catalase (CAT) in both liver and brain of surubim, essential in converting ROS into metabolites. There was a decrease in glycogen observed in the liver and muscle tissue of pintado, increased over time, as an attempt to maintain enough energy to perform metabolic reactions. In the liver and plasma, there was an increase in lactate levels, probably due to a fermentative response of the organism to compensate for the depletion of energy sources, as both glycogen and glucose were reduced (Moura et al., 2017).

Malathion exposure to tambaqui damages the fish's ability to generate energy by cellular respiration, disrupting ATP generation and becoming one of the main sources of ROS in the cells, a time-dependent effect that increases H⁺ leak until 48h after the exposure, indicating an imbalance in the mechanisms dealing with oxidative stress (Souza et al., 2021). Souza *et al.* (2020) reported behavioral changes in five different species (*Carnegiella strigata*, *Corydoras schwartzi*, *Hemigrammus rhodostomus*, *Paracheiroidon axelrodi* and *C. macropomum*) after deltamethrin exposure, including agitation, erratic swimming, loss of equilibrium and body color darkening, with tambaqui having a higher sensitivity, a cause for concern as it is one of the most cultivated species in the Amazon, having a high commercial value.

Acetylcholinesterase (AChE) is responsible for degradation of acetylcholine in the synaptic cleft, thus, disturbances in the acetylcholinesterase activity are good indicators of neurotoxicity (Mela et al., 2013), with reports of inhibitions of its activity in freshwater fish exposed to organophosphate pesticides. The inhibition of AChE leads to the accumulation of acetylcholine in the synaptic cleft, causing continuous stimulation of the muscle and nerve fiber, seen in the erratic swimming and hyperactivity presented by tambaqui exposed to trichlorfon, a common pesticide used in the control of parasite in Amazonian fish farms (Duncan et al., 2020). Braz-Mota *et al.* (2015) also reported decrease of brain AChE activity in tambaqui, also reported for pacu (Venturini et al., 2015), in which the AChE activity was higher than in the muscle, with trichlorfon inhibiting 15% of the activity, even after the recovery period, as for the muscle, the inhibitory effect was observed only after the recovery period. This pattern, also observed for *Oreochromis niloticus* (Guimarães et al., 2007), is likely due to dichlorvos, a trichlorfon derivative, which irreversibly inhibits AChE, leading to a cholinergic crisis, that subsequently causes flaccid paralysis and respiratory failure (Duncan et al., 2020).

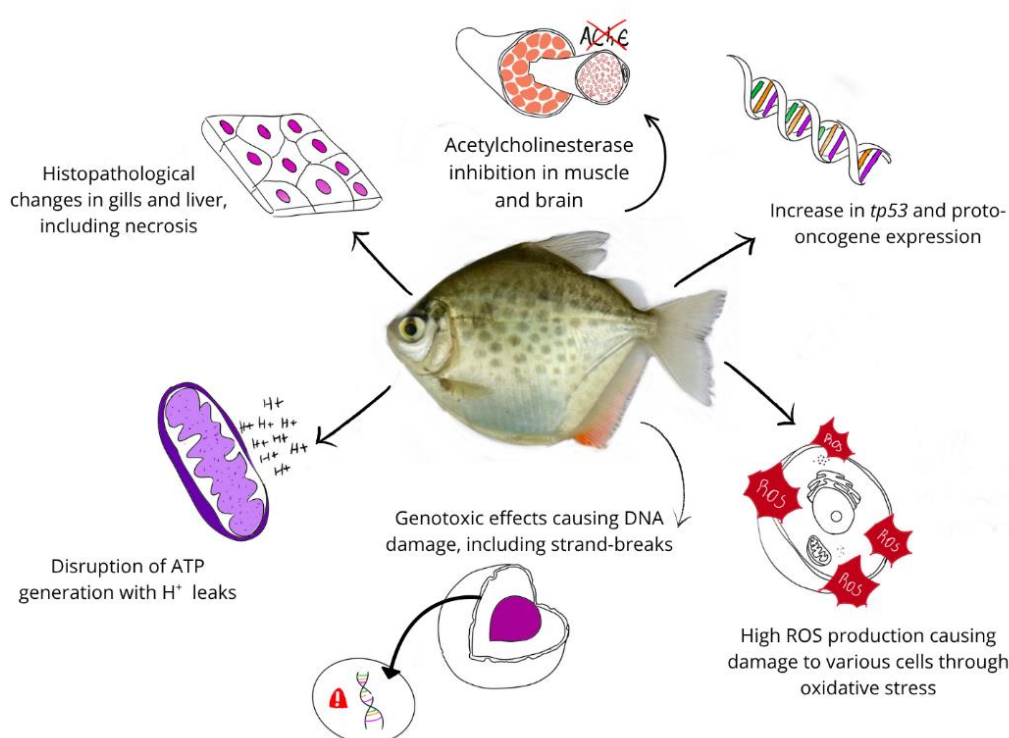


Figure 3. Diagram explaining the main toxic effects of pesticides in Amazon fish.

Histopathological changes in gill epithelia are good indicators of the impact of xenobiotics on fish, due to their large surface area and external location, they are a major site of toxic effects for diverse compounds (Hued et al., 2011). Changes to its tissue impact respiration and ion uptake as gills play an essential role in osmoregulation and acid base equilibrium (Shiogiri et al., 2012). In tambaqui, when exposed to sub-lethal concentrations of glyphosate, there was severe histological damage of different tissues, most of them related to disruption of morpho-functional properties, affecting its respiratory compromise (Braz-Mota *et al.*, 2015). Similarly, Souza *et al.* (2020) reported histopathological damage to tambaqui's gills after malathion exposure, especially hyperplasia, which is an increase in the number of cells, as well as lamellar fusion and necrosis, compromising the gill tissue. When exposed to deltamethrin, tambaqui, along with *P. axelrodi* and *H. rodostomus*, presented lamellar fusion, hypertrophy and hyperplasia in the gills, common changes in fish exposed to aquatic contaminants (Souza et al., 2020). In pacu exposed to glyphosate, the histopathology was greater in the liver with moderate to severe and irreversible damage, with cellular deformation, hypertrophy, lipids inclusion and focus of necrosis, affecting liver function (Shiogiri et al., 2012).

Numerous pesticides are genotoxic, causing DNA damage in those exposed, increasing the occurrence of tumors and overall, negatively affecting the health and reproduction of aquatic organisms. Atrazine, a triazine herbicide that have endocrine disrupting chemicals and causes reproductive issues, can also directly bind to DNA by mechanisms of intercalation and adduct formation between adenine and guanine, caused DNA damage in the blood, gills and liver of curimbatá, with possible apoptosis of gill cells (Santos & Martinez, 2012). Similar results were reported by Calvacante *et al.* (2008) with the same species but those exposed to glyphosate, with presence of micronuclei and other types of nuclear lesions. In *Anguilla anguilla*, results for genetic damage index suggest potential of glyphosate to induce strand-breaks in DNA in branchial cells (Guilherme et al., 2012). In tambaqui, the DNA damage in erythrocytes studied through comet assay were classified as class four, the maximum damage category (Silva et al., 2019).

Exposure to pesticides also tends to change the way genes are expressed in fish, being able to have effects on the fish's physiology and disturbing normal cellular processes. Tambaqui exposed to malathion had an increase in the expression of *tp53*,

the tumor suppressor gene as well as for the genes *atr* and *atm*, both participate in the central pathway of response to genotoxicity, with a change in the *bcl2* (anti-apoptotic gene) and *bax* (pro-apoptotic gene) ratio, with *bax* being positively regulated and *bcl2* being down regulated, an indication of apoptosis (Souza et al., 2023). With strong evidence suggesting that a longer exposure to malathion also increases the expression of the *ras* proto-oncogene, which has a significant part in the carcinogenesis regarding response to mutagenic events and gene overexpression in fish (Souza et al., 2020). Silva *et al.* (2019) showed similar *ras* overexpression in exposure to glyphosate, with moderate damage in the liver tissue, with likely induction of *ras* as an attempt to maintain the survivor and division capacity of hepatocytes.

Therefore, considering the ever-growing agricultural demand for pesticides and constant exposure of the aquatic biota to these xenobiotics, understanding the effects and threats it poses to the physiology of non-model organisms such as fish becomes essential to create systems and legislations to protect the aquatic systems and sustain fish populations, especially the species used as food by local populations.

Heavy Metals

In the 1960s and 1970s, as the population in the Amazon region grew significantly, boosted by industrial growth policies, which included incentives for agricultural expansion, construction of dams and highways and mining activities, the anthropogenic sources of heavy metals grew along with it. However, despite the policies, the region still suffers from a lack of basic infrastructure, with only 14% of Amazonian households having proper sewage treatment and about 70% having proper waste management (Viana et al., 2016). Along with it, due to the urgent need for housing at the time, populations concentrated in peripheral regions and near the streams (Braz-Mota et al., 2024), subsequently, urban streams are frequently polluted, worsened by the high industrial activity of the region. Despite heavy metals entering the Amazonian ecosystem through both natural and anthropic sources, the effects of environmental pollution caused by industrial pollution are much more complex and synergistic as it releases a variety of heavy metals from different sources of activities. As an example, the mining activities alone tend to raise soil levels of arsenic (As), cadmium (Cd), copper (Cu), chromium (Cr), nickel (Ni), lead (Pb) and mercury (Hg) by increasing deforestation, which leads to a series of factors that tend to degrade the

organometallic compounds that bind the heavy metals, easing their transport into the streams (Echevarría et al., 2024).

Domestic and industrial effluents, fertilizers and pesticides with metals in its composition, waste from cattle, pigs and poultry farms are some of the largest sources of heavy metals in aquatic ecosystems, with mining waste seen as the main responsible for water and aquatic biota contamination (Braz-Mota et al., 2024, Lima et al., 2015). As of recently, it has been discovered that Amazon contains almost one-fifth of the global reserves of gas and petroleum along the extreme north coast of South America between Guiana and Suriname, significantly rising the threats to the existence of an essential biome for global climate equilibrium and its local populations. Together with the increase in mining sites and deforestation rates, petrochemical extraction raises significantly the heavy metal contamination, distinctly the spread of Hg in the environment, released during gold extraction and refinement (Echevarría et al., 2024). Different from pesticides, the rise in heavy metal levels in the environment causes larger concentration in carnivorous taxa, due to their feeding of contaminated organisms, as bioaccumulation tends to be closely related to biomagnification process in the elements of the food web, especially fish, who have been the focus of various studies about metal contamination, as they tend to absorb both essential and non-essential metals through contaminated water and food (Lima et al., 2015; Paschoalini & Bazzoli, 2021).

Different aspects of the fish's physiology, ecology and life history are crucial in determining its vulnerability to heavy metal contamination, with its impacts also depending on the context and the exposure to which metal. Seasonal flood cycles also influence the risk for contamination with bioavailability of Hg, Cr, Pb and Ni increasing during rainy season near mining regions in Xingu River, likely due to leaching of these metals into aquatic biota (Ribeiro et al., 2017). Echevarría *et al.* (2024) reported that fish from the Napa and Pastaza rivers, located in the Western Amazon, had higher concentrations during dry seasons, possibly due to a rise in water temperature, which accelerates their metabolic rates and increase in the intake and adsorption of heavy metals. However, even with changes during seasonal floods, biomagnification and bioaccumulation of heavy metals pose as a public health concern as fish are an essential part of human diet and high levels of heavy metals are a risk for both human and fish health, as it leads to several toxic effects, such as interruption of biological

and biochemical processes in those who come in contact with it (Braz-Mota et al., 2024). Therefore, due to various influences of both biotic and abiotic factors in heavy metal contamination in freshwater fish there is a need for broad, representative data on the seasonal and taxonomic distribution of these xenobiotics to provide public guidance regarding when, where and which fishes are safe for consumption.

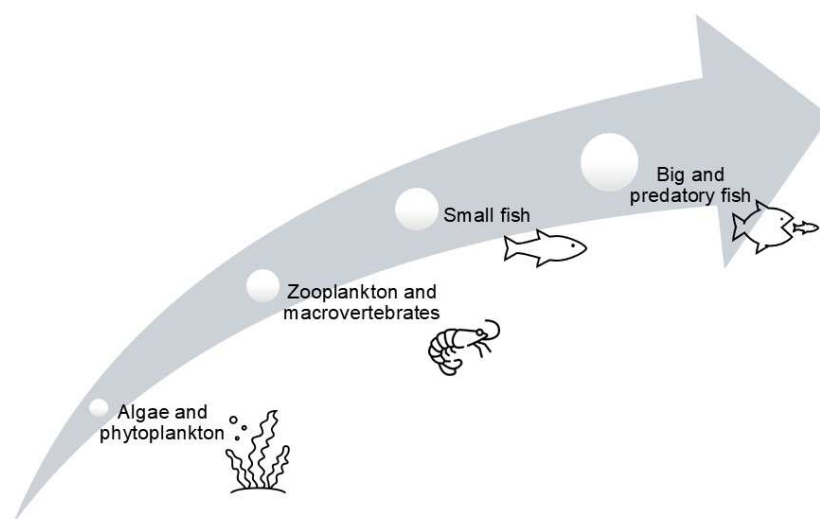


Figure 4. Biomagnification of metals in aquatic environments

In four different species, *Anodus orinocensis* (lapixó-banana), *Curimata vittata*, pescada-amazônica and *Hemiodus unimaculatus* (voador), three being economically important, nine heavy metals were found bioaccumulated in the liver, including Pb and Cr, which even in low concentrations is prejudicial to fish's health as it inhibits gonadal growth (Viana et al., 2020). Arsenic, cadmium and mercury were also present in the muscle tissue of pescada-amazônica found in the middle and lower Araguari River, indicating an increased toxicity for human consumption through a toxic mixture of elements (Costa et al., 2022). Similarly, Hg, Cd, Zn, Cr and Pb were present in the liver, muscle and spleen tissues of pintado, with concentration of mercury and cadmium increasing according to fish size, and levels of lead in all tissues exceeding the safe limit for human consumption (Arantes et al., 2016). Lima *et al.* (2015) reported four metals above the safe limit set by ANVISA (1998), the national sanitary vigilance, chromium surpassed the limit in 27 species, lead in only one, as well as cadmium, and mercury in six species, with the highest concentrations in those at the top of trophic chain. For pirarucu and tucunaré, mercury accumulation was higher (five times for

pirarucu) in rainy seasons, as both are predator fish that migrate into flooded areas during those seasons, this could indicate a higher concentration of Hg in said areas than in the main basin, in contrast, arsenic and cadmium were higher during dry season, but only for pirarucu (Albuquerque et al., 2020).

Different metals have been found to cause metabolic and ionoregulatory disturbances in freshwater fish. Copper is well known for interfering with branchial ionoregulation, in *Paracheirodon axelrodi*, the rate of Na⁺ loss was consistent with the rate suggested to cause mortality, around 30% (Crémazy et al., 2016), as freshwater fish naturally loses ions from the gill to the external media, to maintain its homeostasis, active uptake of these ions from the water is needed, with failure in obtaining Na⁺ homeostasis to be the toxicity target of copper in fish. Braz-Mota et al. (2018) reported similar results for both *P. axelrodi* and *Apistogramma agassizii* (acarazinho), with the former having increased maximum oxidative phosphorylation to compensate for Na⁺ imbalances as Cu tends to compete with Na⁺ for active transport sites, and the latter to deal with gill tissue damages caused by copper toxicity. For tambaqui in soft waters, such as in the Amazonian basin, while copper had no effect on Na⁺ uptake, cadmium promoted a large inhibition Ca²⁺ uptake, with no signs of recovery even after 24h of exposure, likely leading to hypocalcemia, representing the threat of Cd contamination as the limited amount of Ca²⁺ is not enough to out-compete Cd for binding site in the gills (Matsuo et al., 2005).

Various contaminants can directly interact with biomolecules, causing serious oxidative damage, like inorganic mercury, which in short-term exposure, was shown to induce significant changes in antioxidant enzymes such as SOD and CAT in matrinxã, provoking oxidative damage in lipids and proteins (Monteiro et al., 2009). In *Hoplosternum littorale* (tamoatá), toxicity effects to copper showed ROS production far exceeding the antioxidant defense capability and a disruption of redox signaling, contributing to fish mortality (Braz-Mota et al., 2016). Gabriel et al. (2013) reported an increase in SOD and glutathione-S-transferase (GST) activities and in reduced glutathione (GSH) content, a nonenzymatic oxidant, in the liver tissue of tambaqui exposed to manganese chloride, indicating a detoxification process. In *Rhamdia quelen* (jundiá) exposed to manganese, Dolci et al. (2013) described higher lipid peroxidation in both brain and kidney tissues, inhibitory effects on the oxidative phosphorylation on the mitochondria of liver and gill tissue, and a reduction in the

percentage of erythrocytes. An increase in lipid peroxidation was also seen in *Pinirampus pirinampu* (piranambu), with it being proportional to the increase in mercury concentration, same pattern observed in the decrease of catalase (CAT) and glutathione peroxidase (GPx) activities in both muscle and liver tissue (Vieira et al., 2022). The same behavior was seen in other three species, *Cichla* sp. (tucunaré), piraíba, *Semaprochilodus* sp. (jaraqui), with Hg causing disruption in enzymes related to oxidative stress and lipid peroxidation in muscle and liver tissues (Vieira et al., 2023).

Some xenobiotics also take part into different pathologic processes, such is the case of mercury compounds that cause neurotoxic effects and histopathological lesions in the brain, affecting fish behavior and locomotion, seen in matrinxã exposed to inorganic mercury, who presented dark skin pigmentation, erratic swimming, loss of equilibrium and aggressiveness (Monteiro et al., 2009). Salazar-Lugo *et al.* (2013) also reported dark skin and reduced movements in tambaqui exposed to cadmium, along with changes to the head kidney structure, inducing inflammatory process and affecting hematopoiesis cell differentiation, especially granulocytes, likely affecting its function.

In fish, the male gamete tend to be more vulnerable to xenobiotics as its activation is fast and its movement starts when it gets in touch with water, due to this, heavy metals can also impact the male reproductive system, normally seen in a decrease in the sperm motility, speed and trajectory, as observed in *Gymnotus carapao* exposed to cadmium, who presented nuclear alterations in germ cells at different stages of differentiation, a possible indicative of cell death by apoptosis and changes in the sperm morphology (Vergilio et al., 2015). Tambaqui showed the same characteristics, with duration and motility rate decreasing as cadmium concentrations increased, and changes in the motility also seen in copper exposure, which seems to be related to the amount of ROS in the sperm cell, along with a drastic decrease in fertilization and hatching rate (Pinto et al., 2021). Bombardelli *et al.* (2016) reported similar effects for jundiá, with damages to sperm motility even at low concentrations of copper and fertilization and hatching rates at around 40 to 50% of the total amount of oocytes and eggs. Jundiá exposed to cadmium showed similar results, possibly due to damages in the membrane of the gamete and embryonated eggs caused by the metal (Witeck et al., 2011).

To evaluate fish response to environmental pollution, micronuclei test and erythrocyte nuclear abnormalities (ENA) are some of the most common biomarkers to assess DNA damage, an important indicator as bioaccumulation of heavy metals can cause genetic alterations. *Astyanax lacustris* (tambíú) with high concentrations of Pb, Cu, Zn and Ni were found to also have a high frequency of micronuclei, clear evidence of damage caused by chemical contaminants (Viana et al., 2018). Micronuclei were also found in *Prochilodus magdalenae* (bocachico) and *Hoplias malabaricus* (traíra) collected in environments impacted by mercury contamination from gold mining, along with nuclear buds and binucleated alterations in erythrocytes (Cruz-Esquivel et al., 2023). For females of *Colomesus asellus* exposed to a mixture of metals present in the Amazon River estuary, six types of nuclear alterations were found, including lobulated nucleus, binucleated cell and pyknosis with nuclear invagination, nuclear budding and vacuolated nucleus being the most frequent alteration (Viana et al., 2023).

As there are several heavy metal sources that increasingly threaten fish health, inducing diverse health effects and subsequently, causing a rise in mortality, it becomes clear the necessity of a severe environmental monitoring program to aid the preservation of biodiversity, environmental quality and fish health.

6.2. Hygiene Problems

Food safety is defined as the guarantee that food will not cause adverse health effects to the consumer when prepared and/or eaten according to its intended use, it should follow hygienic-sanitary characteristics established by local laws, being a combination of conditions and measures implemented by a food hygiene system, supported by critical control points when appropriate, ensuring safety and suitability throughout the food chain (FAO, 2023). Food business operators are the ones responsible for implementation of Good Hygiene Practices (GHP), practices that aid in the control of potential hazards in food products, either biological, chemical or physical hazards, that are associated with the product and processing it goes through. Biological hazards are microorganisms capable of causing foodborne illness in humans, with most being killed or inactivated through proper cooking procedures and numbers can be reduced by appropriate handling and storage practices that involve GHP and Good Manufacturing Practices (GMP) established for the type of product (FAO, 2023), essential practices in fishery products, as they tend to be easily perishable and are in constant contact

with possible sources of biological contamination, from the streams they inhabit to the ice they are stored in.

Water can be contaminated by different pathogens, including helminths, protozoa, viruses and bacteria, working as a route of transmission for environmental pathogens to humans with dissemination happening through activities such as small-scale fishing, as fish have an almost neutral pH and high-water activity, being susceptible to microorganisms' proliferation (Sousa et al., 2015). Rondón-Espinoza *et al.* (2021) reported high levels of total coliforms and *Pseudomonas* sp. in the surface water of Lagoon Yarinacocha, possibly influencing the health conditions during food handling, in which 40% of the samples obtained from facilities, surfaces and hand of manipulators exceed the maximum allowable limit for coliforms, these findings could be related to the lack of wastewater treatment system in the city where the research took place and while contamination in commercialized fish was low, monitoring of water surfaces allows for easy traceability. In the European Union, regulation no. 853/2004 ensures specific hygiene rules for foods of animal origin, including fishery products, from the vessels used for harvesting to packaging and transport of both fresh and frozen products, with hygiene requirements emphasizing the importance of proper storage conditions and the use of potable water for washing and in the ice used. These requirements are essential as fish can be the host of a great number of pathogenic microorganisms, that come either environmental contamination or improper manipulation throughout its processing, seeing that they are highly perishable, extreme caution to sanitary conditions during all stages of production along with monitoring of water resources are necessary, as to not occur changes to its sensorial characteristics and reduce its shelf life.

Fresh fish, the main form in which fish is sold in the Amazon, can suffer rapid spoilage after harvesting, happening within 12h of their catch in the elevated temperature in tropical regions, with spoilage happening through surface bacteria and oxidation, forming new compounds that change the odor, flavor and texture of fish meat (Ghaly et al., 2010). Proper storage is essential in preserving and extending fresh fish shelf life, with the ice helping to maintain a constant low temperature, to reduce autolysis from digestive enzymes and lipases and bacterial degradation and it provides a gentle cleaning during its melting (Ghaly et al., 2010). Thus, to delay any microbial growth, both spoilage and foodborne ones, the rate of time and temperature during storage

should be carefully maintained, as well as hygiene during handling and exposition of the product and the quality of raw materials (Ferreira et al., 2014), including any water or ice used in the cold chain, it must be fresh due to it directly impacting the quality of the final product, with the proper use and adequate quantity contributing to the preservation of the fish, as temperature stays in a 0-2°C range, delaying enzymatic and bacterial changes (Sousa et al., 2015). Monitoring of possible microbiological and chemical contaminants from water discharge is essential to reduce the risk of both water and fish contamination for human consumption, which in fish farms, it is common to perform through physicochemical variables, including temperature, pH, depth and turbidity, and biological indicators, such as zooplanktons, due to their composition and abundance changing in response to any environmental alteration (Araújo et al., 2024). These hygiene indicators throughout the whole process of fish production are useful to show any possible sanitary failure in it, as well as in the treatments used to eliminate harmful microorganisms.

In Brazil, pisciculture is still a fairly recent practice, seen in the lack of investment and knowledge in this field, as an example, in the system of intensive production, bad handling practices, bad water quality and poor nutrition of the fish are common aspects, reflected in the disturbance of homeostasis of fish, leaving them susceptible to pathogenic organisms (Leira et al., 2017). Between the bacteria with pathogenic potential for both fish and human, motile *Aeromonas*, *Streptococcus agalactiae*, which can be inoffensive if treated correctly, otherwise can cause urinary infections, pneumonia and even meningitis, and *Streptococcus iniae*, causing possible sepsis, toxic shock syndrome and inflammation of the skin in humans (Figueiredo & Leal, 2008; Baiano & Barnes, 2009; Shane & Raabe, 2019). The risk of infection increases for native species when in culture system of floating cages in lakes or dam reservoirs, one of the most common used in the country, where they are raised among farmed tilapia, a non-native species that has a high demand due to the quality of its meat and lack of fish bone, being the most produced fish in Brazil and also considered the main host of streptococcosis, thus providing a pathway of transmission (Tavares et al., 2018; Ministério da Pesca e Aquicultura, 2024). Leal *et al.* (2024) reported *S. agalactiae* infection in wild traíra and farmed pacu that were both in close contact with tilapia, either by being raised in the same tank or cohabiting the same lake in which tilapia were being farmed in the case of traira, both cases create an opportunity for

interspecies adaptation and transmission of the bacteria. Although there was no contact with tilapia, *S. agalactiae* was also found in farmed hybrid Amazon catfish, along with *S. iniae* and *S. dysgalactiae* (Tavares et al., 2018).

Bacteria from the genus *Aeromonas* present a risk for human health, causing gastrointestinal system infections, that when not treated properly, can lead to septicemia, with some species being capable of causing ocular, respiratory and joint diseases, its contamination happens mostly through contaminated food and water, especially fish, thus, they are known as potentially infectious organisms in aquaculture (Pessoa et al., 2019). Medina-Marillo *et al.* (2023) found five different species from the *Aeromonas* genus present in farmed pirarucu and tambaqui, a ubiquitous bacteria found in water and part of the microbiota in Amazonian fish, with four of them, *A. dhakensis*, *A. vronii*, *A. caviae* and *A. jandaei*, infecting not only fish, but are also the ones most commonly associated with diseases in humans. In farmed tambaqui from the Amazonas state, more than half of the bacteria isolated were from the *Aeromonas* genus, with even asymptomatic fish presenting antimicrobial resistance to ampicillin, erythromycin and sulfonamide (Sebastião et al., 2022). As for pintado and two tambaqui hybrids (tambacu and tambatinga) collected in both frozen and fresh forms, *A. caviae*, *A. hydrophila* and *A. eucrenophila* were found, the first two represent a risk for public health as they cause dysentery, fever and vomiting (Silva et al., 2023). Therefore, while *Aeromonas* are present in aquatic environments, inadequate cooling, freezing and handling practices can aggravate its contamination, just as proper conservation and good manufacturing practices can prevent it.

In 2020, the Ministry of Agriculture, Animal Husbandry and Supply (MAPA in Portuguese) established the criteria and sanitary-hygienic conditions for fishing boats of primary production, those who provide the raw material for the industrial processing of fishing products for the national and international market (MAPA, 2020). Since then, a national program for the safety of farmed aquatic biota with information about proper documentation and animal medication, a manual of good practices in the production of farmed fish, containing information from fish well-being to proper physicochemical characteristics of the water for the main cultivated species were released, as well as a leaflet about good practices in artisanal fishing and a four year period to obtain the official certificate of good hygiene-sanitary practices, demonstrating how the concern for food safety in regards to fishery products is fairly recent (MAPA, 2020; MAPA, 2022;

MAPA, 2023). The National Sanitary Vigilance also promoted a program called 'Week of the Fish', in which it shares about the different types of fish products, with a focus on fresh fish that is the most commonly found and sought after, how to properly check for its quality through texture, coloration and smell, to pay attention to any possible physical hazards, such as sand, pieces of plastic, soap, presence of flies, and verify the state of its eyes, as health fish present shiny and salient eyes (Anvisa, 2016).

6.3. Cold Chain Management

Fishing has been a traditional practice for the indigenous and riverine populations in the Amazon region even in pre-colonial times, and now, with the populational and economic growth, commercial fishing has increased its importance in the regional urban markets. It has become an economic activity with the biggest impact on the livelihoods of local and traditional populations, being divided into four subsectors, differentiated by socioeconomic dynamics and sustainable management approaches. Subsistence fishing practiced mainly by indigenous and vulnerable populations, being difficult to quantify its production, commercial fishing who supplies both local and international markets, artisanal fishing, which is also referred to as small-scale fishing (SSF), uses small boats and have limited capital, and sport fishing (Abramovay et al., 2021, p. 23). In Brazil, 99,7% of the fishermen are artisanal fishermen, with the Amazonas state, the biggest state in the country and covered in its entirety by the Amazon forest, having only artisanal fishermen with no industrial fishermen whatsoever (Ministério da Pesca e Aquicultura, 2025). Artisanal fisheries tend to be from households with limited range of operations, who are dependent on local resources and have low investment and simple fishing methods, with their products circulating among local, regional and international systems (Jimenez et al., 2020).

Value chain of SSFs include all activities from pre-harvesting to consumption, with most of the activities being manual with low-cost technologies, which is what makes it accessible for millions of people who have limited resources, reflected in the way that within the Amazon region, the fish is usually sold fresh, cooled with ice, lacking any other conservation method or processing. However, despite the predominance of SSFs, it continues to be a highly informal market, with most of the production, processing and marketing happening outside government regulatory system and many fishers even lacking basic documents to take part into government bureaucracies, because of this,

groups that rely on SSFs could become more marginalized within regional and local markets as the need for formalization increases (McGrath et al., 2015).

While in the catching and harvesting phase, the majority are men, there is a significant number of women present in the post-harvest activities that include handling, processing and marketing, nevertheless, the importance of its value chain and the people involved in it is often overlooked in policies and decision making. Many fishers already get the short end of the deal in terms of economic benefits when compared to other figures in the value chain, as they often lack basic infrastructure, including proper storage facilities, and tend to be in remote places with limited access to market themselves, leading the value chain to be dominated by middlemen, who can use their position as the only link between the fisher and the market, to bring down the value of the fish products (Jimenez et al., 2020; Bartkus et al., 2022). Although trading is the main source of income for fishers and fish workers, access to the market, local or regional, is restricted through various factors, such as lack of information regarding supply and demand, current prices, no structure to keep the fish fresh and weak bargaining power (FAO, 2022). As it stands now, fishers have the option to sell to middlemen or directly to the local buyers (Fig. 7), and while the latter option provides more profit, the difference seldom makes a difference as the ice and fuel needed for delivery are expensive in the remote areas where SSFs are usually located, especially when taking travel time into account. Between Manaus, the capital of Amazonas and Fonte Boa, which has four thousand registered artisanal fishers, is 600km, however, given the geographical disposition, ferry is the main form of transportation, with the trip lasting, in average, 2 days and 21 hours (Bartkus et al., 2022). In addition, there are many areas in the Amazon that paddled canoes are still the prevailing vessel type.

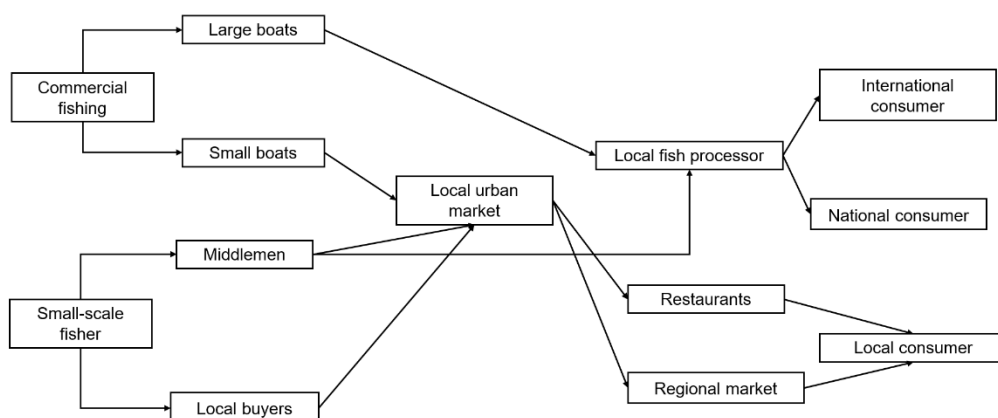


Figure 5. Value chain of SSFs and commercial fishing on the Amazon

Besides having limited access to markets, small-scale fishers also have a long story of conflicts with commercial fisheries, especially the large-scale ones. The main conflict is that, with the increase of commercial fishing in some rivers and lakes, fishers started to see a decrease in local fish stocks. Fisheries management in the form of restricting access to their fishing grounds, prohibiting outsiders from harvesting have been happening since the early 1990s (Lopes et al., 2019). However, article 20 of the Constitution of 1988 declare that lakes, rivers, basin and any water bodies within the Brazilian borders are of public domain, with no restriction as to who can use it. Nevertheless, due to pressure from grassroots movements for community control of floodplain lakes, the Brazilian government has granted the right to some communities to manage their own lake fisheries. In large lakes, the management comes in form of restriction of fishing gears and established quotas or closed periods (Lopes et al., 2019). The rules and restrictions are determined in an agreement between government and community on a case-by-case basis, with federal decrees backing up the decision, providing them with the right to reinforce the rules and have the support of police and/or environmental agencies if necessary.

6.4. Human Health Risks

Exposure to chemicals from pesticides and heavy metals have been expanding with the growth of agricultural and industrial activities in the Legal Amazon region, with rapid urbanization and a lack of basic sanitation aggravating environmental pollution. While human exposure to these xenobiotics has different routes, such as water or air, one of

the main routes of the local population is through contaminated fish consumption, exacerbated by the lack of proper enforcement of maximum tolerable limits for heavy metals and a lack of any limit for pesticides contamination for fishery products, which challenges a proper evaluation of the possible health effects that pesticides have on human health. The current focus of studies is on the exposure of heavy metals as these substances are more easily accumulated due to the biomagnification and bioaccumulation process they go through, with many studies reporting the acute and chronic health risks that exposure to heavy metals can lead, with inhabitants of these polluted areas being routinely exposed to it through different sources and pathways, leading to discussions about advantages and disadvantages of fish consumption, despite the well-known health benefits associated with it.

Trace elements and heavy metals are substances naturally present in the environment, still, anthropogenic activities in different regions increasing their concentration have been a current trend, to the point, metal pollution of surface waters are a global occurrence, amplified in river and lakes of developing countries, degrading water quality and becoming a cause of concern from an ecological and public health point of view as it contaminates the habitat of aquatic biota and the source of drinking water and food for both the fauna and local communities. In the Amazon region, despite its vast size, different sources of pollution have been increasing, with a focus on illegal gold mining, oil and fuel spill from heavy boat traffic and agriculture and livestock expansion from a heavy metal contamination perspective (Viana et al., 2021).

Waichman *et al.* (2025) reported chromium levels exceeding the maximum limit in 83% of samples obtained from fish flesh, including pirarucu and tambaqui, two of the most nationally commercialized species, and mercury in 17%, for 11 different species that were collected in lakes distant from urban and agricultural areas, indicating that the contamination was likely due to geology of the region, deforestation and illegal mining around the area. Similar results were shown by Sousa *et al.* (2015) studies in which four of the five species analyzed presented exceeding values of chromium, especially *Potamorhina latior* (branquinha) collected from downstream of the Madeira River basin who had a value 6.2-times higher than allowed, likely due to being detritivore having a higher exposure to chromium as it is an insoluble element, deposited in bottom sediment. Once chromium enters the bloodstream, it is distributed to almost all the tissues, with its health effects including bronchial asthma, skin allergies, nasal ulcers,

lung cancer and genotoxicity, with a maximum limit of 0.1mg/kg in fishery products established by Brazilian Health Surveillance Agency (ANVISA, 1998; Pokhrel & Pokhrel, 2022)

Cadmium exposure happens mostly through two sources, the first being inhalation of particles during industrial activities and the second through ingestion of contaminated food. Once absorbed, it binds to metallothionein and is stored in the liver and in the kidney, possessing a biological half-life of 17 to 30 years, affecting a number of organs and tissues, including the heart through aortic and coronary atherosclerosis, the lung through fibrosis, the kidney by inducing renal tubular damage, the liver by development of non-alcoholic fatty liver disease and in more serious cases, hepatocellular carcinoma, and chronic renal insufficiency and the central nervous system of children leading to neurological disorders (Castro-González & Méndez-Armenta, 2008; Souza-Arroyo et al., 2022). Traíra and *Ageneiosus inermis* (mandubé) presented similar concentration of the nine metals evaluated, with increases in their bioaccumulation after a period of four years, likely because of implementation of large mineral extraction projects in the upper portion of the Araguari River, where the fish were collected, curiously only cadmium and lead exceed the maximum limits, 0,5mg/kg and 2,0mg/kg respectively, despite both species being carnivorous (Viana et al., 2024). Cadmium was also found outside the values recommend in the muscle tissue of pescada-amazônica retrieved from the middle Araguari River, although not out of the limit, mercury and arsenic were also present, however, when the estimation of daily intake rate was considered, the three metals showed values above the tolerable limits recommend by WHO, indicating a risk to human health from its daily consumption (Costa et al., 2022).

Due to the different sources of contamination, other than fish consumption, currently present in the Amazonian region, the population faces a serious risk when the estimated daily intake (EDI) of a xenobiotic exceeds its reference dose (RfD), estimated as the maximum acceptable dose of a toxic substance in human exposure considering all sources involved. In Souza *et al.* (2025) studies, lead exceeded its EDI for the eleven fish species evaluated, except *Serrasalmus spilopleura* (piranha-doce), and mercury exceeded for all of them. Similarly, Viana *et al.* (2024) reported exceeding reference doses of mercury in all eleven species, cadmium and lead in *Leporinus fasciatus* (piauí-flamengo) and *Curimata incompta* (curimbatá), with lead surpassing

almost 3-times the RfD in curimbatá, with the three elements being considered highly toxic by having a capability of inducing different types of damage to human health. Mercury also exceeded RfD for all species in Waichman *et al.* (2025), chromium did not exceed in only one species, the *Pseudoplatystoma fasciatum* (cachara) and three species presented above the RfD limit for arsenic.

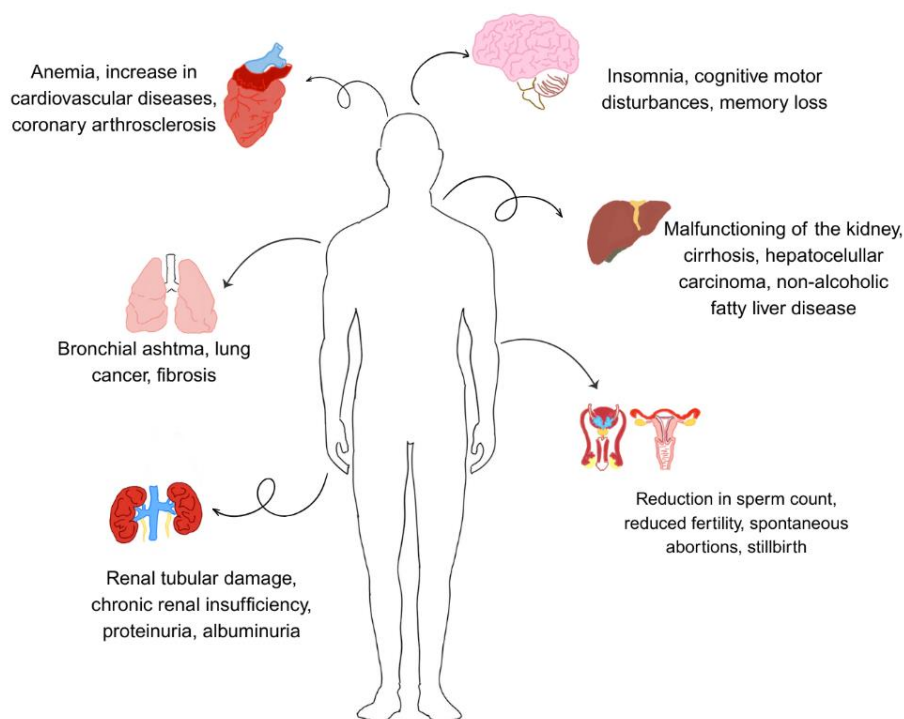


Figure 6. Human health effects of heavy metal contamination.

Lead is associated with several health problems, it inhibits the synthesis of hemoglobin, interacts with the male reproductive system, affecting sperm count, induces oxidative stress through disturbance of activity of several enzymes, leading to damage in the cell membranes, cell function and in the DNA, with common symptoms of lead poisoning being behavioral changes, diarrhea, anemia, skin allergies and kidney malfunctioning (Collin et al., 2022). For arsenic, it distribution is evenly distributed in organs like skin, lungs, liver and kidneys, causing skin lesions, renal dysfunctions that include albuminuria, proteinuria and chronic kidney disease, cirrhosis, disruptions in the endocrine system leading to diabetes, increase in cardiovascular diseases, it also binds to the hemoglobin, accumulating in the erythrocytes and inducing hemolysis, with anemia being one of the most common symptoms in populations exposed to this xenobiotic (Abdul et al., 2015; Haidar et al., 2023). As for mercury, considered the main contaminant of the Amazon region, its most common form found in contaminated

populations and fauna is the methylmercury, which is absorbed through the gastrointestinal tract and then distributed throughout the body, reaching the brain, where it is able to cross the blood-brain barrier, causing tremors, memory loss, insomnia, hallucinations, cognitive and motor disturbances, and similarly to lead, affects the reproductive system by reducing fertility, spontaneous abortion and even stillbirths, and several other health disturbances (Charkiewicz et al., 2025).

While it is necessary to take the bioaccumulation factor into account as the trophic transfer of bioaccumulated metals increases the health risk for humans, as of now, several fish species present a risk to human health, regardless of feeding behavior, therefore, knowing metal concentrations, their distribution profiles and the health risks they pose are essential to advise the populations in the safest species for consumption and promote pollution recovery projects that can assure the conservation of local fish species and food security.

6.5. Mercury as the Main Contaminant

Mercury is a well-known heavy metal, classified as one of the ten most dangerous chemicals (WHO, 2007). It comes from both natural, such as volcanoes and geothermal activities, and anthropogenic sources, normally emitted into the atmosphere (Driscoll et al., 2013). Once in the atmosphere, it eventually makes its way to different ecosystems, the ones that end up in terrestrial environment can cause serious environmental harm as it is carried to aquatic systems (Grigal, 2002). It exists in three main forms, elemental (or metallic) mercury, inorganic mercury and organic mercury. Its different forms are what determine the route of exposure, absorption, distribution and target organ toxicity, influenced by the dose and the rate of exposure. Elemental mercury exists only in liquid form at room temperature, evaporating when the temperature rises, extending the effects of anthropogenic release, as it can stay suspended up to one year in the atmosphere (Carocci et al., 2013). Its vaporized form also means that it is easily absorbed through mucous membranes and lungs, with the brain being its main target organ (Bernhoft, 2011).

The elemental form oxidizes into inorganic mercury, which includes metallic mercury and mercury vapor, as well as mercurous (Hg_2^{++}) and mercuric (Hg^{++}) salts, and during rainfall, it ends up in soil or water bodies (Bernhoft, 2011; Carocci et al., 2013). A common route of exposure with the metallic mercury vapor is through inhalation during

the process of gold extraction, tending to accumulate in the kidney with reports also showing damage in the gastrointestinal tract, cardiovascular and reproductive system (Teixeira et al., 2018). As for the organic forms, while some are present in the pharmaceutical industry, used as topical disinfectants and preservatives in vaccines (ethylmercury), its most abundant form is the methylmercury (Risher et al., 2002). When the inorganic mercury reaches an aquatic environment, it goes through a chemical transformation by methanogenic bacteria, becoming methylmercury (MeHg) (Carvalho et al., 2024).

MeHg jeopardizes the food chain due to its ability to cross biological membranes and bioaccumulate in the body, deemed the most toxic form of Hg (Gimenes, 2021). It is also the main source of exposure to humans and wildlife as the consumption of high-trophic level fish or other contaminated foods leads to toxic effects due to bioaccumulation and biomagnification of this metal (Kang, et al., 2024). Its main target organ is the central nervous system (CNS), endangering especially those more vulnerable to its toxic effects, such as children, malnourished people, infants and pregnant women, as it can cross the placental barrier and lead to serious consequences during in utero and early development (Crespo-Lopez, 2021).

Methylmercury was the one that brought awareness to the hazardous effects of mercury, as it is the one involved the Minamata Bay incident, where a release of organic mercurial compounds into the sea, resulted in a bioaccumulation of mercury in the local marine organisms, which were a part of the diet of the local population (Zaib et al., 2015). This incident, later, led to 128 countries to sign the Minamata Convention on Mercury, an international treaty endorsed by the World Health Organization to combine international efforts to reduce mercury environmental contamination and help prevent exposure to it (<https://minamataconvention.org/en>). Aside from the convention, it also led to denominating Minamata Syndrome, a set of neurological changes, including coordination disturbances and progressive deterioration of visual and tactile senses (Eto, et al., 2001). Likewise, it helped provide enough information to set a series of guidelines, such as a tolerable weekly intake of 1.6µg per kilogram of body weight defined by WHO (WHO, 2011).

However, while it did help set limits and further investigate the hazardous effects of mercury in human and animal health, it is not uncommon for vulnerable populations to

consume quantities well above the limit set either by WHO or by their country legislation, such as the Amazonian riverine populations (Crespo-Lopez, et al., 2021). Unlike the Minamata incident, these populations have been suffering from chronic exposure due to certain recurring activities in the place they live, for example, the gold mining in diverse Amazon regions with records from as early as 1550 (Nevado, et al., 2010).

Mercury sources in the Amazon

Due to the volcanic sources in the Andes, the Amazon already naturally exhibits high levels of mercury in its soil, which is carried to affluents through erosion and then to the rivers, where it is diluted and it adheres to the sediments (Martoredjo et al., 2024). However, it is only a small reason for the exponential increase of mercury in the area; it is the small-scale gold mining (ASGM), a method for extraction of gold with simple techniques, that accounts for about 70% of mercury emissions in South America and 38% of global anthropogenic emissions, the most predominant source sector (UNEP, 2018). The mercury in the environment that ASMG is responsible for consists of releases to soil and water bodies and emissions directly into the atmosphere. The initial amount of Hg, the presence of environmental control systems, amount of mercury in the amalgam and utilization of emission abatement systems are the main aspects influencing the Hg releases from ASMG (Castilhos & Domingos, 2024).

It became a source of income for an increasing number of people in developing countries with the extraction focusing on short-term results, however, there has been a significant number of studies that discuss the long-term impacts of ASMG, including the inconsistency between environmental sustainability and economic interests, lack of initiatives to improve good mining practices for ASMG and the use of mercury and its impact on animal and human health (Kristensen et al., 2013; Meutia, et al., 2023).

Brazil's government has attempted to establish a complex system of laws to regulate ASMG, however, the applicability of the laws and problems in the design create a contradictory and ambiguous scenario, with the miners, also known as *garimpeiros* in Brazilian Portuguese, seldom complying with it (Massaro et al., 2022). Castilhos & Domingos (2024) suggested that the actual production is eight times higher than the legally declared number. Rising the risk for adjacent cities as these mining regions tend to exhibit high deforestation rates and elevated MeHg concentrations in

inhabitants and fauna, as there are no environmental recovery plans and a disregard for the proper acquisition and use of mercury (Neto, 2024).

However, the Amazonian riverine and indigenous have been suffering from chronic exposure long before the dangers of mercury were known, with records of gold mining in diverse Amazon regions from as early as 1500 (Nevado et al., 2010). Still, it was only at the end of the 1980s, known as the “gold rush” that a concern for the environmental contamination by mercury in the Amazon started. As the gold in the Amazon is found mostly as alluvial deposits, the miners tend to use mercury to capture the small particles (Crespo-Lopez, 2023). In the process, after heating the amalgam of mercury and gold, the mercury vapor releases into the atmosphere, converted into inorganic Hg and afterwards, deposited into the rivers (Carvalho, 2024).

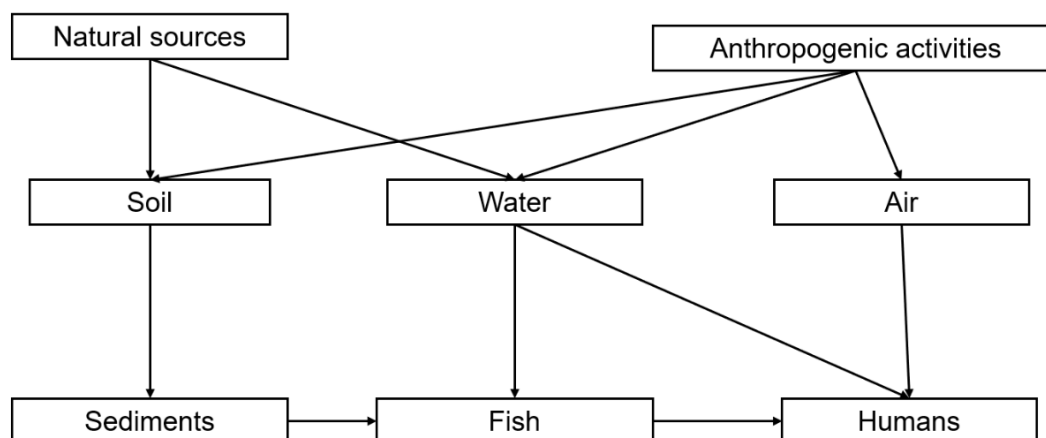


Figure 7. Exposure sources of mercury.

Recently, along with the extensive mining and the already high natural concentration of mercury in the Amazonian soil, other factors including wildfires, deforestation and construction of dams, have been contributing to the large deposition of the heavy metal into the Amazonian ecosystem (Crespo-Lopez, et al., 2011). Deforestation affects the biogeochemical cycle of mercury, as the forest canopies are effective in trapping the atmospheric Hg due to its large surface area, retaining mercury through the stomata; subsequently, the mercury accumulated on foliage is transferred to the soil by litterfall and its decomposition or by throughfall, thus, acting as a Hg sink as it limits its mobility in the environment (Fostier et al., 2015).

Taking up more than a third of the total mercury emissions, around 2220 tons per year, are the terrestrial ecosystem, notably forests, consequently, reducing the load of

mercury being deposited into oceans and freshwater systems; therefore, anthropogenic actions in the land use and land cover changes, which includes deforestation, disturbs Hg fluxes to the atmosphere (Feinberg et al., 2024). Another aspect that might facilitate mercury accumulation in the Amazonas is river damming as the submergence of the terrestrial areas may increase both bioaccumulation and mercury methylation (Arrifano et al., 2018), as their construction result in direct effects on the local mercury dynamics through flooding of previously dry terrestrial areas (Souza-Araujo et al., 2022). Flooding of these areas leads to the remobilization of mercury adsorbed to soil particles and eventual deposition on the bottom of river sediments (Souza-Araujo et al., 2022), which in turn, brings a rise in mercury levels in aquatic organisms that live in such systems (Palermo et al., 2004).

Mercury levels

Total mercury concentration measurement in body tissues give significant information for biological monitoring programs, as even though muscle tissue is the target tissue to analyze accumulation of methylmercury, as it is the main part consumed, however muscle tends to be slow in response to changes in Hg concentration in the environment, reflecting long-term exposure, differently, liver is the best target tissue to monitor short-term exposure, as liver is essential in the elimination and detoxification process of xenobiotics and the main target organ for storage of mercury (Costa et al., 2022). Costa *et al.* (2022) analyzed total mercury concentration in pescada-amazônica, a predatory species, finding an average of 1.09mg/kg in muscle tissue and 1.28mg/kg in liver tissue for both sexes and the hydrological cycle, both values above the limit considered safe for human consumption. The liver and kidney tissues analyzed for corvina were higher, 279µg/g and 115µg/g, respectively, than those in tambaqui, 198µg/g and 88µg/g expected due to the dietary habits as corvina is carnivorous and tambaqui is an omnivorous species (Bittarello et al., 2020).

Cavecci-Mendonça *et al.* (2020) reported higher values for dourada at 0.085µg/g, curimatã in second place at 0.635µg/g and 0.035µg/g for pacu in muscle tissue (Table 2), following the same pattern in liver tissues at 1.196µg/g, 0.635µg/g and 0.74µg/g, respectively. In tucunaré, one of the most consumed species, with samples collected from two different municipalities, one close to a gold mining city and another 600km away from the contaminated area, also presented elevated levels in the liver tissue

when compared to muscle tissue, with the highest concentrations at 0.45µg/g and 0.36µg/g, respectively, while tambaqui showed distinct results for both cities, with muscle tissue having a mean of 0.26µg/g and 0.22µg/g in liver tissue, the highest values, from samples collected near the mining area (Vieira et al., 2011). Matos *et al.* (2025) studies reported the highest total mercury concentration in liver tissues of four different species when compared to other tissues, with the highest value being from *Hydrolycus tatauaia* (pirandirá), at 0.81µg/g in liver tissue and 0.3µg/g in muscle tissue, and from curimatã, at 1.05µg/g and 0.5µg/g. Except for one species, all presented higher Hg levels in liver tissue than muscle, indicating the continuous exposure they suffer to this contaminant.

	Muscle (µg/g)	tissue Liver tissue (µg/g)	Sources
<i>Brachyplatystoma rousseauxi</i>	0.085	1.196	Cavecci-Mendonça et al. (2020)
<i>Mylossoma</i> sp.	0.035	0.635	Cavecci-Mendonça et al. (2020)
<i>Prochilodus nigricans</i>	0.063	0.74	Cavecci-Mendonça et al. (2020)
<i>Cichlia ocellaris</i> in Itaituba	0.36	0.45	Vieira et al. (2011)
<i>Cichlia ocellaris</i> in Barcarena	0.25	0.3	Vieira et al. (2011)

<i>Colossoma macropomum</i> in Itaituba	0.26	0.22	Vieira et al. (2011)
<i>Colossoma macropomum</i> in Barcarena	0.18	0.20	Vieira et al. (2011)
<i>Hydrolycus tatauaia</i>	0.3	0.81	Matos et al. (2025)
<i>Prochilodus nigricans</i>	0.5	1.05	Matos et al. (2025)
<i>Hydrolycus armatus</i>	0.3	0.81	Matos et al. (2025)
<i>Cichla miriana</i> from Teles Pires River	0.17	0.47	Matos et al. (2025)
<i>Cichla miriana</i> from Peixoto River	0.18	0.17	Matos et al. (2025)

Table 2. Mercury content ($\mu\text{g/g}$) in liver and muscle tissue of different species.

The Oswaldo Cruz Foundation (FIOCRUZ), an institution linked to the Health Ministry, responsible for the scientific and technological research and development of health, released a regional analysis of mercury levels in fish consumed by the local population, involving 80 different species. Carnivorous species presented an overall higher average than non-carnivorous species, the highest average was found in a city in Amazonas state, Santa Isabel do Rio Negro, which together with another city in the same state, had half of the species a concentration above $0,5\mu\text{g/g}$, but the highest concentration was found in the capital of Acre state, demonstrating the contamination

risk in fish commercialized in urban centers (FIOCRUZ, 2023). Anjos *et al.* (2016) reported that for 50 individuals collected, from 14 different species, including commercially important species, half of them presented methylmercury levels above the threshold limit in the muscle tissue, with *Cichla monoculus* (tucunaré-amarelo) having the highest concentration at 2,2mg/kg, surpassing the limit of 1.0mg/kg set by ANVISA (Resolution 42/2013) for predatory fish and carnivorous species having the highest mean total of MeHg. Gama & Silva (2020) described similar results for nine predatory species, in which all presented some level of contamination in the muscle tissue, with 39.7% of them surpassing 0.5mg/kg and five species, *Serrasalmus rhombeus* (piranha-preta), *Hoplias aimara* (manjuma), tucunaré-amarelo, piramutuba and traíra, showed greater bioaccumulation potential, having a positive correlation between mercury concentration in the muscle tissue and body weight and length. These results indicate the importance of considering bioaccumulation when advising the population on safe fish consumption.

Diverse studies have shown methylmercury levels in riparian and indigenous population ever since early 1980s, as the main consumers of native fish species, through hair samples, as hair is one of the body's excretion pathways, a common biomarker for recent dietary exposure and collection is non-invasive (Feingold *et al.*, 2020). In Pará state, the Munduruku indigenous people requested to FIOCRUZ an assessment of mercury contamination for in their territory, divided in three different villages, due to a rise in gold mining in a nearby area. The average prevalence of exposure for all villages that exceed 6.0µg/g was 57.9%, with the *Sawré Aboy* village presenting the highest prevalence at 87.5% and consequently, presenting the highest average at 11.5µg/g and the highest level at 23.9µg/g registered in a 10-year-old boy, and participants from *Sawré Aboy* and *Sawré Muybu* villages with levels above 10µg/g showing somatosensory dysfunction, alteration in verbal fluency and in some cases, cerebellar ataxia (Basta *et al.*, 2021). Another assessment carried out in three regions within the Yanomami indigenous villages, requested by the chairman of Hutukara Yanomami Association (HYA), showed concentrations above 6µg/g for 6.7%, 27.7% and 92.3% of the populations from Paapiu, Waikás Ye'kuana and Waikás Aracaça villages, respectively, for Waikás Aracaça village, a two-year-old girl presented a level of 15.3µg/g, a value close to the average of the adult group at 16 µg/g, higher than in other villages, likely due to its proximity to ASMG activities (Vegas *et al.*, 2018). It is

important to note that many of these villages have limited access to basic healthcare, adding to their vulnerability to endemic diseases of the region, such as malaria and tuberculosis. Mercury contamination in indigenous populations is not exclusive to Brazil, with Colombian indigenous population in the Yaigojé Apaporis National Natural Park presenting greater mercury concentrations than reported for other indigenous communities throughout South America, with an average of 22.98µg/g, and 86% of participants presenting concentrations higher than 10µg/g (Valdelamar-Villegas & Olivero-Verbel, 2020).

As for riverine population, a study made in the Madeira River basin, the second most important gold mining region, analyzed mercury concentrations in forty-five communities, and even though no correlation was found between fish species and high mercury concentrations, 78% of the communities reported eating fish two times per day during the week, and except for one, all presented average levels above 6µg/g, of which sixteen had average levels greater than 16µg/g, the limit established by WHO (1976) in which is toxicological symptoms start (Bastos et al., 2006). Another study done in Madeira River, however, near a hydroelectric project, analyzed riverine populations from five different areas with varying levels of remoteness and if the area was upstream or downstream the river. All communities presented high Hg levels, with a decreasing concentration, the closer the community was to the nearest urban center, Porto Velho, capital of Rondônia state, which means that Cuniã village, the most isolated out of the five, with no means of regular transportation, had the greatest average concentration at 6.36µg/g, it was also the community in which 57.7% of the population reported eating fish daily (Hacon et al., 2014). Similar results were shown by Meneses *et al.* (2022), in which 75.6% of the participants had Hg blood levels greater than 10µg/L, samples were gathered from eight riverine communities and from the urban area of Santarém, with urban area residents presenting a mean of 21.8µg/L and the highest concentration at 247.1µg/L, and riverine population with a mean of 50.6µg/L and the highest concentration at 296.5 µg/L, and overall, 82.1% of participants that exhibited altered blood pressure, also exhibited elevated Hg levels, as well as 79.6% of those who presented altered weight. These findings indicate that while riverine populations suffer from a higher exposure, likely due to dietary habits as fish is the main source of protein for many, Hg contamination also impacts the urban

population, regardless of proximity to mining sites, showcasing the broadness of mercury contamination in the environment.

7. Challenges

Overfishing

Overfishing is defined when exploitation of fish stocks reduces them below an acceptable level, overfished ecosystems tend to change between target species due to depletion of stocks of economic importance, switching to more abundant stocks. There are three recognized types of overfishing. Ecosystem overfishing happens when the ecosystem's balance is modified, with the balance tilting towards smaller species, seen in the reduction of large predatory species and increase of small forage type species. Recruit overfishing happens when the mature adult no longer has the capacity to reproduce due to insufficient adult population to produce offspring. Lastly, growth overfishing is when the average size of a harvested species is smaller than it would be if that species was allowed to grow its full size, reducing the total yield (Shakouri et al., 2010). Symptoms of an overfished ecosystem are a reduction in diversity, decrease in mean trophic level, increased by catch, decline in aggregate production of exploitable resources, greater anthropogenic habitat modification, higher variability in abundance of species and changes to alternative stable species regimes (Shakouri et al., 2010; Murawski, 2000). Population status of fish species can be separated into unfished, well-managed, overexploited and depleted, with sustainable fisheries aiming for well-managed, also called maximally sustainably fished species, which is when the catch is at maximum level without declining of fish populations below the most productive level (Castello et al., 2014).

The management of Brazilian fisheries have relied on minimum catch size, such as 1.5m for *Arapaima gigas*, and closed season regulations, known as *piracema*, but compliance to it is poor, attributable to lack of government resources and large geographical areas, as well as being open access resources, meaning that all citizens have equal rights of use (Castello et al., 2014). The increasing urban demand for fishes and fishery products has led to overexploitation of significant species, being the one of the main aspects contributing to the decline of freshwater fish stocks, seen in the rise of juvenile fish sold in the regional markets (Pereira et al., 2023). Overfishing of multiple species heavily affects biodiversity, which erodes the sustainability of long-term

fisheries, as there is lower potential for biomass compensation in communities with less species (Heilpern et al., 2022). Favored harvesting of fish focuses on large individuals, inducing changes in the population structures as smaller fishes with earlier reproduction survive more easily (Correa et al., 2015). The high vulnerability of large fishes can cause reduction of stocks in multi-specific tropical fisheries by the 'fishing down' process, also lead to the decrease in the average trophic level in the landings, with a few ecosystem indicators already showing some fluctuations in recent years, showing the greater capture of larger species occupying the highest trophic levels (Pereira et al., 2023).

Even though the rise in environmental degradation is a major concern, it appears that intensive and/or excessive fishing pressure are the main drivers for the decline of fishing stocks, including recruitment overfishing, which is when reproductive populations are depleted, and growth overfishing, when excessive number of young fishes are captured, both types leading to an increase in fish mortality rates that surpass maximum sustainable yield (Prestes et al., 2022). Catfishes are one of the most vulnerable species due to productivity and susceptibility characteristics, which include late maturity, low intrinsic rates of increase in the population, migration pattern needed to complete life cycle raising vulnerability to capture and dependence on vulnerable habitats (Pereira et al., 2023). In the central part of the basin, stocks of *Colossoma macropomum*, popularly called *tambaqui*, have been exhausted, with a reduction of up to 50% in body size and catch rate within 1000 km of Manaus, the capital of Amazonas and the largest consumer in the region, consequently (Pereira et al., 2023).

However, even with the migratory species of catfish being the most exploited, there is no legal recognition of which species should be considered migratory and therefore, no special protection, with management strategies being applied by NGOs and academics at a local scale, that are, unfortunately, not sufficient to tackle the full scale of fish migrations (Prestes et al., 2022). There has been an instance where the local communities, upon noticing the drastic decline of pirarucu in the 1950s and the subsequent continued reduction, made conservation efforts, leading to an increase in the population species and positive impacts on the structure of fish gathering of lakes that are managed for their protection (Pereira et al., 2023)

The lack of action and information by the local government is alarming, seen in the fact that *Arapaima gigas*, known as *pirarucu*, one of the most sought-after species, was put in the IUCN Red List of Threatened Species in 1996 and it remains listed as 'Data Deficient', meaning there is not enough information to make a direct, nor indirect evaluation of its risk of extinction based on its distribution and/or population status, the same reason it is not in Brazil's own's list of endangered species (World Conservation Monitoring Centre, 1996; Castello et al., 2014). Together with the limitation in the flow of data due to many spatially scattered fisheries, using diverse types of gear to capture a wide diversity of species, located in regions with difficult access, it becomes clear the need of governmentally integrated and centralized actions in ensuring long-term sustainable small-scale fisheries (Heilpern et al., 2022).

Damming

Hydropower is currently the main source of renewable energy, being responsible for almost 50% of the renewable energy generated in 2023, as well as the leading element in future renewable energy portfolios as well, with many emerging economies investing in the construction of large dams (Flecker et al., 2022; Energy Institute - Statistical Review of World Energy, 2024). In Brazil, hydropower has been the main source of energy of the Brazilian electricity system for decades, in part due to the abundance of this resource at a national level, with a generator system with a capacity of more than 150 W (Empresa de Pesquisa Energética). As part of the Decennial Plan of Energy Expansion, the Brazilian government approved the construction of several dams along the Amazon basin for the purpose of providing energy for the largest cities in the country as well as supply to the growing industrial necessity (Arrifano et al., 2018). However, as plans for hydropower expansion continue to grow, it becomes urgent the need for strategic dam planning that helps minimize total environmental impacts.

In addition to overfishing, the decline of fish populations can also be linked to river dams, as its construction causes major impacts on the aquatic fauna, resulting in the fragmentation of river connectivity, impacts on the riverine geomorphology, obstruction of migratory routes, changes in the physical-chemical and biological aspects that form the local habitat, and at the same time, causing local extinctions and reduction in the abundance of fish species (Begossi et al., 2019; Doria et al., 2018). The dams separate the feeding and growing areas from the breeding ones, lowering the chances

of long-term survival of populations and destabilization of aquatic food chains by a cascade of effects that lead to the removal of predators (Pereira et al., 2023). Prestes et al. (2022) found that the construction of dams that block upstream migration of *Brachyplatystoma rousseauxii* have contributed to its further decline due to major loss of spawning areas. It also decreases fluvial habitat heterogeneity and trap sediments, influencing river productivity and water quality within the reservoir and downstream reaches, as well as easing the establishment of exotic species (Keppeler et al., 2022)

Beyond the threats to the local flora and fauna, dam constructions affect the livelihood and well-being of fishers as there is a geographical and occupational displacement, along with decrease in income and no alternative for employment, leading to a rise in food insecurity and lack of food quality (Doria et al., 2018). Moreover, it has been known that the implementation of hydropower dams impacts directly the mercury dynamics as the flooding of previously dry terrestrial ecosystem induces the remobilization of mercury adsorbed to soil particles culminating in deposition on bottom river sediments (Souza-Araujo et al., 2022). Along with the direct impact onto the aquatic fauna, as well as the impacts due to the construction and functioning of the dams, they also exacerbate the deforestation problems as it increases the development of roads and associated infrastructure, with lack of indication from the development agencies that such concerns are even considered (Begossi et al., 2019).

Deforestation and Climate Change

Although 2024 was the year with the largest percentage drop in deforestation in 15 years, this was followed by an upward trend that reached its highest in 2021 at 13.038 km² of clear-cut forests, caused mostly by agro-industrial cleaning for pasture, a failure for the National Policy on Climate Change that committed to reduce deforestation by 80% in 2020 (INPE, 2022). The floodplains of Amazon are between the most complex ecosystem on the planet, having a high level of biodiversity and responsible for the food security and provision of various to the local populations, it also already shows a 70% reduction in the forest habitat in the Lower Amazon (Renó et al., 2016). Continuous deforestation heightens the alarming consequences that extend beyond terrestrial environments, as its forests positively affect the diversity of freshwater fish communities in the tropics by having a high heterogeneity in food materials and physical structures in the freshwater habitats (Lo et al., 2020).

Riparian canopy covers, in temperate streams, are an essential parameter in arranging fish fauna in relation to its longitudinal distribution and to deforestation (Bojsen & Barriga, 2002). Clearing of the canopy covers has a significant impact on local temperatures, as it intercepts and reflects the solar radiation and by evapotranspiration, which dissipates the heat as well as aiding the water flow from deep soil layers up to the atmosphere (Ilha et al., 2018). The impact is already seen within the 'Amazonian Arc of Deforestation', an area of 500 thousand km² where the agricultural advances into the forest and where the highest rates of deforestation are found, the complete forest clearing increased the mean air temperature by five Celsius degrees (Silvério et al., 2015). Additionally, loss of forest of cover accelerates erosion processes and the carrying of nutrients, sediments and pollutants into the water systems (Freitas et al., 2021).

Predictions on the effects of climate change in the Amazon Basin point to a rise in temperatures during dry season and an overall decrease in rainfalls, with climate phenomena such as the El Niño-Southern Oscillation already causing droughts in amazonian rivers (Barros et al., 2020). The loss of floodplain forests, together with climate change, is expected to decrease significantly the probability of fish species to survive long term, due to the fragmentation and loss of habitat, and changes in the stream thermal regimes (Ilha et al., 2018; Capitani et al., 2021). It has been demonstrated that along with the air temperature, the mean daily temperatures in streams in deforested areas were three to four degrees higher than in stream found in forested areas (Macedo et al., 2013). Tropical species are expected to be more vulnerable to warming streams, as many of them seem to have narrower thermal ranges when compared to temperate and subtropical species, tending to live closer to their thermal limits, with small increases possibly reducing performance at an individual and populational level (Campos et al., 2019). With temperature being one of the most important environmental factors directly influencing the biodiversity structure, the increasing temperatures have already begun showing changes in the phenology and geographic distribution of species, the two most common biological responses associated with it (Ilha et al., 2018). Areas with lessened riparian covers tend to be more homogeneous, favoring generalist fish species that have feeding strategies that let them stay in habitats with anthropogenic changes (Freitas et al., 2021). There are studies that have indicated that deforestation and subsequent increase in

temperatures affect fish body size at individual and populational levels, with a significant lower mean body mass found in populations from deforested streams (Ilha et al., 2018).

Considering that the Amazon has an annual hydrologic cycle with drastic changes in water depth that creates temporary flooded forests in the floodplains adjacent to the main river during rainy season, enlarging the area in which fish can move around and play a role in migration patterns, droughts caused by climate change pose a danger to fish population. Although drought has been happening for a long time, the frequency (2005, 2010, 2015, 2016, 2020, 2023-24) have increased as well as the magnitude and intensity, with each subsequent one breaking new record, with El-Niño, worsening the situation. According to the Institute of Sustainable Development of Mamirauá, in 2023, there was a high mortality of two river dolphins, boto cor-de-rosa and tucuxis, reaching 159 deaths (<https://mamiraua.org.br/noticias/emergencia-de-botos>), likely due to high water temperature and decreased oxygen concentration. Fish suffer from similar fate, as their habitat suffers low thermal variations and they already live in temperatures close to that of their upper thermal limits, with temperatures in drought rising as far as 39°C, even the most thermally tolerant will be seriously affected, seen in the same drought that killed river dolphins caused a mass mortality event of Amazonian fish (Braz-Mota & Val, 2024).

As for the Amazonian populations, droughts severely impact their lives. Their main source of food and income slowly becomes depleted and as many of them still rely on well water for drinking and cooking, they also suffer from reduced water availability, impacting the productivity of local crops that are essential for community subsistence, and overall, creating major food insecurity, possibly driving these populations to migrate to urban areas, raising inequality and potential social conflicts with the risk of malnutrition (Padilha, 2025). Another effect of hydrological droughts is the navigational challenges, as sandbanks and boulders became visible in low water level, river courses became narrower, limiting route options and increasing costs of transportation, compromising access to food, fuel and medical supplies for riverine and indigenous populations, isolating them and lowering their life quality (Lima et al., 2024). When added to lack of preparedness of governmental agencies in dealing with such a crisis, acting after the disaster reaches drastic levels and focusing only on temporary

remedial actions, local communities must develop their own practices to increase their resilience to such emergencies (Lima et al., 2024).

8. Conclusion

Although there has been increasing concern for the numerous threats to the Amazonian aquatic ecosystem and to the livelihood of those who depend on it, there still seems to be a lack of governmental capacity and coordination into taking more severe measures of preservation and conservation of freshwater systems. In 2020, the International Union for Conservation of Nature called for protection of 80% of the Amazonian territory by 2025, however, this resolution was mostly aimed at forests, failing to acknowledge the interconnectedness of forest and rivers, a failure in conservation planning. The rise and diversity of anthropogenic activities in the Amazon basin release heavy metals and pesticides indiscriminately, critically threatening the preservation of local aquatic biota, and if not controlled soon, they will not be able to survive, meaning the loss of the world's richest freshwater biodiversity. In addition to it, the contamination carries over to the local populations, with some cases already demonstrating toxicological symptoms caused by the bioaccumulation of mercury, the most abundant and common contaminant found in the Amazon. These threats, with the ongoing climate change, indicate the urgency for action to guarantee the survival and life quality of this ecosystem.

Key areas for further investigation by researchers and policy makers include implementation of quality standards for contamination of pesticides and heavy metal for the preservation of aquatic biota and maintenance of food safety, research on different trophic fish levels to understand what the main exposure pathways are, modes of action, how biological effects of pesticides and metals differ among them, stricter regulations about the use of pesticides, research on possible pesticides contamination in human through fish consumption, implementation of monitoring stations for registration about environmental levels of these contaminants and biomonitoring programs for vulnerable populations.

In addition to health risks, artisanal fisheries and populations who rely on subsistence fishing are often excluded and ignored in discussions about implementations of large-scale projects and the environmental and social impacts it brings to the region, when the knowledge held by traditional populations, passed through generations, can aid

ecological assessment and management, promoting biodiversity preservation (Doria et al., 2018). Fishers' knowledge is essential to recognize conflicts about the state of natural resources, fishing regulations and environmental conservation, however, their invisibility extends to proper management of fisheries, seen in the recently established good manufacturing practices despite being an activity present since colonial times, contributing to the lack of accurate and reliable data and monitoring of fish stocks, social and environmental parameters and ecosystem dynamics, leading to biased and poorly advised decisions. Coupled with the poor enforcement of the few environmental laws that exist, riverine and indigenous are constantly under risk of losing their main nutritional source.

Recommendations to combat this include the establishment of monitoring programs of artisanal, subsistence and commercial fisheries across the Amazonian basin for better assessment of fish stocks, considering yield, ecology and biology of fish species, enforcement of laws against deforestation and illegal mining, enforcement of closed season and minimum catch size regulation, stricter guidelines and requirements for implementation of large-scale projects as well as improvement in the criteria and research designs for environmental impact assessments, better public policies and improvement of government capacity to manage planning, construction and operation of these projects and promote and facilitate participation of fishers and indigenous communities in discussion forums throughout the project implementation.

This review thesis explored the nutritional and economical relationship between traditional Amazonian populations and native fish, revising the ways in which the different risks to its existence interact with them and how the combination of these factors, with few known countermeasures, collaborate to a faster degradation and depletion of natural resources in the Amazonian biome, and lastly, with perspectives of future improvement if current deficiencies and core issues are addressed by the main parties involved in them.

9. References

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