Mercury pollution in pan-amazonian indigenous communities: a portrait of reality

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ABSTRACT

This article discusses the issue of mercury contamination in the Amazon, a bioaccumulative metal used in artisanal gold mining. This socio-environmental problem has directly affected indigenous and riverine communities, causing neurological, cardiovascular, digestive and reproductive problems. Based on an interdisciplinary scientific perspective that aims to consider the complex reality of Amazonian indigenous peoples, the goal is to propose measures that can assist these communities in addressing this issue. In addition to the literature review on the subject, a research conducted by FioCruz in the Sawré Muybu Indigenous Land (Pará) in 2019, which is currently one of the most mercury-contaminated regions in Brazil, was used as a reference. The proposals for action include educational and preventive measures, guidance to the government, environmental and health monitoring, and the strengthening of the capacities of indigenous communities to deal with contamination. The study highlights the significance of an interdisciplinary and collaborative approach to tackle this intricate and pressing issue in the Amazon

Keywords: Amazon, mercury, indigenous peoples.

Introduction

The Amazon encompasses nine South American countries and its extent amounts to one-third of all remaining tropical forests in the world. This biome is home to more than half of the planet's biodiversity and is made up of at least ten distinct types of forests. The Amazon Basin, which expands over an area of 6.9 million km^2, plays an indispensable role in the climate and global hydrological cycle, being responsible for storing about 20% of the world's fresh water (Ab'Saber 2003). Over the past 11,000 years, the Amazon has been preserved and cultivated by a multitude of indigenous groups. These groups have upheld a symbiotic relationship with the ecosystem, revealing a deep connection between human communities and the biome (Neves 2006).

Although illegal gold mining is not a recent phenomenon in the Brazilian Amazon, the expansion of these activities has accelerated significantly in recent years. This expansion has been fueled by the rise in global gold prices and the inadequacy of regulations and oversight tailored to the complex economic, social, and political dynamics underlying this practice (Skidmore, 2022). In the context of this expansion, the use of mercury (Hg), a metal with high toxic potential, has posed significant challenges in terms of socio-environmental impacts. While its use in mining is allowed under authorization from the National Mining Agency (ANM), effective oversight and control of the trade, use, and disposal of mercury have proven problematic, particularly in the Northern region of the country, where this metal illegally reaches the mining sites.

Despite Brazil having undertaken international commitments to reduce mercury use, as established by the Minamata Convention, such commitments have encountered significant obstacles to their effective implementation. The trading of clandestine gold in the legal market, for example, is facilitated by financial firms authorized to purchase this metal (DTVMs), which often lack due diligence or oversight over the cited ore provided by the sellers (Skidmore, 2022). Such challenges have contributed to making the mercury issue one of the main socio-environmental problems in the Amazon currently. Illegal mining has led to significant deforestation and the displacement of local communities, while the use of mercury in gold extraction has caused severe damage to the environment, with the release of more than 1,000 tons of mercury per year from illegal mines (Skidmore 2022).

Indigenous and riverine communities in the Amazon are particularly affected by this problem, since their survival is directly related to access to and interaction with local biodiversity and a potentially contaminated environment

(Basta & Hacon 2020). Mercury is often used to amalgamate gold, helping to separate it from other substances. This almalgam is heated, causing the mercury to evaporate, leaving behind the gold. However, evaporated mercury does not disappear, it is released into the air and can be inhaled or settle in soils and bodies of water in the surrounding area. In addition, a portion of the mercury used in the amalgamation process does not evaporate, remaining in liquid form or in the form of small droplets and can thus be deposited in rivers or soil, affecting essential ecological processes such as decomposition and nitrogen fixation.

This mercury can also enter the food chain when it is converted by bacteria into methylmercury (MeHg), an organic form of mercury that is easily absorbed by organisms. MeHg is bioaccumulative, that is, it accumulates in the tissues of animals, especially in fish, and can be transferred to humans when they consume these animals. Chronic exposure can cause a variety of health problems, including neurological, cardiovascular, digestive, and reproductive problems (Heck 2014, Basta & Hacon 2020). In addition, mercury is particularly harmful to pregnant women, as it can affect the development of the fetus. In summary, mercury can kill or cause health problems in a wide range of animals, including fish, birds and mammals.

The region where the Munduruku indigenous people live, on the banks of the Tapajós River in Pará, is currently one of the most mercury-contaminated areas in Brazil (Risso *et al*. 2021). A field study conducted by FioCruz in 2019, within the Sawré Muybu Indigenous Land (IL), found that in the areas most affected by illegal mining, nine out of every ten Munduruku individuals were contaminated by the metal (Basta & Hacon 2020). This research included neurological, pediatric, genetic evaluations; skin samples and hair strands; measurement of hemoglobin levels, weight and height, as well as the assessment of mercury contamination in fish in the area. Considering this study, the objective of this article is to discuss measures that can be adopted by Amazonian indigenous communities that suffer similar processes. To this end, a bibliographic review of the scientific literature on the subject was carried out, including institutional and legal frameworks, medical recommendations, action plans in the health, environmental and socioeconomic areas, as well as an anthropological approach that takes into account the complex Amazonian reality. The problem that motivated the development of the present work is: how does mercury pollution cause problems in pan-Amazonian indigenous communities? This understanding will be built based on experiences encountered within the Munduruku Indigenous Community.

Sawré Muybu idigenous area: historical and social context

The Sawré Muybu indigenous land, located in the state of Pará (Brazilian Amazon), is part of the set of territories inhabited by the Munduruku indigenous people (Wuy jugu), whose nation extends along the Tapajós River basin (Figure 1):

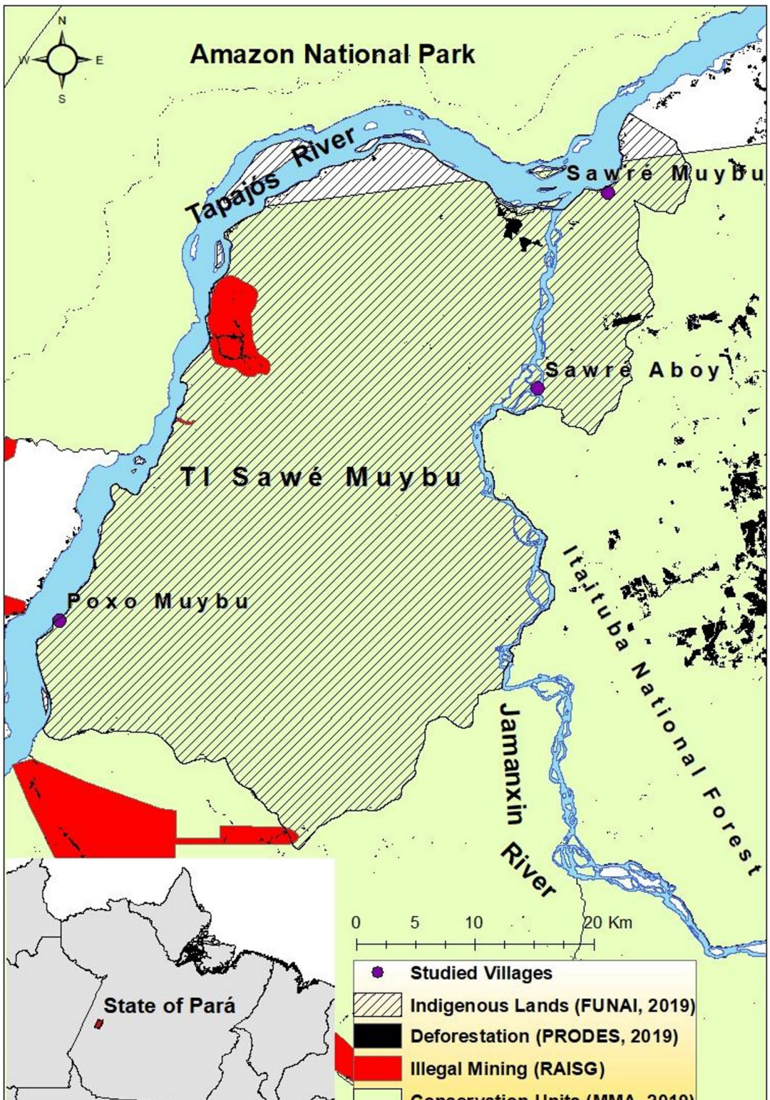


Figure 1 Map of the study area. Adapted: Just & Hacon 2020.

The Munduruku are historically recognized for their inclination towards warfare, which allowed them to impose their cultural presence in the Tapajós Valley. After the conquest, the Munduruku managed to resist the European invasion until the 18th century. During this period, missionaries led colonization efforts and facilitated the exploitation of natural resources in the hinterlands, such as cumaru wood and cocoa. However, the greatest extractive expansion experienced by the Munduruku occurred during the rubber *boom* in the 19th century. Rubber extraction led to a violent and rapid occupation of the Tapajós region, resulting in a direct assault on the indigenous population. These peoples were used as slave labor in the extractive activity (Melo 2008)

After the conclusion of the rubber extraction cycle, the territories inhabited by the Munduruku gained new value in the capitalist market due to the discovery of gold reserves in the area during the last third of the 20th century. During this period, the escalation of illegal gold mining intensified as a result of internal colonization processes sponsored by the State, such as the construction of the Trans-Amazon Highway in 1972. This pressure has escaleted in recent decades, particularly during the presidency of Jair Bolsonaro, who promoted policies aimed at strengthening the extractive fronts, which represented a setback for the advances achieved in the protection of these peoples, such as the demarcation of their territory. As Wark and Wyllys (2022) point out:

> The incursions of outsiders continue to this day, bringing violence and diseases, such as the measles epidemic of the 1940s that decimated the population, and now the mercury poisoning from wild mining. More recently, since Bolsonaro took office in January 2019, attacks by illegal miners and, directly or indirectly, by large ranchers, soybean growers, and other land grabbers have only increased, with the complicity of local and national authorities, especially after a decision by the Supreme Federal Court obliging the government to protect the Yanomami and Munduruku indigenous peoples. Bolsonaro promised not to keep "prehistoric men in zoos," not to "demarcate another centimeter" of the Amazon, and incites any kind of violence to get away with it because, for him, "where there is indigenous land, there is wealth beneath it" (Wark & Wyllys 2022).

The intensification of extractive activities in the territories inhabited by the Munduruku has led to a rapid increase in the contamination levels of essential resources for the survival of this people. Fishing is their main subsistence activity, which also supports ritual practices and community exchange. In addition to fishing, hunting, gathering and agriculture are indispensable practices for the life of the Munduruku, whose mechanisms of cultural reproduction are intrinsically related to the conservation of the environment, since it guarantees the continuity of their productive, religious and cultural practices. It's noteworthy that, for the Munduruku, the elements that define their tribes are rooted in the nature that surrounds them, so the conservation of the environment is a fundamental requirement for preserving their founding myths and the perpetuation of their ancestral language (Scopel *et al*. 2018).

The impact of mining pollution extends beyond considerations of the long-term effects that this activity can cause. This situation already shows an immediate impact not only on the inhabitants of the Munduruku territory, but also on future generations. According to a study conducted by the Oswaldo Cruz Foundation (Fiocruz) and the Center for Scientific Innovation of the Amazon (CINCIA) in cities adjacent to mining areas such as Sawré Muybu, Sawré Aboy and Poxo Muybu, 57.9% of its inhabitants have mercury levels in the body higher than the safety levels established by international standards. The main source of exposure to MeHg for indigenous peoples is the consumption of fish, which are contaminated in the waters of rivers exposed to artisanal mining. The contaminated fish, in turn, initiate a food chain that transfers mercury to individuals and even to their children through pregnancy or breastfeeding (Basta & Hacon 2020).

The accumulation of challenges that this group currently faces seriously jeopardizes their material and cultural survival. Therefore, their struggle is focused on territorial defense for the conservation of their forests and rivers, against threats such as mercury pollution derived from mining. Given this situation, the aim of this study is to undertake a holistic approach to the complex reality of Sawré Muybu, within the framework of concrete proposals for the potential execution of direct actions aimed at reducing the advancement of extractive activities in the territory.

Institutional and legal framework for the use of mercury

The Minamata Convention on Mercury (Ministry of the Environment of Peru, 2016) is a global treaty, established to safeguard human health and the environment from the harmful impacts of this element. Established in 2013 by the United Nations Environment Programme, this convention was ratified by

128 nations by the year 2021. The name "Minamata" dates back to the Japanese city that, in the 1950s, witnessed a devastating episode of mercury poisoning, resulting in thousands of lives lost and a lasting impact on the health and quality of life of the survivors. This international pact recognizes the magnitude of mercury as an environmental issue of global scale and aims at the proper management of this metal, mitigating its deleterious effects. To fulfill this purpose, the Convention stipulates a series of strategies aimed at controlling and decreasing the use, trade and disposal of mercury. Such strategies include the gradual extinction of mercury mining and its use in products such as batteries, fluorescent lamps and thermometers, as well as requiring the safe storage and disposal of mercury-containing waste. In addition, the Convention stresses the importance of international cooperation, technology transfer and capacity building as means to support the implementation of agreed commitments.

Faced with the serious dangers associated with the use of mercury, both Brazil and the international sphere have taken actions to discipline its use and mitigate its deleterious effects. In the Brazilian context, the main legal framework guiding the use of mercury is currently constituted by the "National Plan for the Reduction of the Use of Mercury in Artisanal and Small-Scale Gold Mining" (PNMC), established in 2022 by the Ministry of Mines and Energy (MME) and detailed in Sohn (2022). This plan outlines guidelines and strategies aimed at mitigating the use of mercury in gold mining, an activity highlighted as one of the main sources of environmental pollution. In addition, the PNMC aims to encourage the application of safer and more sustainable alternative technologies. Furthermore, it is based on a variety of international legal instruments aimed at regulating the use of this toxic metal.

The Judiciary and the Legislative branches have also been taking action against the improper use of mercury. In September 2021, the Federal Supreme Court (STF) unanimously ruled on the unconstitutionality of Law 1.453/2021 from the State of Roraima, which allowed licensing for mining activities involving the use of mercury. The law, challenged by the Sustainability Network through a Direct Action of Unconstitutionality (ADI) 6.672, was deemed by the rapporteur, Justice Alexandre de Moraes, as contrary to the federal model of environmental protection, which requires specific environmental permits for different phases of potentially polluting activities. In addition, the law was seen as a violation of the right to an ecologically balanced environment, according to article 225 of the Federal Constitution, and as a usurpation of the exclusive competence of the Union to legislate on mineral resources and metallurgy, in accordance with article 22, item XII, of the same Constitution.

The Bill 1011, proposed by Senator Randolfe Rodrigues in 2023, establishes the "National Policy for the Prevention of Mercury Exposure" and the "Mercury Exposure Control System" (SICEM), both aimed at monitoring mercury exposure in the Brazilian population, especially in regions affected by illegal mining. The project foresees cooperation between different levels of government and encourages epidemiological studies, providing data collected by SICEM to researchers. Additionally, it establishes an ongoing awareness campaign about the risks of mercury exposure and designates November 8th as the National Day to Combat Mercury Exposure and Intoxication. This legislation is particularly relevant in a context where Brazil, as a signatory of the Minamata Convention, seeks to reduce the use of mercury in gold mining and control its import and usage, especially in illegal activities, in compliance with international commitments.

These actions were triggered after studies revealed the alarming situation faced by the Munduruku people. Between 2018 and 2019, there was a drastic increase of 101.12% in the length of the devastated rivers in the Munduruku territory, jumping from 88.5 km to 178 km. According to a report by Greenpeace in 2020, the year in which President Jair Bolsonaro sent to Congress Bill 191/2020 - proposing the release of Indigenous Lands (TIs) for mining and energy exploration - a new wave of intense activities in the region becomes evident (Dantas 2021). As a result, on May 29, 2020, Greenpeace filed a complaint with the Federal Public Ministry of Pará (MPF-PA), requesting the immediate and permanent withdrawal of the miners from the Munduruku and Sai Cinza TIs. On June 16, the MPF filed a lawsuit requesting that the Federal Police (PF), the Brazilian Institute of the Environment and Renewable Natural Resources (Ibama), and the National Indian Foundation (Funai) take action against illegal mining on indigenous lands in southwestern Pará and identify those who "consistently demonstrate disregard for compliance with laws that recognize indigenous rights and ensure environmental protection" (Greenpeace Brasil 2020).

In summary, the issue is complex and requires a multidimensional approach that unites local, national and international spheres. The Minamata Convention and national plans such as the PNMC are significant steps in this direction. However, it is still critical to increase public awareness of the risks of mercury exposure, implement alternative technologies in mining, and strengthen legislation and enforcement. After all, the protection of human health, the preservation of indigenous rights and the conservation of the environment are shared responsibilities, which demand the continuous and engaged collaboration of all the actors involved.

In December 2022, the Brazilian Socialist Party (PSB) filed a Direct Action of Unconstitutionality (ADI) 7273 with the Supreme Federal Court (STF) in an attempt to review the State's regulatory power over mining activities in the forest, including on indigenous lands. The arguments exposed say that the principle of good faith is highly questionable and misplaced. With that being said, the Distributors of Securities and Securities (DTVM) now adopt and store only the information provided by the sellers, who in many cases are squatters and illegal miners. It is also mentioned that Law 12,844/2013 aims to provide relief to family farmers who had losses caused by problems in the harvest (climatic events, for example), and not to deal with the transportation and commercialization of gold in the Amazon, or in Indigenous Lands (STF 2023).

Socio-environmental diagnosis

Environmental impact caused by the use of mercury in biotic components (flora and fauna) and abiotic components (soil, water and air)

Mercury is the third most toxic element on the planet, according to the U.S. Government Agency for Toxic Substances and Disease Registry (Rice *et al.* 2014). This metal occurs naturally in low concentrations in virtually all geological environments and takes various forms: elemental (or metallic), inorganic (e.g., mercuric chloride), and organic (such as methylmercury and ethylmercury) (Crespo-Lopez *et al.* 2019, Gerson *et al.* 2022). All of these forms of mercury have different toxicities and different implications for ecosystems because they are pollutants and bioaccumulative (UN Environment 2019).

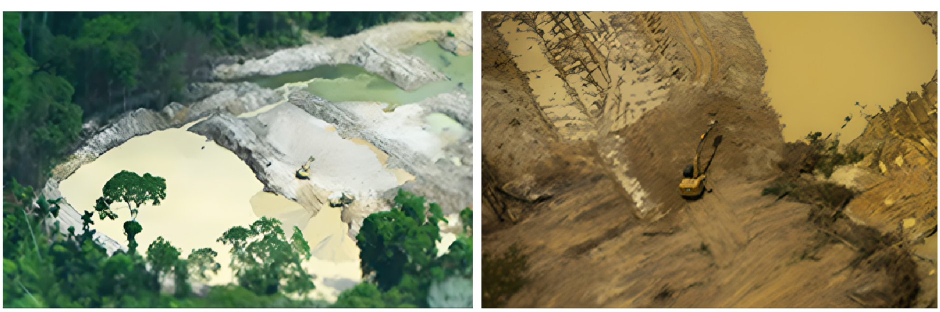
Naturally occurring mercury is introduced into the environment through volcanic eruptions and ocean emissions. Once on the air, it can travel thousands of miles in the atmosphere before being deposited back on earth in the form of rain, which involves the deposition of mercury through the actions of precipitation, snow or fog (UN Environment 2019), or dry gas, which occurs when mercury particles or vapor are deposited directly on the earth's surface (Steenhuisen & Wilson, 2019). The anthropogenic influence regarding mercury is evidenced by stationary combustion of fossil fuels (24%), biomass (21%), industrial activities (28%), and waste emissions, which include mercury-added products and account for about 7% of global emissions (Global Mercury Assessment 2018).

Anthropogenic activities such as mining pose a high risk to the environment due to deforestation, water quality degradation, and disruptions to associated ecosystems. It is even more concerning for human health due to water body contamination, where microorganisms can transform mercury into MeHg, which accumulates in fish, crustaceans, and animals that consume fish, including humans. (Steenhuisen & Wilson 2019, Crespo-Lopez *et al*. 2019, UN Environment 2019, Basta *et al*. 2021). These activities have had a historic impact on the Amazon (Sonter 2017, Paiva 2020, Couto 2021), causing intensive changes in land use (Asner 2016) and polluting fresh water with mining tailings (Webb 2004). Furthermore, the impacted areas continue to expand, encompassing both protected and unprotected regions of the Amazon basin (Roy 2018, Ferrante 2019, Rorato 2020), causing the environmental impact to grow disproportionately and making it more challenging to measure, resulting in serious consequences and negative impacts that cannot be remedied or mitigate (Tarras-Wahlberg 2000, Asner 2016).

From a historical point of view, mercury has been widely used in South America by the Spanish colonizers in gold and silver extraction activities. Between 1550 and 1880, about 200,000 metric tons of mercury were released into the environment (Malm 1998). Nevertheless, it is estimated that approximately two-thirds of the mercury present in the environment has been released during the 20th century, and the dispersed mercury load today is three times greater than that of the early 1900s (ibid.). Currently, the mercury used by illegal miners in the Brazilian Amazon would have clandestine origin in illegal markets located mainly in Bolivia. To give an idea of its high usage, for every kilogram of illegally extracted gold, approximately 2.8 kilograms of mercury are used (Indaga 2021), and it is estimated that illegal mining activity releases, on average, about 24 kilograms of mercury per square kilometer of prospected area (ACTO 2018). As pointed out by the Amazon Cooperation Treaty Organization (ACTO) in its 2018 Transboundary Regional Diagnostic Analysis of the Amazon Basin, it is estimated that the Brazilian Amazon alone received 2,300 tons of mercury until 1994, and then recorded volumes around 150 tons per year.

Mercury is extremely volatile and, in addition, does not disintegrate, that is, it does not disappear with time, but changes between different chemical forms (Crespo-Lopez *et al*. 2019, Gerson *et al*. 2022). In fact, the spread of mercury is governed by a complex global and transboundary cycle, which affects the atmosphere, hydrosphere and geosphere (UN Environment 2019, Gerson *et al*. 2022). This polluting cycle begins with the separation of gold from rock particles, sand, or other associated materials through the amalgamation process, with mercury then separated from gold through heating. This process takes place in open air and releases vapors that directly impact the health of individuals in contact, leading to organic, neurological, cognitive, and psychological deficits due to inhalation (Mercury and Health, 2017). Finally, once cold, this gas can be transported in air masses over long distances and recycled between major environmental compartments, such as lake sediments and subsurface soils, contaminating the living things that depend on these resources (UN Environment, 2019).

Contamination of soil and water resources are the most significant impacts caused by the incorrect discharge of mercury (Calderon 2020). As shown in Figure 2(a), illegal mining activity does not implement remediation or mitigation measures after the mineral extraction process. These practices lead to the formation of water pools and extensive areas of land contaminated with mercury exposed to the open air, which, through the action of microorganisms like anaerobic bacteria and fungi, have the capacity to methylate mercury in aquatic and terrestrial ecosystems (Beckers and Rinklebe 2017, UN Environment 2019, Crespo-Lopéz *et al*. 2021) This bioaccumulates in living beings (fish, macroinvertebrates, people, plants, etc.), altering the food chain of these ecosystems (Bayón 2015, Global Mercury Assessment 2018, El Comercio 2020). Another negative impact is the accumulation of sterile material from rock residues (Figure 2b), which modifies the physiography of the terrain and causes changes in land use (Calderón 2020), altering the habitat and causing sedimentation problems in the surrounding lake systems (Cao 2020).



(a) (b)

Figure 2 Impacts of illegal mining on the Tapajós River and on indigenous lands of the Munduruku people. a) Pools of contaminated water exposed along the Tapajós River; b) Debris generated by gold mining and the formation of dams for sedimentary accumulation. *Photo:* Adapted from Greenpeace Brazil 2020.

In aquatic environments, these conditions often include anoxic conditions (low oxygen) and a high level of organic matter. This is also a valid condition for terrestrial environments, where methylation can be facilitated in areas like wetlands due to the presence of certain plant species that promote microbial methylation (Crespo & López *et al*. 2021, Gerson *et al*. 2022).

However, in terrestrial ecosystems, this process is generally not as problematic because inorganic mercury tends to be less bioavailable in soils and therefore less available for absorption by organisms. Conversely, aquatic organisms can absorb different forms of mercury, primarily through food (indirect absorption), and, in a lesser extent, directly from water (direct absorption) (UN Environment 2019). Indeed, the mercury taken up by organisms undergoes bioaccumulation, a process through which organisms can absorb the contaminant more quickly than they eliminate it (Molina *et al*. 2010). Biomagnification can also occur, whereby the concentration of this pollutant increases as it moves to higher trophic levels in the food chain (Leung *et al*. 2017, Basu *et al*. 2022). In other words, as the trophic level in the food chain increases, MeHg accumulates and becomes concentrated in the tissues of higher-level predators, such as large fish and marine mammals. Therefore, carnivorous fish that feed on other fish can accumulate particularly high levels of MeHg in their tissues (Mahhaffey 1999, Leung *et al*. 2017, Basu *et al*. 2022).

Another resource affected by illegal mining is the flora. The ability of tropical evergreen forests to absorb mercury is favored by factors such as a large leaf area index and the duration leaves remain on the plant (Wohlgemuth *et al*. 2020; Feinberg *et al*. 2022). In other words, the longer lifespan of leaves also promotes absorption and higher concentrations of mercury in the forest vegetation of these ecosystems (Pleijel *et al*. 2021), which translates into impacts on indigenous populations and communities that depend on subsistence agriculture and the use of non-timber forest products.

In addition, the deforestation processes in these territories in the exploration and exploitation phases have caused the degradation and loss of all vegetation as can be seen in Figure 2 (a) (b), in addition to the alteration of drainage systems and the destruction of the habitat of numerous species of fauna associated with these ecosystems (Minam 2016). Thus, deforestation in these areas, which between 2010 and 2020 grew by 495%, according to a study conducted by the organization MapBiomas (MapBiomas 2020, Salazar 2021). The MapBiomas report points out that 65% of mining activities in the Brazilian Amazon basin are not legal and that the installation of "Garimpos" has quintupled on indigenous lands and grown 301% in conservation areas. Mining activity extended to an area of 6,500 hectares per year between 2010 and 2020, showing an average annual increase of 1,500 hectares in the period from 1985 to 2009 (MapBiomas 2020, Salazar 2021).

The Munduruku territory is one of the 34 protected areas in Brazil where illegal mining is present (Inpe 2021) and accounts for 60% of deforestation alerts in indigenous lands in the Amazon, identified by the National Institute for Space Research (Inpe) between January and April 2020 (Instituto Igarapé 2020). With the aid of satellite images, it was determined that in 2021, there was a 58% increase in the deforestation rate (Inpe 2021).

Impacts on human health

From a historical perspective, mercury has been utilized for almost 3000 years (Ye *et al*. 2016). Used by the Egyptians, Phoenicians, and Greeks, it held magical significance in alchemy, where it was known as "the messenger of the gods." Its name in the periodic table of elements comes from the Latin word "hydrargyrum" (Hg), which means "liquid silver." (Faria 2003)

The toxic action of mercury on human health has also been known for some time. Indeed, starting from the 17th century, hat-making was a notoriously hazardous occupation, as it involved the use of large quantities of this metal. Mercury poisoning has become so common among hat makers in Victorian Britain that Lewis Carroll is believed to have had the disease in mind when he invented the character of the Mad Hatter in "Alice's Adventures in Wonderland." In addition, the psychotic symptoms of mercury poisoning have been studied since the 18th century, when mercury drugs began to be widely used in the treatment of syphilis (Waldron 1983).

The story of mercury poisoning on both small and large scale has been amply illustrated by Coulter (2016). As mentioned historically, the first well-documented case of acute mercury poisoning due to the consumption of contaminated fish occurred in Minamata, Japan, in 1953. The clinical condition was officially recognized and named Minamata disease in 1956. However, many years later, the definition of this disease in terms of clinical symptoms and extent of lesions is still being debated. Biological measurement (biomonitoring) of mercury in hair, blood, nails, and urine, for example, allows quantifying the exposure and relating it to potential health effects**.**

Currently, the literature on intoxication and exposure to inorganic mercury in humans consists of clinical case reports (Teixeira *et al*. 2018). The most recent research focuses on the study of health effects in cases of chronic, low- or moderate-grade exposure (Ye *et al*., 2016). In this regard, it should be noted that numerous studies are still being conducted and that the clinical manifestations of mercurial syndrome and the pathophysiology of mercury poisoning also depend on the form and, in some cases, the route of contamination by the substance.

Methylmercury is a fat-soluble molecule easily absorbed and bioaccumulated by low-taxon organisms (Mahhaffey 1999) and therefore biomagnified along the food chain (Basu *et al*. 2022). In the Amazon this represents a major problem, as several communities depend on these fish species as a source of protein (Azevedo *et al*. 2020). MeHg neurotoxicity has been documented in several studies (Branco *et al*. 2021, Santos-Sacramento *et al*. 2021, Paduraru *et al*. 2022). This toxin can interact with enzymes, cellular membrane functions, and neurons, causing oxidative stress, lipid peroxidation, and mitochondrial dysfunction. Additionally, it hinders satisfactory synaptic transmission (the connection between a neuron and another cell) and disrupts the proper transport of amino acids within cells (Crespo-López *et al*. 2005).

In the case of the reproductive system, toxicity from MeHg can lead to chromosomal abnormalities (National Research Council 2000). High concentrations of MeHg cause a reduction in sperm count and testicular atrophy (United States Environmental Protection Agency 2001). In pregnant women, mercury is transmitted to the fetus through the placenta (National Research Council 2000), causing issues during organ development (Ha *et al*. 2017). Grandjean *et al*. (2010) reported issues in newborns, such as low birth weight, delayed neuronal development, and overall slow growth of children (United States Environmental Protection Agency 2001). A significant positive correlation has been documented between mercury concentrations in mothers' and children's hair, transmitted through breast milk (Marques *et al*. 2016).

Several symptoms of Minamata disease, associated with high levels of mercury exposure, have been observed in communities in the Amazon (Crespo-Lopez *et al*. 2021). The inhabitants of these communities can consume between two and six times the recommended maximum levels of MeHg (Crespo-Lopez *et al*. 2021), accumulating mercury levels higher than 6.0 µg/g, which is considered a health risk (Basta *et al*. 2021).

Lacerda *et al*. (2020) determined that the inhabitants of the Tapajós community (Pará) had significantly higher concentrations of mercury than the gold miners exposed to mercury vapors in Serra Pelada (Pará). This was linked to visual impairment in the Tapajós community. Basta *et al*. (2021) found somatosensory alterations and verbal fluency issues in individuals over 12 years old. The prevalence was higher in the Sawré Aboy and Sawré Muybu communities, where mercury exposure levels exceeded 10 µg/g (according to WHO, safe accumulation levels should be below 6 µg/g). Oliveira *et al*. (2021) found similar patterns in the residents of Poxo Muybu, despite lower mercury concentrations compared to the aforementioned communities. However, the population levels are also above the safe concentration limit for the body.

Other documented symptoms in Amazonian communities include motor deficits (problems with movement coordination, for example) (Costa *et al*. 2017; Basta *et al*. 2021) and emotional disorders such as anxiety and insomnia (Costa *et al*. 2017). Neuronal development issues have been detected in children, as well as psychomotor problems, visual disturbances (Fillion *et al*. 2013), and difficulty in processing and recalling information (Santos-Lima *et al*. 2020).

Socioeconomic impacts

In addition to the serious impacts on human health, the illegal gold mining and its polluting effects alter the lives of communities, which suffer from it in various ways. First and foremost, it is essential to acknowledge the scope of the problem generated by the constant expansion of the mining front into the territories traditionally inhabited by indigenous peoples in the Pan-Amazon region, particularly the Munduruku people along the Tapajós River. This threat is systematic because Brazil is part of an iron and gold extraction chain in which the country plays a decisive role, as it currently holds one of the world's largest gold reserves, along with others in the Amazon basin, such as Venezuela (Manzoli *et al*. 2021), which also holds a significant reserve located in areas primarily inhabited by Amazonian indigenous peoples.

In this scenario, indigenous peoples experience the greatest externalities of the extraction process in ecological, cultural, and economic spheres, resulting from illegal activities linked to mineral extraction, primarily gold. These activities are carried out using unregulated artisanal techniques that are not guided by any legislation aimed at containing or controlling the impact arising from the environmental liabilities left by this activity in the territory.

In the case of the Munduruku population and others in the Amazon basin, impacts stand out in the concentration of common goods, such as pollution in aquifers, soil deterioration, and the impact on flora and fauna, often consumed by these groups. On the other hand, illegal mining is detached from the state's tax system, as its activity goes undeclared, leading the state to bear its consequences (environmental remediation) without benefiting from its profits. According to a report from IWGIA, in the Tapajós basin, the Munduruku territory, at least "30 tons of gold per year, approximately R$ 4.5 billion in undeclared income, which is six times more than the legal activity in the region," are extracted (Alcántara 2021).

In the indigenous community areas, mining resorts to acts of violence and extortion by mining groups towards its inhabitants, degradation of the indigenous community fabric, recruitment processes, and pressure exerted by miners, occupation and establishment of external hubs whose social development occurs within a framework of urban dynamics and extensive pollution. This is further compounded by the alteration of the consumption habits of these communities, introducing new products detrimental to their health and social fabric, such as alcohol and drugs.

These impacts develop in parallel with an ecologically compromised context, widely contaminated by chemical residues such as mercury, which spreads in the water and fish consumed by these established populations. At the same time, we must add the forced displacement of communities threatened by the presence of miners, which, concurrently, leads to other phenomena, such as the labor exploitation of these communities, as well as the trafficking and sexual exploitation of children(Matos, 2016).

A study conducted by the NGO Global Initiative against Transnational Organized Crime in 2016 showed the links between illegal gold mining and organized crime in countries such as Bolivia, Brazil, Colombia, Ecuador, Guyana, Mexico, Nicaragua, Peru and Venezuela. The investigation revealed that this activity contributes to phenomena such as funding insurgent groups, money laundering, and corruption. In addition, it causes the forced displacement of the local population, accelerates environmental destruction and promotes the labor and sexual exploitation of its inhabitants (Global Initiative Against Transnational Organized Crime 2016).

In this scenario, mining has contributed to the exacerbation of one of the fundamental problems historically faced by Amazonian indigenous communities, which is the lack of demarcation of their territories. From this, one can get an idea of the legal void that enables the appropriation, contamination, and destruction of the lives and the environment of these communities. This state of abandonment became more extreme during the tenure of Jair Bolsonaro's administration, characterized by policies that turned genocidal and anti-indigenous. These policies facilitated the expansion of extractive activities in Amazonian territories, even in areas designated as protected.

Action plans

The development of an action plan requires a solid understanding of the sector in which mining activities take place, in order to support the formulation of realistic and effective strategies that are in line with the law and to measure progress in their implementation (Keane *et al*. 2023). This requires data collection regarding the utilization and practices of mercury in small-scale gold mining (ASGM) sites, stakeholder consultations, as well as reliable literature and socio-economic, health, and environmental information, as demonstrated by O'Neill & Telmer (2017).

The information should focus on data such as: the estimated amount of mercury used by the sector, the estimated amount of gold extracted, the estimated number of miners involved in the sector (by gender), and detailed geographical information about artisanal and small-scale gold extraction. Additionally, qualitative information has been collected, including the presence of worst practices, as well as various documented environmental, health, and socioeconomic information (Keane *et al*., 2023).

Environmental Impacts

Assessment of the importance of impacts

The assessment of the environmental impact will be conducted based on the significance and adverse effects caused to the environment, the geographical extent of the impact, the duration and frequency, the irreversibility of the impact, and the magnitude of the alteration of the component. The application of these criteria is subjective and will require justification with quantitative and qualitative data from the environmental assessment.

The suggested criteria for assessing the significance of the impact on the environment will be as follows: vegetation physiognomy, protected area or species; regional or global importance of the resource (flora and fauna); relationship of the resource with local populations; and socioeconomic factors. The suggested criteria for assessing the geographical extent of the impact on the environment will be related to whether the impact is local, regional, or international; the duration of the impact will be linked to the temporal scale of the activity, whether it's temporary, short-term, long-term, or permanent; frequency, based on the rate at which the activity occurs or repeats over a certain period of time, whether it's intermittent, seasonal, or constant; risk, based on the likelihood of the impact occurring: unlikely or probable; reversibility (resilience), determined by whether the impact is irreversible or the resource recovery is short or long-term; and the magnitude of the alteration of the environmental component, whether it's small, moderate, or significant; along with a plan for continuous monitoring of the influence of mercury on the environment. This information will be used to propose measures for controlling and mitigating the impacts caused to the environment.

Review and strengthening of the regulatory and procedural framework

The review of regulations and formalization procedures is proposed, involving the revision of the regulatory framework and assessing the need for updates. Additionally, conducting a mining census and updating the registry to understand the current situation (number of miners involved in the sector) are also proposed.

Strategy for reducing mercury releases and exposure risks, and eliminating worst practices

Promoting the adoption of efficient technologies for gold extraction and processing without using mercury involves conducting research on market-available technologies that could be applicable to the context, transferring applicable technology knowledge to the community, and fostering partnerships with universities and research centers to include alternative mercury-free technology research. Additionally, providing education and information through the development of training programs based on lessons learned and successful cases.

Strategy for controlling illegal trade and the use of mercury

Strengthen the control and monitoring system for the trade and use of mercury, by planning and executing control operations in coordination with competent state institutions, to verify the use of mercury.

Strategy for reducing illegal mining extraction

By enhancing local capacities for preventing and combating illegal mining activities and promoting alternative productive endeavors to discourage mining development in sensitive areas, as well as implementing intervention and early warning plans in areas vulnerable to the expansion of illegal mining.

Food

Carnivorous fish species, being at the top of the food chain, tend to accumulate higher amounts of mercury in their bodies (Leung *et al*. 2017). Therefore, it is advisable to avoid consuming these species until mercury levels are deemed tolerable as food.

In this regard, it is proposed to directly engage with local communities, in collaboration with Funai, to raise their awareness about the issue of mercury and its consequences. It is possible to identify fish species that are safer for consumption; for example, herbivorous and/or detritivorous fish with lower mercury concentrations. However, the abundance of aquatic species with these characteristics is lower. Another crucial measure would be to implement alternative protein sources. In the Amazon region, there are numerous plant species with high protein content, such as (Shanley *et al*. 2012):

- Bacuri – *Platonia insignis* Mart. 100 grams (g) of pulp contains 1.9g of protein.
- Burití, – *Mauritia flexuosa* L.f. whose pulp contains 11% protein.
- Brazil nut – *Bertholletia excelsa* Bonpl. whose flour contains up to 46% protein. Walnut can contain 12 to 17 percent protein, which is half the content present in beef and twice the calories.
- Patauá – *Oneocarpus bataua* Mart. 100 g of oil contains 3.3 g of protein, slightly more than cow's milk.

This is an emergency strategy that could drastically reduce mercury intake in indigenous communities. However, these measures should be introduced gradually and in line with local traditions, as these resources are essential for their survival.

Socioeconomic

It's important to acknowledge the pivotal role played by indigenous communities like the Munduruku in safeguarding their vital spaces and assets for proper management, organization, delimitation, and utilization of their resources. To achieve this, it's crucial to establish a legal framework of recognition (territorial demarcation) and consultation concerning the use and exploitation of the territory by third parties or under dynamics that deviate from the community's traditional practices.

In this situation, three fundamental aspects come into play for the restoration of the territory and the affected communal structure due to the ecological and spatial deterioration caused by mining activities. The first aspect involves the detoxification of soils and rivers that impact the flora and, particularly, the consumable fauna (fish), which leads to the contamination of the inhabitants of the region. Secondly, there's the economic compensation arising from mining activities that directly affect the communities, preventing them from continuing their traditional productive practices. Lastly, there's the strengthening of the communal structure of the Munduruku people and other Amazonian indigenous and quilombola communities, who are socially impacted by recruitment, violence, and other strategies aimed at undermining the communal core in the presence of extractive fronts such as gold mining.

At the international level, it is important to highlight ecological consciousness and human solidarity in order to raise awareness about the consequences of consuming products or goods with proven ecological and social impacts, such as gold and other metals. Cultural degradation within communities should be averted by establishing a concrete state authority presence that safeguards indigenous populations like the Munduruku and other Pan-Amazonian peoples.

It's also important to control the resources derived from this activity, thereby preventing the excessive introduction of settlers associated with or near this type of occupation. This approach helps curb the development of semi-urban centers or villages within the Amazonian territory, which can carry substantial social and ecological impacts due high levels of pollution. It is also necessary to consider constant monitoring of decontamination and ecological restoration processes, where the self-organized participation of peoples plays a key role.

Conclusions

Among the practices employed in mining, one that has caused a significant impact is the use of mercury as an intrinsic component of the amalgamation process and subsequent gold recovery, an activity that has been carried out for decades within the Munduruku territory, systematically threatening human health and the environment. Impacts such as deforestation, loss of biodiversity, water body contamination, bioaccumulation in living organisms, and human health issues have been part of the reality of this area. Given this challenge, it is essential for state institutions to take a leading role and commit to constant monitoring, as well as establishing qualitative and quantitative indicators for tracking and assessment. This approach aims to propose strategies that encompass revising and strengthening the regulatory and procedural framework, controlling illegal mercury trade and usage, enhancing capacity, facilitating technology transfer, and promoting social and gender inclusion.

In recent years, the national governments that are signatories to the Minamata Convention have prepared "Initial Assessments of Minamata" reports to verify compliance with the obligations set forth in the protocol, which came into effect in 2017. The outcomes of these reports raise concerns, as it seems that governments and health ministries in various countries have not fully engaged in adhering to the signed agreements. Specifically, it appears that many nations have neither implemented the public health strategies (health data collection, healthcare professionals' training, and awareness initiatives through healthcare facilities) nor the strategies to prevent the exposure of vulnerable populations.

In this scenario, three fundamental approaches have been identified to comprehensively address the issue, focusing on both the ecological environment and the communities inhabiting it. The first involves the urgent implementation of river and soil decontamination processes, achieved through innovative solutions in collaboration with those communities and their environmental knowledge. Secondly, there's the economic restitution to communities affected by mining, as well as the promotion of traditional productive activities that provide viable survival alternatives, steering the population away from illegal dynamics driven by gold mining. Thirdly, it is necessary to formulate strategies to restore and enhance the communal structure of Amazonian indigenous and quilombola communities, encompassing effective state intervention to limit the expansion of colonization fronts and the infiltration of external actors into these communities' territories.

These processes undoubtedly should prominently involve community leaders. For this purpose, Law 1011 of 2023 (mentioned in the Legal Framework) introduces positive innovations, particularly by emphasizing the requirement to develop local strategies originating from communities and coordinating them with broader projects at the federal and national levels (Chapter III).

However, these are general recommendations, as the proposals should be adapted to the reality of the peoples inhabiting this territory. Clearly, the creation of an overarching intervention plan, studied on a broad scale, has its limitations, since each empirical reality presents ethnographic specificities that must be considered in developing practical solutions. In this regard, ethnobiology and ethnoecology – understood as the study of the knowledge, perceptions, and practices of human communities in relation to their surrounding environment – are indispensable analytical tools to ensure the effectiveness of any specific action plan.

Regarding the implementation of a health intervention plan, for instance, it's crucial to acknowledge the limits of medicine, based on therapeutic intervention techniques that take into account the anatomical and physiological dimensions of each organism. In other words, it's imperative to consider the meaning patients attribute to their illness experiences. Neglecting this dimension could undermine therapeutic effectiveness itself. Human experience is symbolically organized, and illness itself should be viewed as a culturally shaped experience. For a better understanding, the impact of mercury on health is depicted in Figure 3.

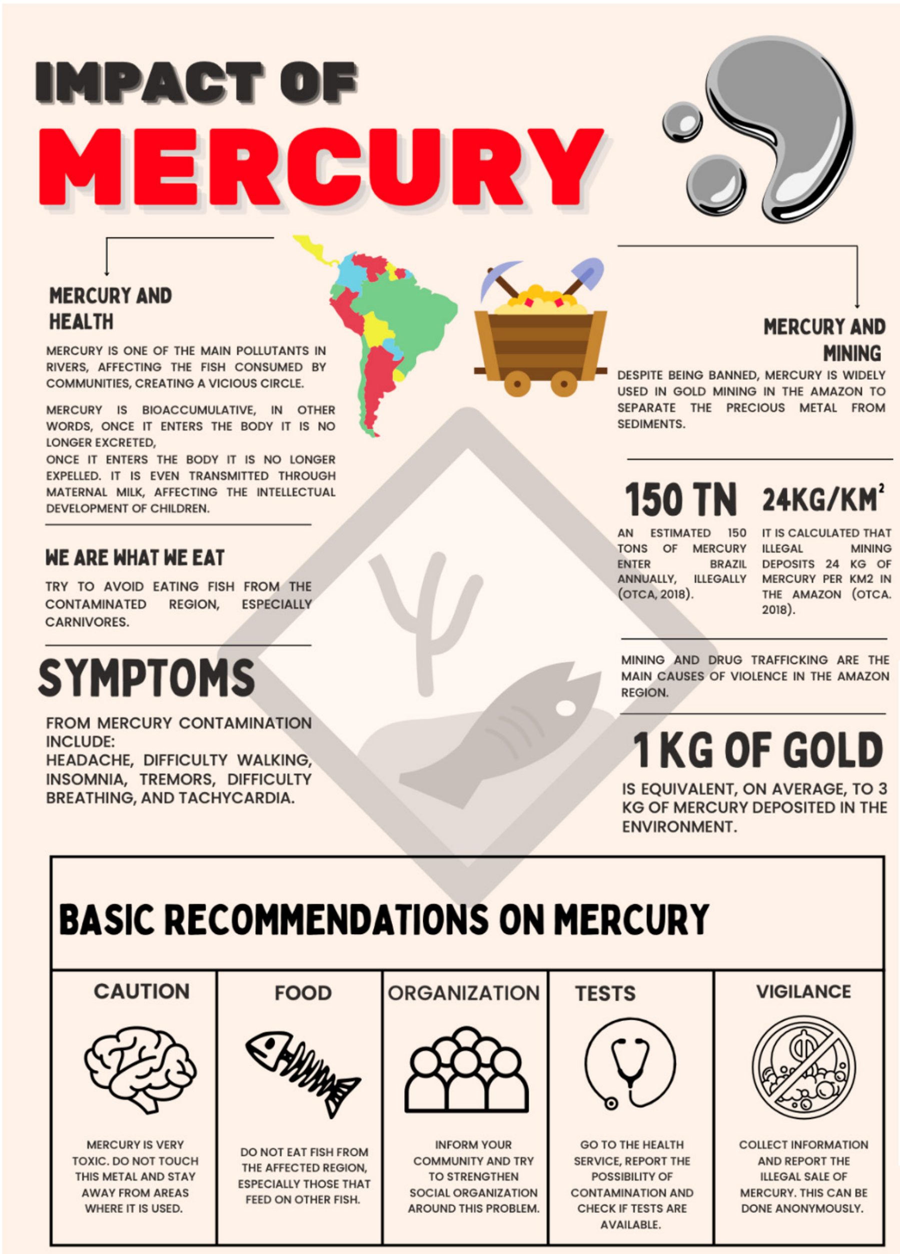


Figure 3 Infographic on mercury and mining.

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References

AB'SABER, A. **Os domínios de natureza no Brasil: potencialidades paisagísticas**. São Paulo: Ateliê Editorial, 2003.

ALCANTARA, M.L. **El dilema colonial de Brasil**: minería del oro y deforestación en la Amazonía. 2021. Disponível em: https://debatesindigenas.org/notas/137-dilema-colonial-de-brasil.html. Acesso em: 23 mar. 2023.

ASNER, Gregory P; TUPAYACHI, Raul. Accelerated losses of protected forests from gold mining in the Peruvian Amazon. **Environmental Research Letters**, [S.L.], v. 12, n. 9, p. 094004, 1 set. 2016. IOP Publishing. http://dx.doi.org/10.1088/1748-9326/aa7dab.

AZEVEDO, Lucas Silva; PESTANA, Inácio Abreu; NERY, Adriely Ferreira da Costa; BASTOS, Wanderley Rodrigues; SOUZA, Cristina Maria Magalhães. Mercury concentration in six fish guilds from a floodplain lake in western Amazonia: interaction between seasonality and feeding habits. **Ecological Indicators**, [S.L.], v. 111, p. 106056, abr. 2020. Elsevier BV. http://dx.doi.org/10.1016/j.ecolind.2019.106056.

BASTA, P. C, HACON, S. S. **Impacto do mercúrio na saúde do povo indígena Munduruku, na bacia de Tapajós**. Fundação Oswaldo Cruz (Fiocruz), 2020.

BASTA, Paulo Cesar; VIANA, Paulo Victor de Sousa; VASCONCELLOS, Ana Claudia Santiago de; PÉRISSÉ, André Reynaldo Santos; HOFER, Cristina Barroso; PAIVA, Natalia Santana; KEMPTON, Joseph William; ANDRADE, Daniel Ciampi de; OLIVEIRA, Rogério Adas Ayres de; ACHATZ, Rafaela Waddington. Mercury Exposure in Munduruku Indigenous Communities from Brazilian Amazon: methodological background and an overview of the principal results. **International Journal Of Environmental Research And Public Health**, [S.L.], v. 18, n. 17, p. 9222, 1 set. 2021. MDPI AG. http://dx.doi.org/10.3390/ijerph18179222.

BASU, Niladri; ABASS, Khaled; DIETZ, Rune; KRÜMMEL, Eva; RAUTIO, Arja; WEIHE, Pal. The impact of mercury contamination on human health in the Arctic: a state of the science review. **Science Of The Total Environment**, [S.L.], v. 831, p. 154793, jul. 2022. Elsevier BV. http://dx.doi.org/10.1016/j.scitotenv.2022.154793.

BAYÓN, A.; JAPHY, W. **Tundayme: El Despojo Minero Avanza**. 17 Dec. 2015. Disponível em: https://www.planv.com.ec/historias/sociedad/tundayme-el-despojo-minero-avanza. Acesso em: 21 mar. 2023.

BECKERS, Felix; RINKLEBE, Jörg. Cycling of mercury in the environment: sources, fate, and human health implications. **Critical Reviews In Environmental Science And Technology**, [S.L.], v. 47, n. 9, p. 693-794, 3 maio 2017. Informa UK Limited. http://dx.doi.org/10.1080/10643389.2017.1326277.

BRANCO, Vasco; ASCHNER, Michael; CARVALHO, Cristina. Neurotoxicity of mercury: an old issue with contemporary significance. **Neurotoxicity Of Metals**: Old Issues and New Developments, [S.L.], p. 239-262, 2021. Elsevier. http://dx.doi.org/10.1016/bs.ant.2021.01.001.

CAO, Yanbo; ZHU, Xinghua; LIU, Bangxiao; NAN, Yalin. A Qualitative Study of the Critical Conditions for the Initiation of Mine Waste Debris Flows. **Water**, [S.L.], v. 12, n. 6, p. 1536, 28 maio 2020. MDPI AG. http://dx.doi.org/10.3390/w12061536.

ROBLES, Paola Valentina Calderón. **Estado actual de la minería de oro en Ecuador**: gran minería vs minería artesanal. 2021. 58 f. Dissertação (Mestrado) - Curso de Engenharia de Recursos Naturais, Universidad Politécnica de Catalunya, Barcelona, 2021.

COSTA JUNIOR, José Maria Farah; LIMA, Abner Ariel da Silva; RODRIGUES JUNIOR, Dario; KHOURY, Eliana Dirce Torres; SOUZA, Givago da Silva; SILVEIRA, Luiz Carlos de Lima; PINHEIRO, Maria da Conceição Nascimento. Manifestações emocionais e motoras de ribeirinhos expostos ao mercúrio na Amazônia. **Revista Brasileira de Epidemiologia**, [S.L.], v. 20, n. 2, p. 212-224, jun. 2017. FapUNIFESP (SciELO). http://dx.doi.org/10.1590/1980-5497201700020003.

COULTER, Margaret A.. Minamata Convention on Mercury. **International Legal Materials**, [S.L.], v. 55, n. 3, p. 582-616, jun. 2016. Cambridge University Press (CUP). http://dx.doi.org/10.5305/intelegamate.55.3.0582.

COUTO, Thiago B. A.; MESSAGER, Mathis L.; OLDEN, Julian D.. Safeguarding migratory fish via strategic planning of future small hydropower in Brazil. **Nature Sustainability**, [S.L.], v. 4, n. 5, p. 409-416, 11 jan. 2021. Springer Science and Business Media LLC. http://dx.doi.org/10.1038/s41893-020-00665-4.

RESPO-LOPEZ, Maria Elena; AUGUSTO-OLIVEIRA, Marcus; LOPES-ARAðJO, Amanda; SANTOS-SACRAMENTO, Leticia; TAKEDA, Priscila Yuki; MACCHI, Barbarella de Matos; NASCIMENTO, José Luiz Martins do; MAIA, Cristiane S.F.; LIMA, Rafael R.; ARRIFANO, Gabriela P.. Mercury: what can we learn from the amazon?. **Environment International**, [S.L.], v. 146, p. 106223, jan. 2021. Elsevier BV. http://dx.doi.org/10.1016/j.envint.2020.106223

DANTAS, J, E. **A morte dos rios**. 01 Dez. 2021. Disponível em: https://www.greenpeace.org/brasil/blog/a-morte-dos-rios/. Acesso em: 25 mar. 2023.

SILVA, Stephani Ferreira da *et al*. Seasonal variation of mercury in commercial fishes of the Amazon Triple Frontier, Western Amazon Basin. **Ecological Indicators**, [S.L.], v. 106, p. 105549, nov. 2019. Elsevier BV. http://dx.doi.org/10.1016/j.ecolind.2019.105549.

DOS SANTOS-LIMA, Cassio *et al*. Neuropsychological Effects of Mercury Exposure in Children and Adolescents of the Amazon Region, Brazil. **Neurotoxicology**, [S.L.], v. 79, p. 48-57, jul. 2020. Elsevier BV. http://dx.doi.org/10.1016/j.neuro.2020.04.004.

EL COMERCIO: LIMA, PERÚ. 2020. **La Actividad Minera Ilegal en el Norte de Esmeraldas se realiza en 52 Frentes**. 2020. Disponível em: https://www.elcomercio.com/actualidad/ecuador/mineria-ilegal-intensa-prohibiciones-esmeraldas.html. Acesso em 21 mar. 2023.

EISENBERG, L., KLEINMAN, A. Clinical social Science. *In*: **The relevance of social science for medicine**. 1981. p. 1-23.

FARIA, Marcília de Araújo Medrado *et al*. Mercuralismo metálico crônico ocupacional. **Revista de Saúde Pública**, [S.L.], v. 37, n. 1, p. 116-127, fev. 2003. FapUNIFESP (SciELO). http://dx.doi.org/10.1590/s0034-89102003000100017.

FERRANTE, Lucas; FEARNSIDE, Philip M. Brazil's new president and 'ruralists' threaten Amazonia's environment, traditional peoples and the global climate. **Environmental Conservation**, [S.L.], v. 46, n. 4, p. 261-263, 24 jul. 2019. Cambridge University Press (CUP). http://dx.doi.org/10.1017/s0376892919000213.

FILLION, Myriam; LEMIRE, Mélanie; PHILIBERT, Aline; FRENETTE, Benoît; WEILER, Hope Alberta; DEGUIRE, Jason Robert; GUIMARÃES, Jean Remy Davée; LARRIBE, Fabrice; BARBOSA JUNIOR, Fernando; MERGLER, Donna. Toxic risks and nutritional benefits of traditional diet on near visual contrast sensitivity and color vision in the Brazilian Amazon. **Neurotoxicology**, [S.L.], v. 37, p. 173-181, jul. 2013. Elsevier BV. http://dx.doi.org/10.1016/j.neuro.2013.04.010.

GERSON, Jacqueline R. *et al*. Amazon forests capture high levels of atmospheric mercury pollution from artisanal gold mining. **Nature Communications**, [S.L.], v. 13, n. 1, p. 559, 28 jan. 2022. Springer Science and Business Media LLC. http://dx.doi.org/10.1038/s41467-022-27997-3.

GLOBAL INITIATIVE AGAINST TRANSNATIONAL ORGANIZED CRIME. **Organized Crime and Illegally Mined Gold in Latin America**. 2016. Disponível em: https://globalinitiative.net/wp-content/uploads/2016/03/Organized-Crime- and-Illegally-Mined-Gold-in-Latin-America.pdf. Acesso em: 23 mar. 2023.

GRANDJEAN, Philippe *et al*. Adverse Effects of Methylmercury: environmental health research implications. **Environmental Health Perspectives**, [S.L.], v. 118, n. 8, p. 1137-1145, ago. 2010. Environmental Health Perspectives. http://dx.doi.org/10.1289/ehp.0901757.

GREENPEACE BRASIL. 2020. **Em meio à Covid, 72% do garimpo na Amazônia foi em áreas "protegidas"**. 25 Jun. 2020. Disponível em: https://www.greenpeace.org/brasil/blog/em-meio-a-covid-72- do-garimpo-na-amazonia-foi-em-areas-protegidas/

HA, Eunhee *et al*. Current progress on understanding the impact of mercury on human health. **Environmental Research**, [S.L.], v. 152, p. 419-433, jan. 2017. Elsevier BV. http://dx.doi.org/10.1016/j.envres.2016.06.042.

HECK, C. **La realidad de la minería ilegal en países amazónicos**. Sociedad Peruana de Derecho Ambiental, 2014.

IGARAPE INSTITUTE. **Terra Indígena Munduruku**. 2020. Disponível em: https://terrasindigenas.org.br/pt-br/terras-indigenas/3770. Acesso em: 21 mar. 2023.

INDAGA - OBSERVATORIO NACIONAL DE POLÍTICA CRIMINAL. **La minería ilegal en la Amazonía Peruana. Amazonía y Crimen**. Ministerio de Justicia y Derechos Humanos del Perú, 2021.

INPE - INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS. São José dos Campos: 2021. Disponível em: https://www.gov.br/inpe/pt-br. Acesso em: 21 mar. 2023.

LACERDA, Eliza Maria da Costa Brito *et al*. Comparison of Visual Functions of Two Amazonian Populations: possible consequences of different mercury exposure. **Frontiers In Neuroscience**, [S.L.], v. 13, p. 1, 21 jan. 2020. Frontiers Media SA. http://dx.doi.org/10.3389/fnins.2019.01428.

LEUNG, H. M. *et al*. Monitoring and assessment of heavy metal contamination in a constructed wetland in Shaoguan (Guangdong Province, China): bioaccumulation of pb, zn, cu and cd in aquatic and terrestrial components. **Environmental Science And Pollution Research**, [S.L.], v. 24, n. 10, p. 9079-9088, 10 maio 2016. Springer Science and Business Media LLC. http://dx.doi.org/10.1007/s11356-016-6756-4.

MAHAFFEY, K.R. Methylmercury: a new look at the risks**. Public Health Reports**. v. 114, n. 5, p. 396–399, 1999.

MAPBIOMAS. **Mapeo Anual de Cobertura y Uso del Suelo de la Amazonía**. 2020. Disponível em: https://amazonia.mapbiomas.org/

MARQUES, Rejane C. *et al*. Traditional living in the Amazon: extended breastfeeding, fish consumption, mercury exposure and neurodevelopment. **Annals Of Human Biology**, [S.L.], v. 43, n. 4, p. 360-370, 21 jun. 2016. Informa UK Limited. http://dx.doi.org/10.1080/03014460.2016.1189962.

MINISTERIO DEL AMBIENTE DE PERÚ - MINAM. **Aprende a prevenir los efectos del mercurio**. 2016. Disponível em: https://repositoriodigital.minam.gob.pe/bitstream/handle/123456789/92/BIV01760.pdf?sequence=1&isAllowed=y. Acesso em: 21 mar. 2023.

NATIONAL RESEARCH COUNCIL (US). **Toxicological Effects of Methylmercury**. Washington (DC): National Academies Press (United States), 2000.

NEVES, E.G. **Arqueologia da Amazônia**. Rio de Janeiro: Jorge Zahar, 2006.

ORGANIZACIÓN DEL TRATADO DE COOPERACIÓN AMAZÓNICA - OTCA. **Informe Análisis de Diagnóstico Transfronterizo Regional de la Cuenca Amazónica**. 2018. Disponível em: http://otca.org/project/analisis-diagnostico- transfronterizo-regional-de-la-cuenca-amazonica-adt/.

OLIVEIRA, Rogério Adas Ayres de *et al*. Neurological Impacts of Chronic Methylmercury Exposure in Munduruku Indigenous Adults: somatosensory, motor, and cognitive abnormalities. **International Journal Of Environmental Research And Public Health**, [S.L.], v. 18, n. 19, p. 10270, 29 set. 2021. MDPI AG. http://dx.doi.org/10.3390/ijerph181910270.

PADURARU, Emanuela *et al*. Comprehensive Review Regarding Mercury Poisoning and Its Complex Involvement in Alzheimer's Disease. **International Journal Of Molecular Sciences**, [S.L.], v. 23, n. 4, p. 1992, 11 fev. 2022. MDPI AG. http://dx.doi.org/10.3390/ijms23041992.

PAIVA, Paula Fernanda Pinheiro Ribeiro *et al*. Deforestation in protect areas in the Amazon: a threat to biodiversity. **Biodiversity And Conservation**, [S.L.], v. 29, n. 1, p. 19-38, 16 out. 2019. Springer Science and Business Media LLC. http://dx.doi.org/10.1007/s10531-019-01867-9.

QUARANTA, Ivo *et al*. La trasformazione dell'esperienza. Antropologia e processi di cura. **Antropologia e Teatro. Rivista di Studi**, [S.L.], p. 3, 17 out. 2012. Antropologia e Teatro. Rivista di Studi. http://dx.doi.org/10.6092/ISSN.2039-2281/3187.

RICE, Kevin M. *et al*. Environmental Mercury and Its Toxic Effects. **Journal Of Preventive Medicine & Public Health**, [S.L.], v. 47, n. 2, p. 74-83, 31 mar. 2014. Korean Society for Preventive Medicine. http://dx.doi.org/10.3961/jpmph.2014.47.2.74.

RISSO, M.; SEKULA, J.; BRASIL, L. *et al.* **Impacts on Yanomami and Munduruku Populations**. [s.l.]: Igarape Institute, 2021. Disponível em: https://www.jstor.org/stable/resrep30586.11. Acesso em 23 mar. 2023

RORATO, Ana C *et al*. Brazilian amazon indigenous peoples threatened by mining bill. **Environmental Research Letters**, [S.L.], v. 15, n. 10, p. 1040a3, 1 out. 2020. IOP Publishing. http://dx.doi.org/10.1088/1748-9326/abb428.

ROY, Bitty A.; ZORRILLA, Martin; ENDARA, Lorena; THOMAS, Dan C.; VANDEGRIFT, Roo; RUBENSTEIN, Jesse M.; POLICHA, Tobias; RÍOS-TOUMA, Blanca; READ, Morley. New Mining Concessions Could Severely Decrease Biodiversity and Ecosystem Services in Ecuador. **Tropical Conservation Science**, [S.L.], v. 11, p. 194008291878042, jan. 2018. SAGE Publications. http://dx.doi.org/10.1177/1940082918780427.

SALAZAR, J. Brasil: **Minería ilegal creció un 495% en la última década**. 2021. Disponível em: https://camiper.com/tiempominero-noticias-en-mineria-para-el-peru-y-el-mundo/brasil-mineria-ilegal-crecio-un- 495-en-la-ultima-decada/. Acesso em 21 mar. 2023.

SANTOS-SACRAMENTO, Leticia *et al*. Human neurotoxicity of mercury in the Amazon: a scoping review with insights and critical considerations. **Ecotoxicology And Environmental Safety**, [S.L.], v. 208, p. 111686, jan. 2021. Elsevier BV. http://dx.doi.org/10.1016/j.ecoenv.2020.111686.

SCOPEL, D.; DIAS-SCOPEL, R.; LANGDON, E. J. Community Health Workers in Central-Southern Amazonia: Na Ethnographic Account of the Munduruku People of Kwatá Laranjal Indigenous Land. **Journal of the Society for The Anthropology of Lowland South America,** [S.L], v. 18, n. 1, p. 72-91, 2022.

SCOPEL, Daniel *et al*. A cosmografia Munduruku em movimento: saúde, território e estratégias de sobrevivência na amazônia brasileira. **Boletim do Museu Paraense Emílio Goeldi. Ciências Humanas**, [S.L.], v. 13, n. 1, p. 89-108, abr. 2018. FapUNIFESP (SciELO). http://dx.doi.org/10.1590/1981.81222018000100005.

SENADO FEDERAL. **Projeto de Lei n° 1011**, Institui a Política Nacional de Prevenção da Exposição ao Mercúrio no país e dá outras providências. 2023.

SHANLEY, P. CYMEYS, M. SERRA, M. & MEDINA, G. **Frutales y plantas útiles en la vida amazónica**. 2 ed. [S.L]: Organización de las Naciones Unidas para la Alimentación y la Agricultura, Centro para la investigación Forestal Internacional y Pueblos y Plantas Internacional, 2012. ISBN 978-92-5-307007-7

SOHN, Hassan. **Desenvolvimento do Plano de Ação Nacional para a Mineração Artesanal e de Pequena Escala de Ouro no Brasil**: avançando para a extração de ouro sem mercúrio. 2022. Disponível em: https://www.gov.br/mme/pt-br/assuntos/noticias/mme-lanca-projeto-para-plano-de-acao-nacional-para-extracao-de-ouro-sem-mercurio/DesenvolvimentodoPlanodeAo.pdf. Acesso em: 17 jun. 2023.

SONTER, Laura J. *et al*. Mining drives extensive deforestation in the Brazilian Amazon. **Nature Communications**, [S.L.], v. 8, n. 1, p. 1, 18 out. 2017. Springer Science and Business Media LLC. http://dx.doi.org/10.1038/s41467-017-00557-w.

TARRAS-WAHLBERG, N. Håkan *et al*. Environmental Impact of Small-scale and Artisanal Gold Mining in Southern Ecuador. **Ambio**: A Journal of the Human Environment, [S.L.], v. 29, n. 8, p. 484-491, dez. 2000. Royal Swedish Academy of Sciences. http://dx.doi.org/10.1579/0044-7447-29.8.484.

UNITED STATES AGENCY INTERNATIONAL DEVELOPMENT - USAID. **Minería aurífera ilegal**. 2022. Disponível em: https://www.usaid.gov/peru/our-work/illegal-gold-mining. Acesso em: 21 mar. 2023.

UN ENVIRONMENT. **Global Mercury Assessment**. 2018. Disponível em: https://www.unep.org/resources/publication/global-mercury-assessment-2018?_ga=2.227987165.1902135672.1680109127-65431850.1679843779. Acesso em 29 mar. 2023.

U.S. ENVIRONMENTAL PROTECTION AGENCY. **Methylmercury** (MeHg). 2021. (CASRN 22967-92-6).

WARK, J., WYLLYS, J. **La resistencia Munduruku en Brasil evidencia la perversidad del sistema**. 2022. Disponível em: https://www.opendemocracy.net/es/lucha-munduruku-evidencia-perversidad-sistema-brasil/. Acesso em 23 mar. 2023.

WALDRON, H., A., Did the Mad hatter have mercury poisoning? **British Medical Journa**l, v. 287, p. 1961, 24-31 dec. 1983.

WEBB, Jena; MAINVILLE, Nicolas; MERGLER, Donna; LUCOTTE, Marc; BETANCOURT, Oscar; DAVIDSON, Robert; CUEVA, Edwin; QUIZHPE, Edy. Mercury in Fish-eating Communities of the Andean Amazon, Napo River Valley, Ecuador. **Ecohealth**, [S.L.], v. 1, n. 2, p. 59-71, nov. 2004. Springer Science and Business Media LLC. http://dx.doi.org/10.1007/s10393-004-0063-0.

YE, Byeong-Jin *et al*. Evaluation of mercury exposure level, clinical diagnosis and treatment for mercury intoxication. **Annals Of Occupational And Environmental Medicine**, [S.L.], v. 28, n. 1, p. 1-8, 22 jan. 2016. Korean Society of Occupational and Environmental Medicine. http://dx.doi.org/10.1186/s40557-015-0086-8.

TEIXEIRA, Francisco B. *et al*. Exposure to Inorganic Mercury Causes Oxidative Stress, Cell Death, and Functional Deficits in the Motor Cortex. **Frontiers In Molecular Neuroscience**, [S.L.], v. 11, p. 125, 15 maio 2018. Frontiers Media SA. http://dx.doi.org/10.3389/fnmol.2018.00125.

WHO. **Guia passo a passo para o desenvolvimento de uma estratégia de saúde pública para a extração de ouro artesanal e em pequena escala no âmbito da Convenção de Minamata sobre o Mercúrio**. 2021. Disponível em: https://apps.who.int/iris/bitstream/handle/10665/340411/9789240023246-por.pdf. Acesso em 25 mar. 2023.

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