Guimaraes, JRD. 2020. Mercury in the Amazon: Problem or opportunity? A commentary on 30 years of research on the subject. *Elem Sci Anth*, 8: XX. DOI: https://doi.org/10.1525/elementa.032

COMMENTARY

Mercury in the Amazon: Problem or opportunity? A commentary on 30 years of research on the subject

Jean R. D. Guimaraes[1,*]

The aim of this text is to present a critical overview of Hg research in the Amazon along the last 30 years, discussing some of the lessons learned and the unique challenges that the complex Amazonian environment can place to researchers working on mercury. The description provided here is based on our long-term research with mercury in this tropical rainforest environment and may be particularly relevant for those initiating mercury studies in the tropics.

Keywords: Gold mining, Methylmercury, Soil erosion, Human exposure, Environmental management

Introduction

Mercury is indeed a fascinating element. Besides being a metal, it is also a planet, an alchemic symbol, a god, and the first metal used by our humanoid ancestors, as a red pigment in cave paintings, many thousands of years ago.

Hg has a series of unique properties. Its metallic form, Hg^0, is liquid and volatile at room temperature and forms amalgams with many other metals including gold and silver. When released to the atmosphere, Hg vapor (Hg^0) can travel for months before being oxidized to Hg^{2+} and be washed down by rain to land and water surfaces. There it can be reduced and released again to the atmosphere, cycling in the environment among the atmosphere, ocean, and land for centuries to millennia (Selin, 2009). Volatility makes Hg a global issue, and not surprisingly, the main international conference on Hg in the environment is called ICMGP, an acronym for the International Conference on Mercury as a Global pollutant, held every 2 years since its first edition in Gavle, Sweden, 1990.

The toxic effects of Hg vapor and Hg salts are known since antiquity, but it was only in the 1950s that the dramatic Minamata accident revealed the toxicity of monomethyl-Hg (MeHg), classified today as one of the six more toxic known molecules and a potent neurotoxin. The accident was caused by a large and inadvertent MeHg production during polyvinyl chloride production in the Chisso Co. chemical factory where Hg was used as a catalyzer and MeHg-laden effluents contaminated the Minamata Bay. There it exhibited very strong bioaccumulation and biomagnification along the marine food chain, leading to hundreds of serious intoxications, teratogenic effects (**Figure 1**), and an estimated and still disputed toll of approximately 1,800 casualties (Ministry of the Environment, Government of Japan, 2020). In 1969, Swedish scientists showed that MeHg can be formed from Hg^{2+} by natural microbiological activity in sediments (Jensen and Jernelov, 1969), triggering a worldwide research effort on the presence of Hg and MeHg in aquatic systems and their food chains and the consequent human exposures due to fish intake (Forstner and Wittman, 1979). It became clear that inorganic Hg releases in water bodies could result in exposure and neurotoxic effects at great distances from the original release points, depending on the presence or absence of favorable conditions for MeHg formation along the waterway and on food habits of the local populations. Clearly, features of the Hg environmental cycle other than volatilization and atmospheric transport contribute to the global scale of Hg distribution and of the concern with its effects on humans and other species.

At this point, the reader who is not familiar with Hg may have realized that tackling environmental Hg issues with a minimum of effectiveness requires the participation of a number of disciplines, of which the most obvious so far are chemistry, analytical chemistry, atmospheric sciences, hydrology, microbiology, ecology, and toxicology. If human exposure is a concern, add health sciences and social sciences such as sociology and/or anthropology to the discipline basket. We have all been trained in a strongly disciplinary and fragmentary setting, so gathering all those professionals around issues that no single discipline is capable of solving is a challenge in itself and requires a level of humility, flexibility, and solidarity that not many scientists are capable of.

Maybe because of that, coordinated research projects on Hg have historically been proposed only in response to relevant or drastic socioeconomic pressures, such as the

[1] Instituto de Biofisica Carlos Chagas Filho, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil

* Corresponding author:
Email: jeanrdg@biof.ufrj.br

Figure 1. A victim of Minamata disease. In this 1973 photo, a woman holds a victim of "Minamata disease," or mercury poisoning, in Minamata, Japan. The girl has a malformed hand, like many victims of the disease who suffer from physical deformities among other symptoms. Credit: AP Photo, File. DOI: https://doi.org/10.1525/elementa.032.f1

Minamata accident and its long-lasting human toll, the Iraq and Guatemala Hg accidents, involving diversion to human consumption of wheat seeds that were planned for agricultural use and were treated with organo-mercurial fungicides, with hundreds of casualties, malformations, and other health sequels (Bakir et al., 1973). Minamata remains a strong symbol of environmental risks related to Hg and of public health costs caused by industrial activities. An international convention to reduce Hg use and emission was proposed in 2013 in Kumamoto, Japan, the main town of the Kyushu island where Minamata is located. It was signed by 128 countries including Brazil and came into effect in 2017 (Gustin et al., 2016; Hsu-Kim et al., 2018).

Sweden became a leading country in Hg research in the 1980s and 1990s due to two such important environmental issues involving Hg. One, the agricultural use of seeds treated with organo-mercurial fungicides (Borg et al., 1965; Ackefors, 1971), which led to a repetition of the silent spring described by Rachel Carson in her eponymous book in 1962, caused by DDT, which killed the birds that fed on contaminated insects. In Sweden, mass bird mortality was caused by their direct foraging of MeHg-treated seeds. The other issue was the extensive development of paper mills, which benefited from the abundant local timber supply but required the installation of many chloro-soda factories that contaminated thousands of lakes with inorganic Hg (Björklund et al., 1984). To this day, fish consumption bans or catch-and-release advisories are issued for most lakes in Sweden and North America due to high MeHg in fish, among other pollutants (Krabbenhoft and Rickert, 2018).

Early Hg studies in the Amazon: Artisanal gold mine spikes the interest for Hg research

In the case of Amazonia, the awakening of Brazilian geochemical scientists to Hg issues was a long and winding process, triggered by a massive gold rush following the steep rise of gold prices in international markets in the early 1980s. Artisanal miners used metallic Hg to amalgamate gold from sediments of the Madeira and Tapajos Rivers, among others, and some important primary gold deposits such as in Serra Pelada. After separating the heavier fraction of the sediments in sluice boxes, metallic Hg is added to the concentrate and mixed, and the resulting amalgam is burnt under a gas torch in open air to force Hg volatilization and recover gold.

Until the gold rush, Hg in the environment had never been a relevant issue in Brazil. Not surprisingly, analytical facilities and trained personnel for Hg determination in environmental samples were simply not available, and the first efforts in this direction started essentially from scratch. But the research facilities of the country were—and still are—concentrated in the southeastern region, thousands of miles from the gold rush sites. Travel costs, lack of basic infrastructure, and frequent violence outbursts in the gold mining areas all conspired against the involvement of local scientists.

It took a combination of improbable factors to change this. First, the extraordinary series of images from the Serra Pelada gold field miners by the Brazilian photographer Sebastiao Salgado, produced in 1986. This series shows thousands of miners climbing up the steep slope of a giant muddy pit of up to 200 m depth, with soil sacks on their

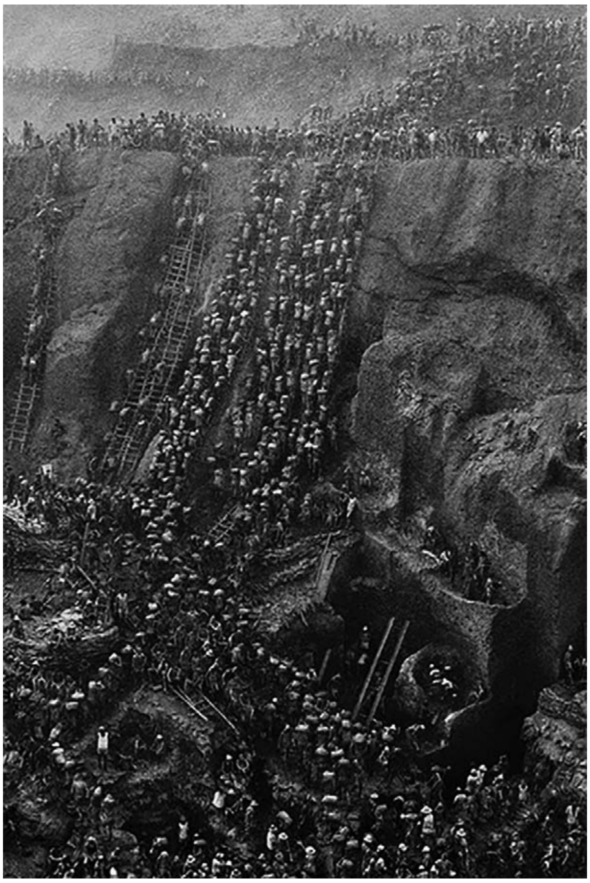

Figure 2. Serra Pelada gold mine in 1986. Miners climb the mine pit cliff with sacs of soil that will be extracted for gold at the surface of the pit. Photo © Sebastiao Salgado. DOI: https://doi.org/10.1525/elementa.032.f2

back, so numerous that at first sight one thinks of ants, not humans. At the peak of its activity, nearly 80,000 persons, mostly mine workers, lived in the Serra Pelada mining area (Armin, 1995). Salgado's mind-bogging and eye-catching images (example in **Figure 2**) motivated the visit of a BBC team that made a documentary on this and other gold fields in the Amazon, bringing the subject to international attention.

Coincidentally or not, some decades earlier the personal courage and talent of an American photographer, Eugene W. Smith, who documented the Minamata accident, was effective to attract the attention of the media and general public to the issue of Hg contamination. His iconic image of a Japanese mother bathing her boy affected with cerebral palsy is forever associated with the accident itself and more generally to the risks of environmental pollution by industries.

The first scientific studies on Hg in the Amazon

Among the Brazilian journalists of the BBC team, Junea Mallas kept documenting gold mining in the Amazon and contacted scientists from different Brazilian research institutions, trying to motivate them to study the environmental impacts of Hg releases by gold mining. She succeeded in bringing Dr. Martinelli, from Sao Paulo University in the state of Sao Paulo to the Madeira River gold mining areas (**Figure 3**), which resulted in the first publication with data on Hg in the Amazon environment, in Madeira River sediments and biota (Martinelli et al., 1988). At the same time, Prof. Ary Ott, the dean of the Federal University of Rondonia, situated in Porto Velho, on the Madeira River, witnessed daily the hundreds of dredges sucking river sediments to extract gold by amalgamation, right in front of the city. Like Ms. Mallas, he was also trying hard to contact research teams to start projects on Hg in the region. He managed to recruit Prof. Wolfgang Pfeiffer, from the Federal University of Rio de Janeiro, and his then PhD student Olaf Malm to Porto Velho, as well as Prof. Luiz Drude de Lacerda, from Universidade Federal Fluminense, state of Rio de Janeiro, starting a long-lasting collaboration.

The first concern of this small team was to implement reliable total Hg measurements in sediments and fish, adapting a cold vapor generator to an existing atomic absorption spectrophotometer. Complete method standardization and good performance in intercomparison exercises and in analysis of standard reference materials were achieved after around 2 years, the same time interval that teams from other countries took to reach similar goals, building on a similar previous experience with other heavy metals. In parallel, long field participatory observations in gold fields allowed the team to estimate that approximately 1 kg of metallic Hg was required for the extraction of a kilo of gold and that around half of the added Hg was lost in sediments and soils, the other half being volatilized during amalgam burning (Pfeiffer and Lacerda, 1988; Lacerda et al., 1989; Malm et al., 1990). A rudimentary but reliable method for measurements of Hg in air was also set up, based on battery-operated vacuum pumps and air bubbling in acid $KMnO4$ solutions, leading to breaking a lot of glassware in the field but also to quantifying the huge occupational exposures during amalgam burning and the environmental exposure by inhalation around the burning sites. Combined with soil and vegetation Hg data at increasing distances from the burning site, these data showed that amalgam burning increased Hg levels in soils up to a distance of approximately 500 m from the source. These custom-made but efficient paraphernalia were adequate to measure high atmospheric Hg levels, but it took a further decade before reliable measurements of background air and water Hg were made in Brazil, by researchers from the University of Campinas, in the state of Sao Paulo (Fostier et al., 2000; Magarelli and Fostier, 2005; Jardim et al., 2010). Later, methods for THg measurement in urine were also standardized and used to monitor occupational exposure to Hg vapor in dredges and gold shops (Malm et al., 1995, 1998). The challenge of measuring air Hg in the field using glass bubblers was a strong push to start using passive biomonitors such as the epiphytic bromeliad *Tillandsia usneoides*, which could be deployed simultaneously in a number of sites to map atmospheric Hg distribution (Fonseca et al., 2007). This was applied successfully to map environmental and occupational exposure in a chloro-

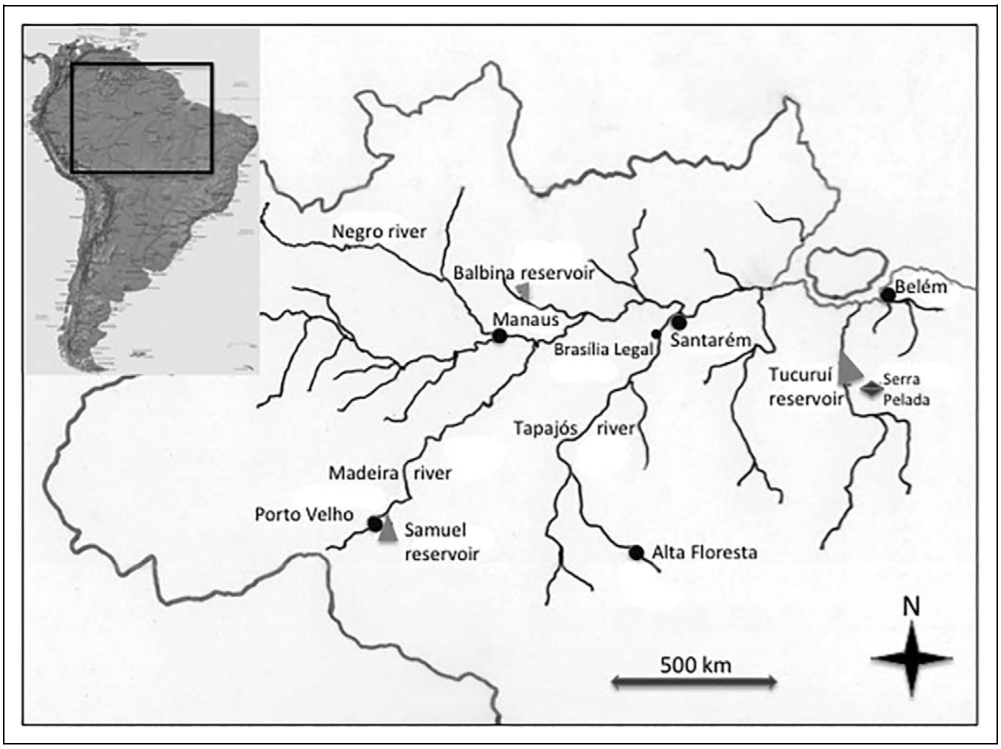

Figure 3. Schematic Brazilian Amazon map showing the riversheds, reservoirs, and cities or villages mentioned in the text. Note that reservoirs built in the last 20 years are not shown and that the river network of the basin has been considerably simplified for clarity (map). DOI: https://doi.org/10.1525/elementa.032.f3

soda factory in Rio de Janeiro (Calazans and Malm, 1997) and also in Alta Floresta, an Amazonian gold trade center city, to trace the dispersion of Hg vapor emitted by gold shops (Malm et al., 1998).

Amalgam burning in the field and in the cities

Gold miners sold their burnt amalgams to the myriad of gold shops that opened in the main towns near gold mining areas, such as Porto Velho and Itaituba. In these shops, the amalgams were burnt again and further purified in rudimentary fume hoods with no Hg scavenging or retention, exposing the unsuspecting neighbors to very high air Hg levels (Malm et al., 1995). A decade later, when the gold mining activity had plunged and most gold shops had closed and been converted into regular homes or small businesses, air Hg levels in these dwellings were still a matter of concern (Bastos et al., 2004). Pfeiffer and Malm also developed an efficient retort for recovery of Hg from amalgams during burning and made extensive field demonstrations of the retort use to miners in different gold fields. However cheap, portable, and efficient, the retorts were never widely adopted by miners. Good intentions do not necessarily result in good results, and the episode demonstrates how multidisciplinarity can be essential for a successful intervention. An anthropologist would have warned that amalgam burning in a closed and opaque vessel deprives the miners of a magic and crucial moment that tells this little community, gathered in expectation around the heated crucible, if their painstaking efforts of the last weeks or months have been rewarding or not. Many years later, Kiefer et al. (2015) designed transparent and cheap glass retorts to bypass this limitation of the metal retorts.

The evolution of research from sediments to biota

The next step was to evaluate Hg in fish and in riverine communities that rely heavily on fish as a protein source. The data from the Madeira River showed high human exposure to Hg, with hair THg in the range of 1.1–73 μg/g (Malm et al., 1995), with no clear distinction between sites upstream or downstream gold mining areas, or between data obtained during the gold rush and those obtained in subsequent years. The same applied to sediments and fish THg (Malm et al., 1997).

However, no data on Hg in any kind of environmental matrix were available for the pre-gold rush period, as studies on Hg started some time after the onset of the rush itself. In those years, the support for research in Brazil was very scarce—but still better than presently—and most field campaigns for Hg studies were done in collaboration with visiting—and financing—foreign scientists, from Japan, Germany, Sweden, and England, among others. Data were therefore inevitably scattered in time and space and did not show a clear fingerprint of gold mining Hg emissions in the Madeira or Tapajos River sediments or fish. Researchers from the Instituto Nacional de Pesquisas na Amazonia in Manaus showed that the highest THg levels in fish and human hair were found in the blackwater Negro River watershed, untouched by gold mining (Silva-Forsberg et al., 1999), adding a further layer of complexity to the issue.

Hg sources in the Amazon, a long debate

The contribution of gold mining to Hg levels in the Amazon environment is a matter of debate since the late 1980s. Biomass burning has been suggested as a relevant Hg source (Veiga et al., 1994) as well as the huge Hg emissions during the Spanish colonial silver mining period. Pfeiffer and Lacerda (1988) estimated that Hg emission to the environment during the gold rush was approximately 100 tons/years, during approximately 10 years, while the total Spanish colonial Hg emissions due to silver and gold mining from 1550 to 1930 are estimated to have been of approximately 260,000 tons (Lacerda, 1997). Streets et al. (2019) estimate a total south American anthropogenic Hg emission of 222,600 tons between 1510 and 2010 but suggest that less than 5% of the Hg emissions during the Spanish Colonial period reached the atmosphere.

Despite the spatiotemporal scattering of Hg data in the Amazon and the complexity and dimension of the studied watersheds, most early publications on Hg in the Amazon assumed that gold mining Hg emissions explained the presence of Hg in the local environment, simply because it seemed logical and because other sources of Hg had not yet been demonstrated and quantified. Another relevant reason for that is that, even before the first sample was taken and analyzed for Hg, a societal verdict had already been made on gold mining, and the media reverberated the mantra: Gold miners are illegal, violent, ignorant, and stubborn; they smuggle gold, drugs, and weapons; exploit prostitution; and, last but not least, pollute the ecosystems with Hg. However sketchy, inexact, and unfair, this narrative still prevails in the mind of the general public and, worse, of many scientists. I remember my surprise when visiting a gold mining field for the first time in 1991 and realizing that it was more organized, safe, and clean than most Amazonian towns I had visited so far. The take-home message here is that to understand a complex process such as artisanal gold mining, or any other, you must go to the field and witness as much as possible, as long as possible and talk with all relevant social actors you may find. Stay long enough or return often enough, so that people stop saying what they think you want to hear because they know you will see enough to realize by yourself whether their narrative is true or not. Media can give an idea of what is happening but are rarely exempt from conflicts of interest. Sometimes, these are expressed by simply not mentioning some subjects, perceived as inadequate for the main sponsors' agenda of the moment.

Communicating an invisible risk

The issue of communicating data on Hg in fish to riverine populations was a special challenge. It is difficult to explain to traditional communities that their lifestyle may cause Hg-related health risks and that some of their favorite fish species, mostly the top piscivores, are considered unsafe by WHO due to their higher Hg content. Too bad they are also the species with higher market value. Hg, WHO? All this was new and uncomfortable for the riverine peoples, as they had no other available protein source. So they had a problem and were not aware of it, and now they knew and had no option to avoid it. Despite the scientific importance and quality of the first fish Hg data, one can honestly wonder whether the embarrassed diffusion of high Hg fish species lists was useful to riverine communities, or counterproductive. On the other hand, knowing is not believing, and riverine peoples wondered why these scientists were so concerned about an invisible problem, as they had never experienced or seen any health problem related to the consumption of high-Hg fish species.

Indeed, these effects are subclinical and can only be demonstrated by simple but specific vision, coordination, and dexterity tests. In fact, the existence of the problem itself was a subject of skepticism among many villagers. We must remember that for the present-day laypeople worldwide, Hg is just a silvery liquid metal seen in thermometers and used by gold miners. It is very easy to see, while Hg vapor or Hg salts are not. An old and much respected fisherman leader once told me publicly, "You know, outsiders rarely come here and when they do it is generally bad news, so we really appreciate your concern about our health and mercury and stuff, but I must tell you, even before the gold rush, I used to look into the stomach of the fish I caught, and in the last 50 years, I never saw any quicksilver there." To move out of the corner where he had successfully put me, I had to give the example of three glasses of water, one with sugar, the other with salt, and a third with no addition, which would be visually identical but with different compositions, tastes, and health effects. I do not know whether this was convincing or not, but they invited me to a fish barbecue where we indulged generous and delicious portions of high-Hg fish. It is just another example that risk and risk perception are two distinct entities that seldom meet. Failing to recognize this can compromise a research or intervention project and produce indifference or hostility rather than collaboration. Risk communication is a knowledge field in itself, more related to social than to environment sciences, and the awful truth is that none of the Hg researchers of the time—mostly biogeochemists—had the training for it, including myself.

More support, more projects, little progress

After the above discussed pioneering works of Pfeiffer, Malm, Lacerda, and others, the early 1990s witnessed a multitude of research projects on Hg in the Amazon. Aula and other Finnish colleagues made the first study of Hg in a large Amazonian reservoir, Tucurui, on the Xingu River just downstream from the Serra Pelada gold fields (Aula et al., 1994). Akagi and colleagues (1995) from the National Institute for Minamata disease in Japan, made in the Tapajos River the first MeHg measurements in fish and human hair in the region. David Cleary, a British anthropologist, made the first in-depth analysis of the social and work relations within gold mining communities. He deconstructed most of the negative stereotypes on the subject (Cleary, 1990) and later coordinated a large intervention project with EU funds in the Tapajos region, to implement a lab in Santarem for Hg measurements in human and environmental samples. The project also made field tests and demonstrations to improve gold extraction and reduce Hg use.

At the same time, many Brazilian federal- and state-level institutions such as the Health Ministry, the National Department for Mineral Production, the Center for Mineral Technology, and groups from universities in the Amazon were planning or doing research projects on Hg in the main Amazon Rivers. Despite the sizable teams and resources involved, the outputs were often frustrating. The projects concerned health, or biogeochemistry, or social aspects, failing to include all dimensions of this complex subject and concluding, almost invariably, that more studies were necessary. This was unfortunately not a Brazilian privilege; the same could be said of the vast majority of Hg studies worldwide in those years. Repeated failure of disciplinary projects is often needed before scientists acknowledge that the conceptual and practical tool box of their discipline alone is not sufficient to understand the problem, not to mention proposing reasonable interventions to mitigate it.

By the mid-1990s, gold mining international prices had collapsed; the Collor government (1990–1992) had confiscated all financial assets in an attempt to control hyperinflation, leading to a solvency crisis that was fatal to gold mining. The gold rush was over, and media attention and research support for Hg studies in the Amazon vanished altogether. This was not the end of the story. At the peak in gold prices that triggered the 1980's rush, a kilo of gold was worth 22,843 USD. In the mid-1990s, it was worth 12,500 USD; in mid-2011, 57,305 USD; and on 3 March, 2020, 52,936 USD (Goldprice Org., 2020). Needless to say, this is fueling a new gold rush in the Amazon and elsewhere, less massive and more discrete than in the 1980s. Now, some miners are using cyanidation, alone or in combination with amalgamation, to recover gold from new gold deposits and from mine waste left behind by the miners from the 1980s. Maybe it would be a good moment for a new visit by a BBC documentary team.

Hydroelectric reservoirs in the Amazon and Hg

The construction of large hydroelectric dams in the Amazon has always been controversial. Due to the low declivity of the basin, the dams flood large areas for a modest electricity production, the worse examples in that aspect being the Balbina reservoir, on the Uatuma River, near Manaus, and Samuel reservoir, near Porto Velho, on a Madeira River tributary. In the Amazon as elsewhere, damming produces the "reservoir effect" on Hg levels in fish, that increase sharply after damming, to slowly decrease as the reservoir ages (Drew Bodaly et al., 2007; Pestana et al., 2019). Although Tucurui has been more studied for Hg than other dams in the Amazon, the only published study documenting fish mercury increase after damming in Brazil concerned the Manso reservoir, near Cuiaba (Hylander et al., 2006). Many factors explain the reservoir effect, as dams are efficient sediment traps and consequently Hg traps, in addition to the release of Hg from the flooded soil and vegetation. They also tend to be stratified, and the suboxic or anoxic conditions of their hypolimnion turn them into efficient bioreactors for MeHg production, significantly increasing fish Hg downstream, as shown by Boudou et al. (2005) in the Petit-Saut dam in French Guyana and by Kasper et al. (2012) in Tucurui. Hg in human hair of riverine peoples living near the Tucurui dam are among the highest in the Amazon and comparable to or higher than those found in areas with significant gold mining activity (Arrifano et al., 2018). In addition to their impact on the cycling of Hg, these dams promote a significant production of greenhouse gases in the reservoir water column itself and in the turbulent flow in and downstream from the turbines (Fearnside, 1995; de Faria et al., 2015).

On top of this nonexhaustive list of environmental impacts of the so-called clean energy source, the flooding of large areas often forces the dislocation of Amerindian populations or the reduction of their reserves, making the licensing process longer and more complex. As a consequence, small hydroelectric plants, much simpler to license, are being constructed in many watersheds, but though their licensing is individual, they are constructed in a cumulative cascade. Little is known on the effect of series of small dams on a same watershed on the cycle of Hg (Cebalho et al., 2017).

Agriculture fells the rainforest and exacerbates mercury exposure

In 1994, taking advantage of an existing cooperation agreement between the Federal University of Para (UFPA) in Belem and Universite du Quebec a Montreal (UQAM), two UQAM professors (Donna Mergler, environmental epidemiologist, and Marc Lucotte, aquatic biogeochemist) approached UFPA to propose the inclusion of a Hg project in the agreement, which had so far no ongoing project on environmental sciences. UFPA agreed and Prof. Marucia Amorim, citogeneticist, embarked in the project with her team. The Canadian project leaders had some previous experience with Hg from a few projects developed in Canada and French Guyana. They had a small but motivated team, 15,000 CAN$ of seed money from the Canadian International Development Research Center (IDRC), a custom-made cold vapor atomic fluorescence detector, and the promise of more and better funding from the same funding source if the pilot project succeeded. After many weeks of hard sampling work on the Tapajos River with UFPA partners and logistic support from the Brazilian Navy in Santarem, followed by many other weeks processing the samples in UQAM's laboratories, they wrote an ambitious proposal that was initially granted a 300,000 CAN$/year IDRC support for 3 years. It was named CARUSO in reference to the movie "Fitzcarraldo" by the German filmmaker Werner Herzog, issued in 1982.

The first phase of this project was built on the then generally accepted assumption that the main cause of mercury contamination in the Tapajos River was gold mining (**Figure 4**) but ended demonstrating that most of the mercury actually came from soil erosion following deforestation for agriculture. This bold conclusion was based on a series of evidences. First, it was shown that Hg burden in local soils was one order of magnitude higher than in soils from North America and that Hg emissions from gold

Figure 4. Sluice box in operation in the Rio do Rato gold mining field, Tapajos Basin. The pumped soil or sediment slurry is cascaded down a carpet-lined slope that concentrates the heavier fractions of the material. The same system can be set up on a barge to pump and process river bottom material. The gravimetric concentrates are later mixed with metallic Hg, and the resulting amalgams are squeezed in a linen to drip out the excess metallic Hg. The amalgams are then heated with a propane torch in open air to volatilize Hg and recover gold. Photo by the author, 1994 (gold field sluice box). DOI: https://doi.org/10.1525/elementa.032.f4

mining activities could explain at most 3% of the observed soil Hg (Roulet et al., 1998). Second, no downstream gradient was seen in Hg in suspended particles along a 300 km long stretch of the Tapajos, downstream from the main gold mining areas, which would be expected if those were the main Hg source to the river (Roulet et al., 1999). In addition, sediment cores from Tapajos floodplain lakes did show a significant Hg enrichment in their top layers, but Pb-210 dating showed that this enrichment started well before the gold rush, and coincided instead with the acceleration of human colonization of this basin in the 1950s (Roulet et al., 1998; Oestreicher et al., 2017). Moreover, lignin markers and Hg were similarly enriched in the recent sediment layers and exhibited very similar vertical variations, while Hg in sediments was as closely bound to Al and Fe oxides and hydro-oxides as it was in soils (Roulet et al., 2000; Farella et al., 2001).

Detailed soil studies in toposequences with different soil uses showed that irrespective of subsequent agricultural use, slash and burn deforestation caused a preferential lateral erosion of the fine soil particles richer in Hg (Roulet et al., 1998). In soils from North American temperate or boreal areas, Hg is generally strongly associated with carbon (Nave et al., 2017). In the Tapajos basin, in contrast, Hg only showed the same association with carbon in the thin organic horizon and increased significantly with depth, reaching its highest concentrations in the mineral horizon, rich in Fe oxy-hydroxides, which are efficient Hg scavengers (Roulet et al., 2000). Later it was shown, still in the Tapajos basin, that deforestation not only led to Hg loss and transfer to adjacent aquatic systems but also led to fertility losses as the massive cation input to soil caused by slash and burning caused N and P dislocation and downstream transfer (Farella et al., 2007; Patry et al., 2013; Béliveau et al., 2017). Lacerda et al. (2004) and Almeida et al. (2005) made similar studies, respectively, in Alta Floresta and Rondonia, with similar conclusions concerning the influence of deforestation on soil Hg. At this point, it became clear that Hg enrichment in sediments was a direct consequence of old, widespread, and unsustainable agricultural practices rather than of recent gold mining Hg emissions, revealing an unexpected virtuous cycle: Less Hg in fish requires sustainable agriculture.

Mercury in fish and health risks to riverine people

The health component of the project was also quite productive, showing the close coupling between human exposure to Hg and the hydrological cycle, the latter determining the availability and abundance of the higher Hg fish species (Lebel et al., 1997). It also demonstrated that the onset of detectable Hg exposure symptoms started as low as 15 μg/g total Hg in hair and not at 50 μg/g, as suggested so far by WHO (Lebel et al., 1998). Performance in dexterity and coordination tests as well as vision and cardiovascular health was negatively associated with hair Hg levels.

The second phase of the project was an intervention phase focused on identifying and promoting less contaminated fish species, an approach that succeeded in reducing levels of mercury contamination among residents of the community by 40% in comparison to the pre-intervention levels (Fillion et al., 2011). Building on the negative experience of previous projects with risk communication on Hg in fish, the team coined a positive slogan instead: *Eat more fish that do not eat other fish*. A detailed 1-year diet survey, organized by a group of women from the Brasilia Legal community, also showed that Hg body burden in humans was inversely correlated to their frequency of fruit consumption (Passos et al., 2003).

The third and last phase of the project aimed at scaling up the research and intervention to the whole lower Tapajos River basin and creating a region-wide network of key community members to discuss and develop long-term solutions to the problem of river Hg contamination based on modified agricultural practices. It allowed researchers to confirm regionally the connection between Hg body burdens and fruit consumption (Passos et al., 2007) and to show that Se in the local environment varied a lot more than Hg and modulated the effects of Hg exposure (Lemire et al., 2011). Measuring blood samples in a multielemental detector accidentally revealed widespread high Pb levels, caused by the consumption of manioc flour, an important local staple food item, which was dried in non-food-grade metal pans (Barbosa et al., 2009).

Many factors explained the high outputs of the project as a whole. Among them, the availability of data from the many different previous Hg projects, the active participation of local communities, the simultaneous field work of health, environment and social scientists during long periods, the previous learning of Portuguese by the Canadian researchers, the unprecedented continuity of donor support that extended over a decade, the availability of state-of-the-art sampling and analytical methods for Hg and other important parameters, the systematic data return to the participating communities, the separate workshops with mothers, fishermen, farmers, decision makers and other social actors, the attention to gender, equity, and power issues. Gathering all or many of these features in a single project is not trivial nor guarantees success but may significantly reduce the chances of concluding that more studies are necessary.

By seeking and blundering we learn

As expected, some mistakes were also made. To help identify the approximately 40 different fish species and their respective Hg content ranges during the phase II intervention, we prepared small plasticized posters to be hanged in kitchens. They showed the fish grouped by colors: red for high Hg, orange for average Hg, and green for low Hg fishes. This color code makes sense for people who have already seen a traffic light but was completely arbitrary for riverine communities of the early 1990s that had no cars at all and only a few televisions, powered by electric generators in special occasions. The posters were also sometimes interpreted literally: A fishermen once declared "Nice poster, all important fish are there, good, but I must be sincere with you: I never caught a red *pescada* or a green *pacu*, in my village *pescadas* are grey and *pacus* are brown." Another example of a serious mistake was the nice color comic strip we prepared, illustrating the key facts about Hg in the Tapajos, its pathways and effects, the role of agriculture in the issue, and so on. Even the methylating bacteria that convert the "nice" Hg into "bad" Hg were there. The comic strip was drawn by two excellent, young male graphic artists from Santarem, and it was only after printing and distribution that we realized the key role of local women in the project, especially in its intervention phase, was not sufficiently described in the script.

The project identified and demonstrated many positive intervention possibilities, mainly on diet and agriculture practices, that are applicable to many other regions than the Tapajos Basin and could lead to better ecosystem and human health and more sustainability in fishing and agriculture. At this point, the project became a prisoner of its own success because achieving such goals would require converting its findings into public health and environment policies. Chances of seeing this in the near future in Brazil are close to zero. In a country where nearly 80% of the population is urban, two thirds of the Congress seats are occupied by ruralists like large-scale cattle ranchers or soya planters, whose businesses require complete deforestation of vast land extensions. Our present ultra-liberal federal government is frontally opposed to any restriction of economic activities due to environmental considerations and openly advocates for the suppression of natural parks and other preservation areas as well as of Amerindian reserves, in the Amazon or anywhere else in the country. These are seen as obstacles to productive activities such as logging, ranching, industrial agriculture, and mining, naturally including gold mining. Ironically, we spent decades complaining that the successive Brazilian governments had no defined policy concerning gold mining; now, there is a clear policy: Go ahead and dig, good luck.

Environmental Hg fingerprinting

If decision makers at large change their minds and methods someday, they will have interesting tools at hand to build evidence-based policies. Indeed, the last decade saw the development of multicollector mass spectrometric methods that allow the use of stable Hg isotope ratios to fingerprint the contribution of point sources of Hg to the presence of Hg in the environment, provided the Hg isotope ratios of the source are different from those of local background Hg. Fortunately enough, artisanal gold mining in South America uses metallic Hg imported from other continents, which presents a different stable Hg isotopic compositions than local plants and soils (Guédron et al., 2018), fulfilling the precondition for the use of this

Figure 5. Confluence of the Crepuri and Tapajos rivers, showing the siltation of the Crepuri, caused by gold mining activity. The right margin of the upper Tapajos concentrates a number of tributaries that are heavily mined for gold, such as the Jamanxin, Crepuri, Crepurizinho, and Rato. All of them carry heavy sediment loads to the Tapajos and form plumes like those seen in the picture. They persist for long distances down the Tapajos. Photo by the author, 1994 (river siltation caused by gold mining activity). DOI: https://doi.org/10.1525/elementa.032.f5

method. The latter was recently used to evaluate impacts of gold mining Hg emissions in contrasting environments, such as the Tartarugalzinho gold mining field in Amapa, Brazilian Amazon, and the Puyango watershed in southern Ecuador, which drains to the Pacific after crossing northern Peru and has been intensively exploited for gold since Inca times. The hydrological, topographic, and climatic features of these two areas are very contrasting, and the use of stable Hg isotopic ratios produced equally contrasting conclusions. In the Tartarugalzinho River, gold mining Hg signature was already undetectable 1 km downstream from the gold field (Miserendino et al., 2017), while in the Puyango River, Hg from gold mining predominated in all the watershed, from the gold processing centers to the Pacific ocean (Marshall et al., 2018; Schudel et al., 2018).

The duration of the heated debate over the role of different Hg sources illustrates how the advancements in the understanding of the Hg biogeochemical cycle are closely dependent on analytical chemistry and instrumentation developments.

Cautionary note

The evidence briefly described here and pointing to a limited impact of gold mining Hg emissions on the biogeochemical cycle of Hg in the Amazon must not be taken as more than they are and cannot be generalized a priori to any other geographical and social contexts. With or without gold mining and its Hg emissions, human Hg exposure in the Amazon is still among the highest in the world (Passos et al., 2008) due to the characteristics of this overwhelmingly complex basin and the food habits of its populations. If this type of mining may have limited impacts on Hg in the environment of this region, it does not make gold mining sustainable, as the activity, and mining in general, is by definition unsustainable. Although gold mining is less relevant than ranching and soya plantations as a deforestation driver, gold mining areas are point sources of intense river siltation, one of their most relevant environmental impacts (**Figure 5**). In watersheds with a high density of mining areas, these can contribute up to 94% of the suspended sediments in river water, as shown by Abe et al. (2019) in the Crepuri River, Tapajos basin. In the same basin, Lobo et al. (2016) used satellite images to show the coupling between river siltation and the level of activity of gold mining fields along 40 years. Siltation has long-range effects on downstream fish communities, reducing their diversity and abundance as shown by Mol and Ouboter (2004).

If body count is a criteria for evaluation of mining impacts, maybe we should be more concerned in Brazil about Fe mining. In 2015, a major Fe mining waste pond system collapsed in Mariana in the state of Minas Gerais, causing 19 human casualties downstream and major socioeconomic and environmental impacts on the whole Rio Doce basin, even disrupting coastal fisheries and other activities at its mouth, 500 km downstream the mine. In 2019, yet another Fe waste pond collapsed, this time in Brumadinho, also in the state of Minas Gerais, leaving a toll of 259 confirmed human casualties and 11 missing, and similar impacts downstream. Brumadinho is considered the second largest industrial accident of the 21st century, after Savar, Bangladesh, 2013, where the collapse of an industrial and commercial building made 1,127 fatal victims.

Concluding remarks

I hope this brief testimony about Hg research in the Amazon in the last 30 years may inspire scientists who are venturing into Hg studies, warn them of some obstacles and traps on the way, and reveal the great challenges and opportunities behind studies of an element that seems to incarnate complexity itself. Note that because of its mobility and toxicity, issues involving Hg in the environment are almost always politically sensitive, and hiding behind scientific neutrality will rarely be an option. Evidence-based health and environment policies are not very popular in these times of alternative truths and negationisms of all types. Precisely because of that, we must keep producing the best evidence we can and translate them to the wider audience as possible.

Acknowledgments

The number of persons to acknowledge for a 30-year period is too high to fit here, but I wish to make an homage to important colleagues we lost on this journey, such as Marc Roulet, the first to prove that mining alone could not explain Hg data in soil and sediment profiles; Robert Davidson, who organized the move of the CARUSO project from aquatic geochemistry to agroforestry; Fernando Branches, the Santarem cardiologist that showed the first occupational effects of Hg on health of gold miners of the region and traveled the lower and middle Tapajos at his own expense to deliver health care; and Reinaldo Calixto Campos, who helped develop Hg methods in the early days and helped measuring samples thereafter when other colleagues could not. We miss you all.

Funding information

Along the described 30 years of research, many institutions assured funding, among them UFRJ, CNPQ, CAPES, FAPERJ, Banco Goldmine, all in Brazil, and European Community, SAREC (Sweden), GTZ (Germany), JICA and NIMD (Japan), Imperial College (United Kingdom), IRD (France), and IDRC (Canada).

Competing interests

The authors have no competing interests to declare.

References

Abe, CA, Lobo, FL, Novo, EMLD, Costa, M, Dibike, Y. 2019. Modeling the effects of land cover change on sediment concentrations in a gold-mined Amazonian basin. *Reg Environ Change* **19**(6): 1801–1813.

Ackefors, H. 1971. Mercury pollution in Sweden with special reference to conditions in the water habitat. *Proc R Soc Lond B Biol Sci* **177**(1048): 365–387.

Akagi, H, Malm, O, Kinjo, Y, Harada, M, Branches, FJP, Pfeiffer, WC, Kato, H. 1995. Methylmercury pollution in the Amazon, Brazil. *Sci Total Environ* **175**(2): 85–95.

Almeida, MD, Lacerda, LD, Bastos, WR, Herrmann, JC. 2005. Mercury loss from soils following conversion from forest to pasture in Rondônia, Western Amazon, Brazil. *Environ Pollut* **137**(2): 179–186.

Armin, M. 1995. *Serra Pelada*. Núcleo de Altos Estudos Amazônicos da Universidade Federal do Pará. Papers do NAEA, no. 050, Belém/PA December.

Arrifano, GPF, Martín-Doimeadios, RCR, Jiménez-Moreno, M, Ramírez-Mateos, V, da Silva, NFS, Souza-Monteiro, JR, Augusto-Oliveira, M, Paraense, RSO, Macchi, BM, do Nascimento, JLM, Crespo-Lopez, ME. 2018. Large-scale projects in the amazon and human exposure to mercury: The case-study of the Tucuruí Dam. *Ecotoxicol Environ Saf* **147**: 299–305.

Aula, I, Braunschweiler, H, Leino, T, Malin, I, Porvari, P, Hatanaka, T. 1994. Levels of mercury in the Tucuruí Reservoir and its surrounding area in Para, Brasil, in Watras, CJ, Huckabee, JW eds., *Mercury pollution: Integration and synthesis*. Boca Raton, FL: Lewis Publishers; 21–40.

Bakir, F, Damluji, SF, Amin-Zaki, L, Murtadha, M, Khalidi, A, Alrawi, NY, Tikriti, S, Dhahir, HI, Clarkson, TW, Smith, JC, Doherty, RA. 1973. Methylmercury poisoning in Iraq. *Science* **181**: 230–241.

Barbosa, F, Fillion, M, Lemire, M, Passos, CJS, Rodrigues, JL, Philibert, A, Guimaraes, JRD, Mergler, D. 2009. Elevated blood lead levels in a riverside population in the Brazilian Amazon. *Environ Res* **109**(5): 594–599.

Bastos, WR, Fonseca, MD, Pinto, FN, Rebelo, MD, dos Santos, SS, da Silveira, EG, Torres, JPM, Malm, O, Pfeiffer, WC. 2004. Mercury persistence in indoor environments in the Amazon Region, Brazil. *Environ Res* **96**(2): 235–238.

Béliveau, A, Lucotte, M, Davidson, R, Paquet, S, Mertens, F, Passos, CJS, Romana, CA. 2017. Reduction of soil erosion and mercury losses in agroforestry systems compared to forests and cultivated fields in the Brazilian Amazon. *J Environ Manage* **203**(1): 522–532.

Björklund, I, Borg, H, Johansson, K. 1984. Mercury in Swedish lakes: Its regional distribution and causes. *Ambio* **13**:118–121.

Borg, K, Wanntorp, H, Erne, K, Hanko, E. 1965. *Mercury poisoning in wild animals and game and other birds* *in Sweden* [Kvicksilverförgiftningar bland vilt i Sverige]. Stockholm, Sweden: Statens Veterinärmedicinska Anstalt (SVA); 50.

Boudou, A, Maury-Brachet, R, Coquery, M, Durrieu, G, Cossa, D. 2005. Synergic effect of gold mining and damming on mercury contamination in fish. *Environ Sci Technol* **39**(8): 2448–2454.

Calazans, CF, Malm, O. 1997. Elemental mercury contamination survey in a chlor-alkali plant by the use of transplanted Spanish moss *Tillandsia usneoides* (L.). *Sci Total Environ* **208**: 165–177.

Cebalho, EC, Díez, S, Dos Santos Filho, M, Muniz, CS, Lázaro, W, Malm, O, Ignácio, ARA. 2017. Effects of small hydropower plants on mercury concentrations in fish. *Environ Sci Poll Res Inter* **24**(28): 22709–22716.

Cleary, D. 1990. *Anatomy of the Amazon Gold Rush*. Iowa City: University of Iowa Press.

de Faria, FAM, Jaramillo, P, Sawakuchi, HO, Richey, JE, Barros, N. 2015. Estimating greenhouse gas emissions from future Amazonian hydroelectric reservoirs. *Environ Res Lett* **10**: 124019.

Drew Bodaly, RA, Jansen, WA, Majewski, AR, Fudge, RJP, Strange, NE, Derksen, AJ, Green, DJ. 2007. Postimpoundment time course of increased mercury concentrations in fish in hydroelectric reservoirs of Northern Manitoba, Canada. *Arch Environ Contam Toxicol* **53**(3): 379–389.

Farella, N, Davidson, R, Lucotte, M, Daigle, S. 2007. Nutrient and mercury variations in soils from family farms of the Tapajos region (Brazilian Amazon): Recommendations for better farming. *Ecosyst Envir* **120**: 449–462.

Farella, N, Lucotte, M, Louchouarn, P, Roulet, M. 2001. Deforestation modifying terrestrial organic transport in the Rio Tapajos, Brazilian Amazon. *Org Geochem* **32**: 1443–1458.

Fearnside, P. 1995. Hydroelectric dams in the Brazilian Amazon as sources of 'greenhouse' gases. *Environ Conserv* **22**(1): 7–19.

Fillion, M, Philibert, A, Mertens, F, Lemire, M, Passos, CJS, Frenette, B, Guimaraes, JRD, Mergler, D. 2011. Neurotoxic sequelae of mercury exposure: An intervention and follow-up study in the Brazilian Amazon. *Ecohealth* **8**(2): 210–222.

Fonseca, MF, Bastos, WR, Pinto, FN, Rebelo, MF, Torres, JPM, Guimaraes, JRD, Pfeiffer, WC, Marques, RC, Malm, O. 2007. Can the biomonitor *Tillandsia usneoides* be used to estimate occupational and environmental mercury levels in the air? *J Braz Soc Ecotoxicol* **2(**2): 129–137.

Forstner, U, Wittman, GTW. 1979. *Metal pollution in the environment*. Springer-Verlag, Berlin Heidelberg.

Fostier, AH, Forti, MC, Guimaraes, JRD, Melfi, AJ, Boulet, R, Santo, CME, Krug, FJ. 2000. Mercury fluxes in a natural forested Amazonian catchment (Serra do Navio, Amapa State, Brazil). *Sci Tot Environ* **260**(1–3): 201–211.

Guédron, S, Amouroux, D, Tessier, E, Grimaldi, C, Barre, J, Berail, S, Perrot, V, Grimaldi, M. 2018. Mercury isotopic fractionation during pedogenesis in a tropical forest soil catena (French Guiana): Deciphering the impact of historical gold mining. *Environ Sci Technol* **52**(20): 11573–11582.

Gustin, MS, Evers, DC, Bank, MS, Hammerschmidt, CR, Pierce, A, Basu, N, Blum, J, Bustamante, P, Chen, C, Driscoll, CT, Horvat, M, Jaffe, D, Pacyna, J, Pirrone, N, Selin, N. 2016. Importance of integration and implementation of emerging and future mercury research into the Minamata Convention. *Environ Sci Tech* **50**: 2767–2770.

Goldprice Org. Available at https://goldprice.org/pt/gold-price-chart.html. Accessed 3 March 2020.

Hsu-Kim, H, Eckley, CS, Selin, NE. 2018. Modern science of a legacy problem: Mercury biogeochemical research after the Minamata Convention. *Environ Sci Proc Imp* **20**: 582–583.

Hylander, LD, Gröhn, J, Tropp, M, Vikström, A, Wolpher, H, de Castro, E, Silva, E, Meili, M, Oliveira, LJJ. 2006. Fish mercury increase in Lago Manso, a new hydroelectric reservoir in tropical Brazil. *J Environ Manag* **81**(2): 155–166.

Jardim, WF, Bisinoti, MC, Fadini, PS, da Silva, GS. 2010. Mercury redox chemistry in the Negro river basin, Amazon: The role of organic matter and solar light. *Aquat Geoquem* **16**(2): 267–278.

Jensen, S, Jernelov, A. 1969. Biological methylation of mercury in aquatic organisms. *Nature* **223**: 753–754.

Kasper, D, Albuquerque, P, Fernandes, E, Castelo Branco, CW, Malm, O. 2012. Evidence of elevated mercury levels in carnivorous and omnivorous fishes downstream from an Amazon reservoir. *Hydrobiologia* **694**(1): 87–98.

Kiefer, AM, Drace, K, Seney, CS, Veiga, MM. 2015. Challenges associated with using retorts to limit mercury exposure in artisanal and small-scale gold mining: Case studies from Mozambique, Ecuador, and Guyana. *ACS Sym Ser* **1210**: 51–77.

Krabbenhoft, DP, Rickert, DA. 2018. Mercury contamination of aquatic ecosystems. U.S. Geological Survey Fact Sheet 216–95, Version 1.0. Available at https://pubs.usgs.gov/fs/1995/fs216-95/. Accessed 28 June, 2020.

Lacerda, LD. 1997. Global mercury emissions from gold and silver mining. *Water Air Soil Poll* **97**(3–4): 209–221.

Lacerda, LD, de Souza, M, Ribeiro, MG. 2004. The effects of land use change on mercury distribution in soils of Alta Floresta, Southern Amazon. *Environ Pollut* **129**(2): 247–255.

Lacerda, LD, Pfeiffer WC, Ott, AT, Da Silveira, EG. 1989. Mercury contamination in the Madeira River, Amazon: Hg inputs to the environment. *Biotropica* **21**(1): 91–93.

Lebel, J, Mergler, D, Branches, F, Lucotte, M, Amorim, M, Larribe, F, Dolbec, J. 1998. Neurotoxic effects of low-level methylmercury contamination in the Amazonian Basin. *Environ Res* **79**(1): 20–32.

Lebel, J, Roulet, M, Mergler, D, Lucotte, M, Larribe, F. 1997. Fish diet and mercury exposure in a riparian Amazonian population. *Water Air Soil Poll* **97**(1–2): 31–44.

Lemire, M, Fillion, M, Frenette, B, Passos, CJS, Guimaraes, JRD, Barbosa, F, Mergler, D. 2011. Selenium from dietary sources and motor functions in the Brazilian Amazon. *Neurotoxicology* **32**(6): 944–953.

Lobo, DA, Costa, M, Novo, EMLD, Telmer, K. 2016. Distribution of artisanal and small-scale gold mining in the Tapajos river basin (Brazilian Amazon) over the past 40 years and relationship with water siltation. *Remote Sens* **8**(7): 579. DOI: http://dx.doi.org/10.3390/rs8070579.

Magarelli, G, Fostier, AH. 2005. Quantification of atmosphere–soil mercury fluxes by using a dynamic flux chamber: Application at the Negro river basin, Amazon. *Quim Nova* **28**(6): 968–974.

Malm, O, Castro, MB, Bastos, WR, Branches, FJP, Guimaraes, JRD, Zuffo, CE, Pfeiffer, WC. 1995. An assessment of Hg pollution in different goldmining areas, Amazon Brazil. *Sci Total Environ* **175**(2): 127–140.

Malm, O, Fonseca, MF, Miguel, PH, Bastos, WR, Pinto, FN. 1998. Use of epiphytes plants as biomonitors to map atmospheric mercury in a gold trade center city, Amazon, Brazil. *Sci Total Environ* **213**: 57–64.

Malm, O, Guimaraes, JRD, Castro, MB. 1997. Follow-up of mercury levels in fish, human hair and urine in the Madeira and Tapajos basins, Amazon, Brazil. *Water Air Soil Poll* **97**(1–2): 45–51.

Malm, O, Pfeiffer, WC, Souza CMM, Reuther, R. 1990. Mercury pollution due to gold mining in the Madeira river basin, Brazil. *Ambio* **19**(1): 11–15.

Marshall, BG, Veiga, MM, Kaplan, RJ, Adler Miserendino, R, Schudel, G, Bergquist, BA, Guimaraes, JRD, Sobral, LGS, Gonzales-Mueller, C. 2018. Evidence of transboundary mercury and other pollutants in the Puyango-Tumbes River basin, Ecuador-Peru. *Environ Sci-Proc Imp* **20**: 632–641.

Martinelli, LA, Ferreira, JR, Victoria, R, Forsberg, BR. 1988. Mercury contamination in the Amazon: A gold rush consequence. *Ambio* **17**(4): 252–254.

Ministry of the Environment, Government of Japan. 2020. Available at http://www.env.go.jp/en/chemi/hs/minamata2002/ch2.html. Accessed 3 March, 2020.

Miserendino, RA, Guimaraes, JRD, Schudel, G, Ghosh, S, Godoy, JM, Silbergeld, EK, Lees, PSJ, Bergquist, BA. 2017. Mercury pollution in Amapa, Brazil: Mercury amalgamation in artisanal and small-scale gold mining or land-cover and land-use changes? *ACS Earth Space Chem* **1**: 1–10.

Mol, JH, Ouboter, PE. 2004. Downstream effects of erosion from small-scale gold mining on the instream habitat and fish community of a small neotropical rainforest stream. *Conserv Biol* **18**(1): 201–214.

Nave, LE, Drevnick, PE, Heckman, KA, Hofmeister, KL, Veverica, TJ, Swanston, CW. 2017. Soil hydrology, physical and chemical properties and the distribution of carbon and mercury in a postglacial lake-plain wetland. *Geoderma* **305**: 40–52.

Oestreicher, JS, Lucotte, M, Moingt, M, Bélanger, É, Rozon, C, Davidson, R, Mertens, F, Romaña, CA. 2017. Environmental and anthropogenic factors influencing mercury dynamics during the past century in Floodplain Lakes of the Tapajós River, Brazilian Amazon. *Arch Environ Contam Toxicol* **72**: 11–30.

Passos, CJS, da Silva, DS, Lemire, M, Fillion, M, Guimaraes, JRD, Lucotte, M, Mergler, D. 2008. Daily mercury intake in fish-eating populations in the Brazilian Amazon. *J Exp Sci Env Epidemiol* **1**: 76–87.

Passos, CJS, Mergler, D, Fillion, M, Lemire, M, Mertens, F, Guimaraes, JR, Philibert, A. 2007. Epidemiologic confirmation that fruit consumption influences mercury exposure in riparian communities in the Brazilian Amazon. *Environ Res* **105**(2): 183–193.

Passos, CJS, Mergler, D, Gaspar, E, Morais, S, Lucotte, M, Larribe, F, Davidson, R, de Grosbois, S. 2003. Eating tropical fruit reduces mercury exposure from fish consumption in the Brazilian Amazon. *Environ Res* **93**(2): 123–130.

Patry, C, Davidson, R, Lucotte, M, Béliveau, A. 2013. Impact of forested fallows on fertility and mercury content in soils of the Tapajós River region, Brazilian Amazon. *Sci Total Environ* **458–460**: 228–37. DOI: http://dx.doi.org/10.1016/j.scitotenv.2013.04.037.

Pestana, IA, Azevedo, LS, Bastos, WR, de Souza, CMM. 2019. The impact of hydroelectric dams on mercury dynamics in South America: A review. *Chemosphere* **219**: 546–556.

Pfeiffer, WC, Lacerda, LD. 1988. Mercury inputs into the Amazon region, Brazil. *Env Technol Lett* **9**(4): 325–330.

Roulet, M, Lucotte, M, Canuel, R, Farella, N, Courcelles, M, Guimaraes, JRD, Mergler, D, Amorim, M. 2000. Increase in mercury contamination recorded in lacustrine sediments following deforestation in the central Amazon. *Chem Geol* **165**(3–4): 243–266.

Roulet, M, Lucotte, M, Canuel, R, Rheault, I, Tran, S, Gog, YGD, Farella, N, do Vale, RS, Passos, CJS, da Silva, ED, Mergler, D, Amorim, M. 1998. Distribution and partition of total mercury in waters of the Tapajos River Basin, Brazilian Amazon. *Sci Total Environ* **213**(1–3): 203–211.

Roulet, M, Lucotte, M, Saint-Aubin, A, Tran, S, Rheault, I, Farella, N, Da Silva, ED, Dezencourt, J, Passos, CJS, Soares, GS, Guimaraes, JRD, Mergler, D, Amorim, M. 1998. The geochemistry of mercury in central Amazonian soils developed on the Alter-do-Chao formation of the lower Tapajos River Valley, Para state, Brazil. *Sci Total Environ* **223**(1): 1–24.

Roulet, M, Lucotte, M, Farella, N, Serique, G, Coelho, H, Passos, CJS, da Silva, ED, de Andrade, PS, Mergler, D, Guimaraes, JRD, Amorim, M. 1999. Effects of recent human colonization on the presence of mercury in Amazonian ecosystems. *Water Air Soil Poll* **112**(3–4): 297–313.

Schudel, G, Miserendino, RA, Veiga, MM, Velasquez-Lopes, PC, Lees, PSJ, Winland-Gaetz, S, Guimaraes, JRD, Bergquist, BA. 2018. An investigation of mercury sources in the Puyango-Tumbes River: Using stable Hg isotopes to characterize transboundary Hg pollution. *Chemosphere* **202**: 777–787.

Selin, NE. 2009. Global biogeochemical cycling of mercury: A review. *Ann Rev Environ Res* **34**: 43–63.

Silva-Forsberg, MC, Forsberg, BR, Zeidemann, VK. 1999. Mercury contamination in humans linked to river chemistry in the Amazon basin. *Ambio* **28**(6): 519–521.

Veiga, MM, Meech, JA, Onate, N. 1994. Mercury pollution from deforestation. *Nature* **368**(6474): 816–817.

Streets, DG, Horowitz, HM, Lu, Z, Levin, L, Thackray, CP, Sunderland, EM. 2019. Five hundred years of anthropogenic mercury: Spatial and temporal release profiles. *Environ Res Lett* **14**: 084004.

How to cite this article: Guimaraes, JRD. 2020. Mercury in the Amazon: Problem or opportunity? A commentary on 30 years of research on the subject. *Elem Sci Anth*, 8: xx. DOI: https://doi.org/10.1525/elementa.032

Domain Editor-in-Chief: Alastair Iles, University of California, Berkeley, CA, USA

Guest Editor: Hélène Angot, Institute of Arctic and Alpine Research, University of Colorado

Knowledge Domain: Sustainability Transitions

Part of an Elementa Forum: Mercury in the Southern Hemisphere and Tropics

Published: 00, 0000 **Accepted:** July 16, 2020 **Submitted:** March 19, 2020

ELEMENTA Science of the Anthropocene

Elem Sci Anth is a peer-reviewed open access journal published by University of California Press.

OPEN ACCESS