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Mercury and CO_2 emissions from artisanal gold mining in Brazilian Amazon rainforest

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The Tapajós River basin in Brazil is one of the world's regions most affected by artisanal gold mining (ASGM), which is responsible for the release of mercury and high energy consumption. Mercury, mixed with gold-containing materials and then released through heating to extract the gold, can be recovered using a simple distillation device called a retort. Use of these tools has now become standard. In a comprehensive study, we investigated the use of mercury and energy at 47 mining sites in the Tapajós River basin. These included numerous mines that were operated informally or in some cases even illegally and are therefore not accessible to outsiders. Our survey shows that 1.7 kg of mercury are used per kg of gold extracted, of which only about 0.19 kg of mercury is released into the environment when retorts are used. Overall, this means an annual release of at least ≈2.5 tonnes of mercury in the region, even when retorts are used. We also find that ASGM contributes to climate change through energy consumption responsible for the release of about 16,000 kg of CO_2 equivalent per kilogram of gold. This means that even artisanal gold mining, which uses retorts, has a major environmental impact.

Gold is a commodity that has captivated the human imagination for thousands of years. Demand remains undiminished, with about 4,000 to 5,000 metric tons being produced every year worldwide. About one-third of this production is recovered from recycling (2021: 1,136 t); the rest is newly mined (2021: 3,581 t) (ref. 1). But the mining process is associated with a high environmental impact. Due to gold's low content in rock, large amounts of energy are required. Major concerns arise due to environmental damage by chemicals, social issues and regulatory and governance issues. Recycling gold could substantially reduce environmental impact[2], especially because large quantities of gold are in circulation. It is estimated that the anthropogenic gold stock is about 200,000 tons[1]. But the search for gold goes on because for many impoverished people, digging for gold is synonymous with digging for money. Artisanal and small-scale gold mining (ASGM) supplies about 700 tons every year[1] under particularly problematic conditions. Impacts such as deforestation, the release of toxic chemicals such as mercury and the high impact on climate change associated with fossil energy consumption cannot be ignored. In ASGM, problems are exacerbated by sometimes adverse working conditions and regulatory and governance problems caused by unregulated and sometimes illegal mines.

In numerous field surveys and visits to a high number of ASGM sites in Brazil, mainly in the period of 2018–2022, we investigated mercury use and impact on climate change, providing valuable empirical data for further scientific discussion. Several points make Brazil an interesting object of study. The distribution of ASGM based on the population involved in mining[3,4] shows that with the exception of China, ASGM hotspots are located in tropical rainforests. Brazil is the country with the highest ASGM population in the Amazon rainforest. The world's largest ASGM district, the Tapajós River basin, which is where we conducted our fieldwork, is also in Brazil[5]. Especially in this climate zone, economic activities such as ASGM, the protection of nature and biodiversity and the rights of indigenous peoples clash, as in hardly any other place on earth. ASGM thus represents a prime example of conflicting sustainability goals.

The use of mercury still plays a decisive role in ASGM, although its harmful effects on health and the environment are well known.

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Fig. 1 | The four main mining types of ASGM in the Tapajós. Photographs show (clockwise from top left) underground mining of primary deposits (*filão*), open pit mining of primary deposits (*filão*), open pit mining (*baixão*) of secondary deposits and dredge mining (*draga*) of secondary deposits.

ASGM in Brazil, which is often in remote areas where the government is unable to enforce the law, is an illustrative example of this. In 2017, the United Nations Minamata Convention on Mercury came into force with ratification by around 140 countries (including Brazil). ASGM is one important issue in the convention, with article 7 requiring countries to draft National Action Plans (NAPs) for handling and reducing mercury usage in ASGM[6–8]. But implementation has been slow as gold from ASGM is an economic factor and mercury still plays an important role here. Since the 1990s, attempts have been made to recover mercury through simple distillation devices, called retorts, and thus reduce its release into the environment[9]. But it is unknown how effective this method is. Additionally, in Brazil, ASGM is being mechanized through the use of excavators, which raises the question how this affects the carbon footprint of gold[10].

Artisanal gold mining is prohibited in certain areas of the Brazilian rainforest, for example, in *Reservas Indígenas* and *Parque National*[11]. In these areas, ASGM is illegal and punishable by law. Outside these areas, mining is allowed with a permit. This involves registration at the national mining office (Agência Nacional de Mineração) and filing an environmental impact assessment (*licenciamento ambiental*) issued by the federal states[12]. This is a highly bureaucratic process, and as a result, few miners (garimpeiros) have the complete permit. However, they have the possibility to obtain a permit for mineral exploration with prospect mining (*pesquisa mineral com lavra experimental*) for a limited time, which is then used to mine gold. Although this practice is not illegal, it is in an irregular grey area. There is also illegal gold mining, in which the gold is laundered through legal mining operations that produce no or only small quantities of gold[13]. In addition to deficiencies in the law, there are virtually no official controls in the vast rainforest, apart from a few spectacular actions by the environmental authorities. As a result, most gold mines are informal operations, making it difficult to visit these mines, to gain trust and to conduct surveys. For this study, we visited a large number of both illegal and informal mines and exemplary licensed mines, which is a key feature of this study. A complete ban on gold mining in the Brazilian rainforest would fail as it would be impossible for the state to enforce and would only push gold miners further into remote areas where the potential for conflict with indigenous people would increase. On the other hand, greater formalization—that is, simpler and faster authorization of gold mining accompanied by stronger monitoring—would be a first step towards improving mining conditions.

This is particularly true for the handling of mercury in the mines. Contrary to many opinions, the purchase and use of mercury is allowed in Brazil under certain conditions, and mercury use in ASGM is still standard practice. There is a lack of clear specifications and government monitoring[14]. Although there was a strict government regulation in 1989 that required ASGM to register mercury recovery facilities[15], this was withdrawn in 2015[16]. Here, too, greater formalization of gold mining could substantially improve mining conditions. This would also help Brazil to comply with the spirit and the letter of the Minamata Convention, that is, to substantially reduce the use of mercury. But Brazil has not even fulfilled the formal requirements of the Minamata Convention, which it signed in 2017, and is now more than two years behind in submitting its NAP to the United Nations[17,18].

A unique feature in the Tapajós region is that ASGM uses several different mining methods, which were thus able to be investigated in this study: mining of secondary deposits on land (*baixão*) and by dredges (*dragas*) and mining of primary deposits underground and in open pits (*filão*) (Fig. 1). In so-called primary deposits, gold is embedded in rock veins. When primary gold deposits are eroded and flushed out of the rock as fine gold dust or as small grains, they are called secondary deposits. Baixão is the most common method in the region. This process uses water jets to elutriate gold-bearing soil, pumping it over sluice boxes and amalgamating the gold with mercury, a process well described in many studies[19,20]. The gold production process of the dragas is very similar to the process on land but without the need for water jetting, as the sediments from the riverbeds can be pumped over the sluice box directly[21]. A common technique for mining the filão in ASGM uses amalgamated copper plates to trap the gold in the crushed ore[22]. Sometimes the crushed ore is also leached with cyanide instead of or in combination with mercury use before cyanidation[6] on the amalgamated copper plates to extract the gold. The latter technique should be eliminated as part of the NAP of the United Nations Minamata Convention on mercury.

Social conditions in ASGM mines, deforestation rates and the effects on health of mercury in rivers and soils have been studied many times[6,23–25]. Our team published a separate article on the social aspects of the ASGM sector in the Tapajós region, for example, the absence of the state, the illegality and informality of mining operations, poor working conditions, difficult living conditions, unstable payment of wages and autonomy[26]. Much research on mercury in soils, plants, waters, fish and humans has also been done in the Brazilian Amazon rainforest since the end of the 1980s[5,19,26–28]. Studies of the specific amounts of mercury used and recovered in ASGM are, however, rare. They have small sample sizes of very few different types of mine, and

Fig. 2 | A typical retort. Photograph shows a typical retort as used in the Tapajós region.

there are problems in comparability[21]. Even less research has been done on energy intensity and the climate impact of ASGM. Studies on energy intensity, all in countries other than Brazil, mostly refer to individual mines and specific regions, and there are methodological problems in comparing the results[29–31]. The international discussion about climate change and the contribution of mining to greenhouse gas emissions is gaining importance, which was the motivation for us not only to look at mercury in ASGM but also to determine energy use.

There is still a gap in knowledge about the current extent of mercury use, retort efficiency and the carbon footprint of ASGM. The Tapajós region, which is known to produce at least 15 tons of gold per year[13], provided the opportunity to collect a larger amount of empirical data for different mining methods within a reasonable amount of time. This included mines that were inaccessible to outsiders and about which little in situ data are typically published. In our study, we were able to collect and analyse data on energy consumption, mercury use, loss and recovery from over 100 data samplings at different mines. The Tapajós region is also well suited to this research because here ASGM shows a development in mechanization that might sooner or later take place in other regions of the world. In addition, since the 1990s, there have been several programmes to train miners in the use of retorts, but there is no record of how many of ASGM sites (*garimpos*) in the region use retorts[32].

The loss and recovery of mercury in ASGM

Retorts are very simply built (Fig. 2). Using a gas burner and a distillation, the mercury is evaporated from the amalgam and recovered. The distribution, purchase and use of mercury is not prohibited in Brazil when it is licensed by a competent environmental agency, for example, the Brazilian Ministry of Environment[33,34]. The policies and regulations of ASGM in Brazil are much discussed and criticized because they are too complex, especially for garimpeiros, difficult to monitor and offer many loopholes[19,32,33,35]. On the basis of our surveys, the retorts cost about BRL 1,300 (Brazilian real), while a kilogram of mercury costs about BRL 1,400. Depending on the quality of the retort and the experience of the user, a retort can pay back its cost already after its second use. The results of the measurements of mercury loss and recovery are shown in Fig. 3. The sum of the mercury lost (blue bar), mercury recovered from squeezing the amalgam through a cloth (orange bar) and mercury recovered with the retort (grey bar) equals the total amount of mercury used. In Fig. 3, the values are scattered depending on the experience of the garimpeiros, the quality of the retorts and the geological circumstances, for example, ore grade.

The arithmetic mean of mercury used is 1.7 kg per kg of fine gold (Au). The arithmetic mean of mercury lost is around 0.19 kg per kg of Au (blue line in Fig. 3), taking place at different stages of the gold production. Spillage occurs while mixing the mercury with the gold-bearing concentrate from the carpets or while panning the mercury-concentrate mixture. This leads to metallic mercury emissions to soil and/or river water. The recently introduced practice of separate water basins for panning the gold in a closed system away from the rivers (*piscinas*) is therefore especially important. Another type of loss is leakage, when the mercury is evaporated in the retort, which results in mercury emissions to the atmosphere. Some mercury also remains in the sponge gold, which is first released after the sponge gold is sold to gold shops and formed into a doré bar. There are some indications that after the amalgam is burned for 15 to 20 minutes in a retort, the content of mercury in the sponge gold is rather low[36]. This practice differs from other countries where the amalgam is often first burned in the gold shops.

Figure 3 clearly shows that the loss of mercury is substantially lower than its use. This is a success of the use of retorts, which are able to retain at least 75% of the mercury, depending on the quality of the retort and the experience of the user. What stands out in Fig. 3 is that for the measurements on the Hg13, Hg24, Hg25 and Hg55, the total mercury loss was negative. All the four cases were on *dragas*, meaning that those four measurements recovered more mercury from the riverbed than was originally used. This is in line with results from Balzino et al.[21]. We can conclude that there is a significant amount of metallic mercury in riverbed sediment, most likely from former mining activities. The high mercury levels in sediments in rivers and lakes in the Tapajós region is a well-researched and long known phenomenon[27,28]. In 1994, Reuther already showed that much of the metallic mercury directly released from the mines persists as metallic mercury[27]. *Dragas* function as collectors of old mercury deposits, but they have other major impacts on river flora and fauna. The substantially higher value from measurement Hg34 is due to the fact that old sediments were reprocessed from abandoned *garimpo* tailings (*rejeito*) in which substantially higher gold content was expected by the garimpeiros.

In addition to the mercury recovery potential of the retorts, we also conducted a survey about the acceptance of this technology in the study area. Our results show that 88% of the *garimpos* in the area use a retort. This could be different in other regions, for example, illegal mining in indigenous territories (*reserva indigena*). But as mercury is expensive, there is an economic incentive for miners to use retorts.

Relating our results for the average loss of mercury (0.19 kg Hg kg^{-1} Au) to ASGM gold production in the state of Para, we estimated the annual mercury emissions from ASGM. ASGM gold production is reported to be 10 t Au per year and 18 t Au per year for 2019 and 2020, respectively[13]. This results in total mercury emissions of at least 5 t of mercury in the period of 2019 to 2020. By extrapolating our findings from Para on ASGM gold production to the total gold production in Brazil of 54 tons (ref. 13), we arrive at total emissions of at least 10 t of mercury in the period of 2019 to 2020. This number assumes that every *garimpo* uses a retort, which means it is an optimistic estimate.

Energy consumption by ASGM

Discussions about the environmental impact of ASGM mostly focus on mercury or deforestation, while energy consumption and its impact on climate change are often neglected. Figure 4 shows our results of 34 surveys for energy intensity per kg of fine gold (Au) of the different types of gold mining technique in the Tapajós region. Most available data were on the production of gold from secondary deposits on land with excavators. This is also the most common form of gold mining in the Tapajós region. In the figure a trend can be seen in which the energy intensity per kg of fine gold (kg diesel kg^{-1} Au) of each type of mining in

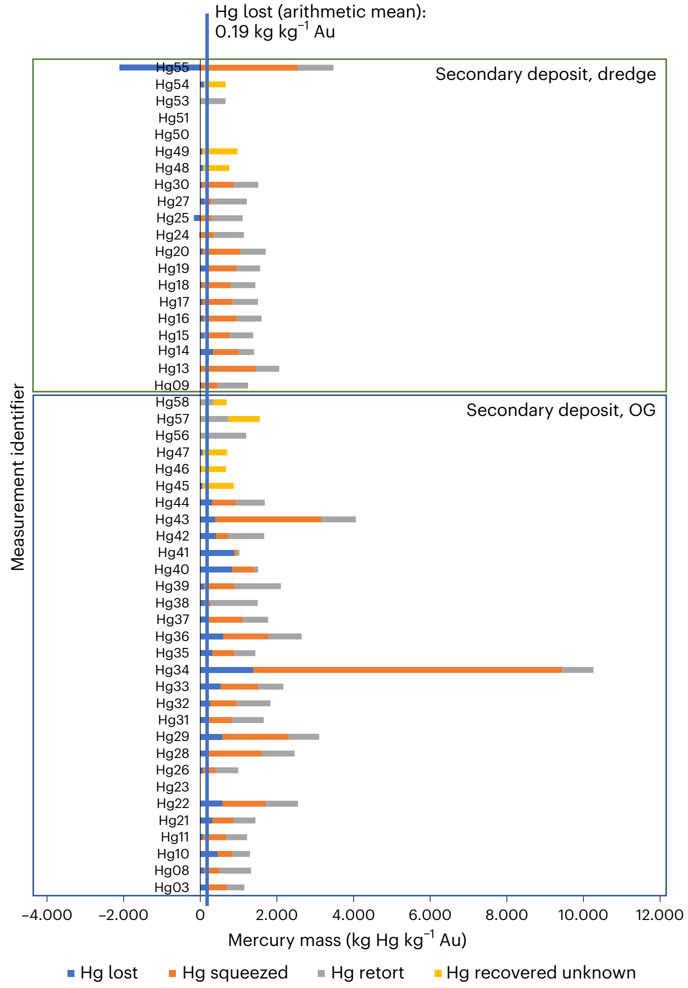

Fig. 3 | Mass balances of mercury loss and recovery. Values in kg Hg per kg of fine gold (Au) from secondary deposits mined by dredging or in overground (OG) operations in the Tapajós region (raw data in Supplementary Table 1).

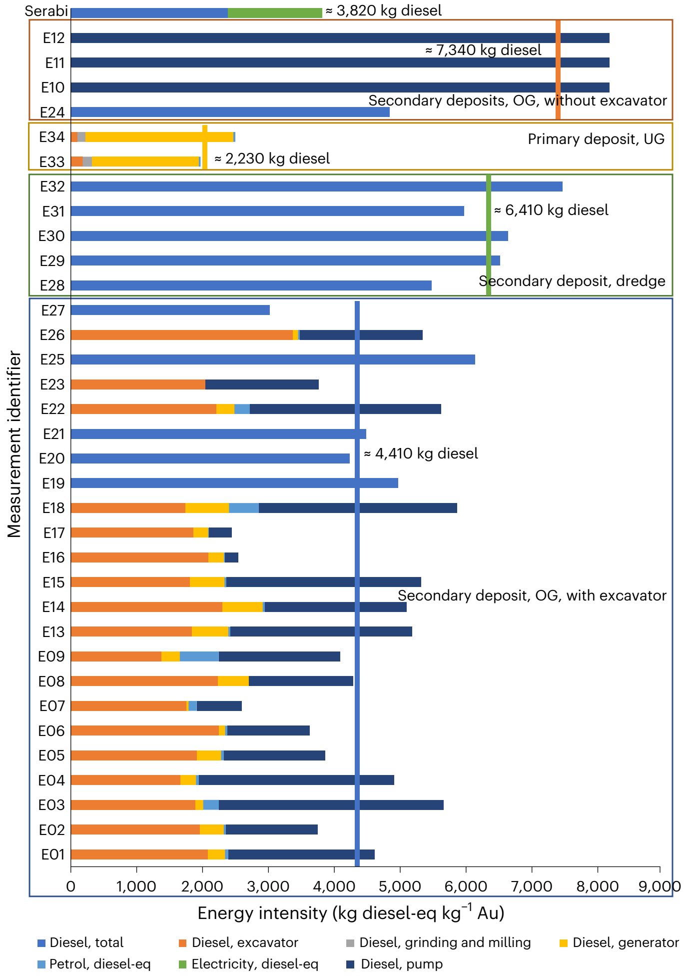

Fig. 4 | Energy consumption per kg of fine gold. Values in kg diesel equivalent (diesel-eq) per kg of fine gold for different gold production techniques in the Tapajós region (without transport). Note: OG and UG stand for overground and underground, respectively (raw data in Supplementary Table 3).

ascending order is: mining of primary deposits underground (2,230 kg diesel kg^{-1} Au), mining of secondary deposits on land with excavators (4,410 kg diesel kg^{-1} Au), mining of secondary deposits on riverbeds with dredges (6,410 kg diesel kg^{-1} Au) and mining of secondary deposits on land without excavators (7,340 kg diesel kg^{-1} Au).

A possible explanation why secondary mining with excavators has lower fuel consumption than the old method without excavators is that digging a pit with an excavator is more efficient than water jetting a pit. Mechanization also makes work for the garimpeiros easier[26] and provides the possibility to remove the fertile topsoil and backfill it later, which, however, based on our experience is rarely done. On the other hand, gold production as a whole is faster with the use of heavy machinery. This might lead to a classical rebound effect, meaning that more mines, and thus more area in the rainforest, are opened in a given time period. Additionally, the use of excavators might lead to the development of more infrastructure such as roads and airstrips in the region[37]. A possible explanation of the lowest fuel consumption for the underground mining of primary deposits is that much of the energy expended in this type of mining is from explosives (≈20 kg explosives kg^{-1} Au) and manual work. The large-scale gold mine (LSGM) Serabi (Fig. 4, bar on the top), located in the same region, has lower fuel consumption (3,820 kg diesel kg^{-1} Au) than the mining of secondary deposits on land with excavators. Serabi is also the only type of mining observed in our research that at least partly uses energy from the grid. Energy from the grid was converted to diesel equivalents (Methods) in Fig. 4 (green bar at the top).

Comparison to other gold production techniques

The carbon footprint expressed in kg carbon dioxide equivalent per kilogram fine gold (kg CO_2eq kg^{-1} Au) of each type of mining in ascending order is: mining of primary deposits underground (9,750 kg CO_2eq kg^{-1} Au), mining of secondary deposits on land with excavators (18,000 kg CO_2eq kg^{-1} Au), mining of secondary deposits on rivers with dredges (25.700 kg CO_2eq kg^{-1} Au) and mining of secondary deposits on land without excavators (29.200 kg CO_2eq kg^{-1} Au). Figure 5 compares the impact on climate change per kg of fine gold (Au) for different gold production techniques, based on our study using literature sources. Our findings show that the climate impact by ASGM is between 10 and 30 t CO_2eq kg^{-1} Au (blue area in Fig. 5). The values for ASGM are in a comparable range to more recent surveys for LSGM by the company SKARN (left bar in the green area in Fig. 5)[38].

In our study, we observed a lower energy intensity, and therefore lower climate impact, with increasing mechanization (compare the second and fourth bars in Fig. 5) because of increased process efficiency. This means that increasing mechanization can actually lead to lower climate impact. But as discussed above, this development could also lead to a rebound effect, which in turn would lead to higher climate impact for the whole ASGM system in Brazil.

The *garimpos* are in remote areas in the Amazon rainforest and all the materials (for example, diesel) have to be transported to the sites by planes, boats or cars depending on the season and location.

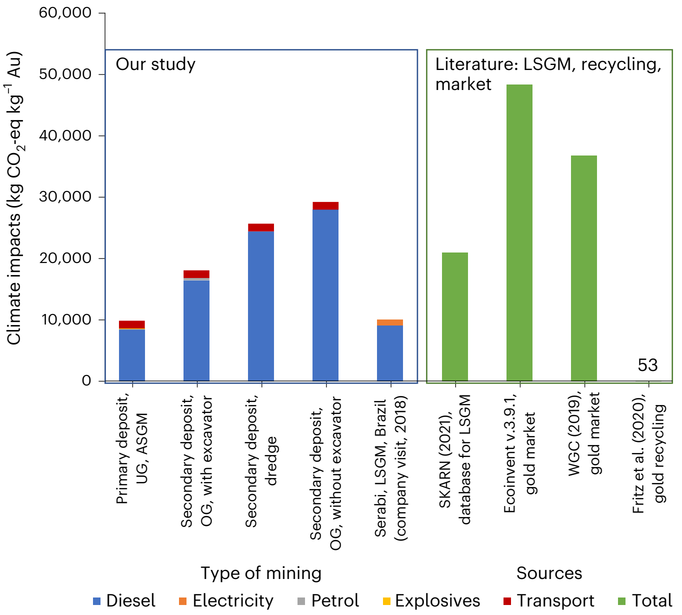

Fig. 5 | Climate impact of gold production from ASGM and LSGM. Comparison of our study and different literature values in kg CO_2 equivalent per kg of fine gold (Au) (data in Supplementary Table 4). Note: WGC stands for World Gold Council.

What stands out is that, according to our study, logistics in the *garimpos* (red section of the first four bars) only has a small contribution (1,260 kg CO_2eq kg^{-1} Au) to overall climate impact. During our expedition in 2018, we also did a two-day company visit to the LSGM site Serabi. The underground gold mine is located in a former *garimpo* in our study area. In Fig. 5 it can be seen that the climate impact by Serabi (fifth bar) is similarly low as underground ASGM (first bar) and has the lowest climate impact compared to the other gold mining techniques. This contrasts with the energy intensity values, where Serabi was comparable to mining of secondary deposits with excavators (blue area in Fig. 4). The reason for this is that Serabi utilizes about ≈40% of their energy from the grid, which in Brazil consists of only ≈10% non-renewables[39].

The climate impact of industrial gold production includes uncertainty arising from a variety of different technologies, countries, energy carriers and deposits, to name just a few sources[38,40,41]. The most accurate data currently available are probably that of SKARN, as they are based on an evaluation of almost 500 assets[38]. The value for LSGM is therefore around 21,000 kg CO_2eq kg^{-1} Au. Overall, the carbon footprints of ASGM and LSGM are comparably high.

For consumers who are not only looking for responsibly sourced gold (that is, without poor working conditions and perhaps without the use of mercury) but are also concerned about climate change, gold from modern industrial recycling is clearly the best solution with a value of 53 kg CO_2eq kg^{-1} Au (bar on the far right). Although, we can recycle only what is in circulation and the amount of gold scrap cannot satisfy market demands.

Discussion

Our research found that retorts are an effective and cheap technology for the reduction of mercury emissions. Moreover, we show that the efforts taken in the region since the 1990s to train garimpeiros in the use of retorts were successful. But our study also shows that even with the use of retorts, the level of emissions occurring is still too high. Brazil's 1989 regulation on mercury use in gold mining (which is no longer in force) specifies the use of retorts in ASGM and a mercury recovery rate of 96% (ref. 34). Our analysis shows that this rate is still far from being reached today. Therefore, our results provide an important insight for policymakers to take further steps to curb ASGM mercury emissions beyond the use of retorts.

An interesting detail was the observation that in some cases, mercury recovery was more than 100%. The reason for this is probably that the metallic mercury content in sediments is already high because gold has been mined in the region for decades with the help of mercury, and mining has also been carried out at old sites or riverbeds. It is not fully understood under what circumstances methylation of this mercury takes place, nevertheless the high mercury content in sediments means that no matter how carefully and responsibly a garimpo is using mercury, its release will continue to occur in future gold mining in the region. Thus, a greater focus on the relationship between mercury emissions and sedimentation could produce interesting findings. A large-scale survey on mercury contamination of soils in the region would also be very helpful at this point.

Additionally, we found that there has been relatively little research on ASGM impact on climate change. Our research shows that ASGM climate impact in the Tapajós varies depending on the process technology used but is overall in comparable ranges to those of LSGM. The increased use of excavators in the *garimpos* during the last 20 years could lead to a lower specific energy intensity due to an increase of efficiency. Besides its positive effects, this trend could also lead to rebound effects or acceleration of infrastructure development, for example, building roads in the rainforest. Our findings regarding the relatively high climate impact of ASGM could have significant implications for certification of environmentally responsible ASGM sites, which has focused on mercury emissions and typically not considered climate impact. This means that when gold extraction in ASGM is labelled as 'responsible', 'fair', 'sustainable' or 'green', its mining may minimize mercury loss but potentially create a non-negligible amount of CO_2 emissions. As the impact on climate change by gold mining mainly results from burning fossil energy, high investment in regenerative energies would be necessary.

A further limitation is that our results refer to the Tapajós region. In other regions, the situation may be different. However, the extensive gold mining in the Tapajós region is diverse and is indicative of how gold mining could develop in other regions of the world, especially through mechanization by machines but also through the use of simple tools such as retorts. In this respect, we consider our analysis to be relevant for ASGM in other countries as well.

Our overall conclusion is that Brazil must finally adopt its NAP of the Minamata Convention and thus fulfil the United Nations requirements on mercury. Additionally, a better and simpler formalization of ASGM permits and effective compliance monitoring are needed. But regardless of this, energy-intensive gold mining, including artisanal mining, still has a long and hard way to go to reduce its impact on the climate.

Methods

Different research methods were used to collect primary data on the consumption of diesel and petrol, mercury use and loss and the quantity of gold extracted. Primary data were gathered through measurements, interviews and questionnaires. The raw data for all our measurements can be found in the Supplementary Tables. For this study, several field trips were undertaken, mainly in the period of 2018–2022 to gather as much primary data as possible, largely through measurements of mercury and energy use and through open-ended, information-oriented interviews with complementary observations[42]. All interviewees were aware of the purpose of the interviews and agreed to it. Research expeditions were made to small villages in the Tapajós region and the cities of Santarém, Itaituba and approximately 50 mining sites. Many contacts emerged from people one member of the research team personally knew, which gave us access to sites that would otherwise be inaccessible to outsiders. Starting with known contacts, snowball sampling was used to expand the network and to avoid bias[43]. Garimpeiros and *donos* (*garimpo* managers) are key actors in the sector, and thus the survey questions were formulated to mainly target these groups. In addition, politicians, scientists, shop owners, nurses, teachers and many other groups were interviewed. These interviews were also used for a social analysis published in 2020[26].

The loss and recovery of mercury by using retorts was measured 47 times in situ and is expressed in a mass balance for different ASGM sites in the Tapajós region. This is in line with the guidance document on how to develop NAPs by the United Nations Environmental Programme project PlanetGOLD[44]. To enable comparability of results (both within the study and with other reported results), it is crucial to know the fine gold (Au) content in the different gold products. For the most part, there are two physical forms of gold products in the *garimpos*: sponge gold and doré. Sponge gold is the product retrieved by evaporating mercury from the amalgam. It is then sold to gold shops, which refine it with borax to retrieve the doré. As the sponge gold is sold by individual garimpeiros in different villages and at different times, it was not possible to determine the gold content in relation to the specific weight of sponge gold. However, we were able to gather primary data on the weight of both sponge gold and doré 12 times from different *dragas* and we determined a fine gold content of ≈88% Au (mass fraction). The fine gold content in the doré (mass fraction) was determined using primary data from ten interviewees (mainly gold shop owners) from six different towns and differs depending on the production process: mining of secondary deposits on land (*baixão*: ≈91% Au) and by gold dredges (*dragas*: ≈93% Au) and mining of primary deposits underground and in open pits (*filão*: ≈78% Au).

The use, loss and recovery of mercury and the extracted gold were analysed by 47 mass balances on site[45]. This direct measurement approach is recommended by the United Nations Global Mercury Assessment[41,46]. To determine whether retort use in the *garimpos* we visited were exceptions or the rule, we conducted an anonymous random survey on retort use with 42 interviews in different bed and breakfasts, restaurants, shops, bars and cabarets in the study area. Of the interviewees, 27 were garimpeiros and 14 were managers or owners of *garimpos*.

The mass balance approach used in this study for mercury is particularly suitable in the rudimentary conditions of the *garimpos* in the Brazilian Amazon rainforest. However, it also poses limitations as we do not know the elemental composition of the samples, but only their absolute weight. Therefore, we cannot say exactly how much mercury is lost at which specific process step, and we were unable to trace the accumulation of mercury in the environment. If the mass balances for mercury use were supplemented by a handheld X-ray fluorescence spectroscopy, it would be possible to gain more informative results. Mass balances would also need to be supplemented with soil, water and flora measurements directly at the site.

The near impossibility of doing unannounced or even undercover observations of the *garimpos* means there is an additional, uncontrolled factor that individuals may have modified an aspect of their behaviour in response to their awareness of being observed by our team (Hawthorne effect). The implications of this might be that less care is taken in gold production than we observed. But it seems very unlikely that garimpeiros work less carefully with mercury, because losing mercury that could be recovered would entail a financial loss for them.

Gold production is characterized as an energy-intensive industry with many associated impacts on climate change[40]. It is not well understood yet how the ASGM sector performs in regard to this matter. We collected data on the energy consumption of 34 different mines using different production processes. We calculated the amount of diesel used and gold produced over a fixed period of time, conducted information-oriented interviews with complementary observations and looked into the accounts of the *donos*.

From some surveys we obtained data on other energy carriers, for example, petrol for chainsaws. To unify terminology and facilitate comparability, we converted these values to their equivalent mass of diesel based on their heating value.

Additionally, we estimated the fuel demand for the logistics (mainly for transportation of fuel to the *garimpos*) needed for the production. Depending on the season and the location or the connection to the road network, the most important means of transport are boats, pickups, trucks and light aircraft. On the basis of our estimates, transport fuel consumption is around 330 kg diesel kg^{-1} Au. This consumption is not included in Fig. 4 and would be added on top of every single data point (except Serabi).

To determine logistics fuel consumption in the *garimpo*, we used satellite and georeferenced data to determine average distances between fuel stations, small towns and *garimpos*. Additionally, we had interview data for specific fuel consumption for different trucks and airplanes. From some surveys, we obtained data on other energy carriers such as kerosene or petrol. To unify terminology and facilitate comparability, we converted these to their equivalent mass of diesel based on their heating value. For the LSGM site Serabi, we also had to convert one energy carrier (electricity) to diesel equivalents. This was done using primary data gathered at the company visit in Serabi in 2018 on site-specific diesel consumption per electricity amount generated (≈0.28 l kWh^{-1}).

Finally, we estimated the associated climate change impact from our survey results on fuel consumption in the section 'Energy consumption by ASGM' and the transport and explosives of gold production from ASGM using the ecoinvent v.3.9.1 database[47].

We observed idiosyncratic and non-standard bookkeeping practices by garimpeiros, some of whom were illiterate[26]. We attempted to validate these figures by comparing them with data from the literature, machine datasheets, mass balances and natural laws. Verifiably incorrect or non-sensical values were removed. Outliers in the data were retained if there was a possible explanation for them.

Ethical statement

All our research was conducted in accordance with the statutes of the Ethics Committee for Research and Publication Projects of Pforzheim University, which is in line with the ethical requirements of the German Research Foundation (DFG). All interviewees were aware of the purpose of the interviews and agreed to it.

Reporting summary

Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

All raw data (anonymous) and data analysis cited in the article are provided in the Supplementary tables.

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Author contributions

Project planning: M.S., B.P.; funding: M.S.; methodology: B.F., B.P., M.S.; on-site data collection: B.P., B.F., L.d.S.T., A.C.d.S.A.; data analysis: B.F., B.P.; validation: M.S.; writing: B.F., M.S.

Competing interests

The authors declare no competing interests.

Additional information

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Study description	In our study, data on energy consumption and mercury use and recovery in the Brazilian Amazon Rainforest were collected through interviews and measurements.
Research sample	Several field trips to aproximately 50 mining sites for interviews on energy consumption. For mercury use and recovery 47 mass balances were done in the mining sites.
Sampling strategy	No sample size calculation was done, as it is very hard to gether data in the remote and irregular gold minining sites in the middle of the Amazon Rainforest. We therefore tried to just gather as much data as possible.
Data collection	Data collection was mainly done by Bernhard Peregovich (UFOPA) and Benjamin Fritz (HS PF). For energy consumption via interviews and questionaires. For mercury use and recovery through measurements (mass balance).
Timing and spatial scale	2018 - 2022
Data exclusions	Verifiably incorrect or nonsensical values were removed. Outliers in the data were retained if there was a possible explanation for them.
Reproducibility	n/a; The measurements are unique.
Randomization	Not relevant, because of the remote character of the mines, that are not open to the public, you can not be selective with you participants. Most of the times, interviewees will not tell you too much about their background in order to stay anonymous.
Blinding	n/a

Did the study involve field work? ☒ Yes ☐ No

Field work, collection and transport

Field conditions	Mainly dry season in Brazilian Amazon Rainforest with little rainfall.
Location	Our results refer to the Tapajós region.
Access & import/export	not relevant
Disturbance	Possibly disturbance with positive effects as individuals might have modified an aspect of their behavior in response to their awareness of being observed by our team (Hawthorne effect).

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