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# Formalizing Artisanal and Small-scale Gold Mining: a Grand Challenge of the Minamata Convention

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## In Brief

The Minamata Convention mandates formalization of artisanal and small-scale gold mining to reduce mercury emissions and releases. In this article, we review the reasons previous attempts to do this have largely failed, outline miner-centric approaches that are more likely to succeed and estimate the likely costs of such approaches. We argue that consumers, large mining corporations, and governments, not small-scale miners, should bear these costs.

## Highlights

- The Minamata Convention requires countries with artisanal and small-scale gold mining (ASGM) sectors to formalize them in order to reduce mercury emissions and releases.
- Previous efforts to reform ASGM to reduce mercury emissions and releases have largely failed.
- Bottom-up (miner-centric) approaches to formalization are needed instead but extending these approaches globally will be expensive.
- We argue that governments, consumers, and large-mining corporations should pay for this.

## Science for Society

Over 20 million miners around the world participate in artisanal and small-scale gold mining (ASGM), often without legal permission, protection, or regulation. Mercury is frequently emitted into the atmosphere or released into land and water as part of the gold mining process. The Minamata Convention on Mercury requires signatories to extend official permission, protection, and regulation to ASGM as part of a strategy to reduce or eliminate the use of mercury in ASGM. Previous attempts to reform ASGM have not succeeded because they have mainly focused on imposing legal requirements and technical substitutes without understanding miners' needs and contexts. Comprehensive miner-centric approaches are needed instead. We estimate the likely costs of extending such approaches globally, and discuss options for governments, large mining corporations, and consumers to pay for them.

**Formalizing Artisanal and Small-scale Gold Mining: a Grand Challenge of the Minamata Convention**

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Summary

Artisanal and small-scale gold mining (ASGM) is the world's largest source of anthropogenic mercury emissions and releases. These have devastating consequences for miners' health and the environment. Most of the >20 million ASGM miners worldwide are not officially recognized, registered, regulated, or protected by state laws.  Formalization—the process of organizing, registering, and reforming ASGM—is mandated by the Minamata Convention on Mercury. Previous attempts to reduce mercury emissions from ASGM have largely failed. Our perspective argues that signatories to the Convention will only succeed in reducing ASGM mercury emissions and releases with comprehensive bottom-up formalization approaches centered around working with miners, and significant external funding from consumers, large mining corporations, and governments. The approximate global five-year cost of this approach could be $355 million USD (upper and lower estimate bounds: $213–742 million) if scaled per country, or $808 million USD ($248 million–$2.17 billion) if scaled per miner.

## Introduction

Over the past three decades, the global appetite for gold has continued to grow, driven by increased consumer demand from Asia and soaring investor demand following spiking gold prices.[1] Artisanal and Small-scale Gold Mining (ASGM) is prevalent in at least 64 countries (Figure 1). The estimated number of ASGM miners increased from ~16 million in 2011[2] to over 20 million by 2020[3], with a corresponding increase in annual production from 380-450 tonnes of gold in 2010-2011 to almost 600 tonnes by 2020[4]. The ASGM sector is worth an estimated US$36 billion[4] but remains largely informal globally—that is, it is not officially recognized or registered, and neither regulated nor protected by state laws. The persistence of informality has been attributed to bureaucratic, financial, and legal barriers[5–7], as well as the lack of incentives among ASGM miners, who commonly rely on traditional or customary land claims, to have their claims sanctioned by governments.[8–10] A structuralist perspective on informality highlights that the cheap and flexible labor force provided by ASGM miners is extremely useful to global capital.[1]

Informality lowers the barriers to entry[11] and encourages widespread participation in ASGM. As such, in many regions around the globe, ASGM activities have become the backbone of rural economies.[12–14] For millions of miners and their dependents, ASGM is the primary source of income[15]. For others, it is a complementary income source that helps them overcome periods of crisis or agricultural low seasons.[16,17] Unfortunately, the lack of oversight and protections arising from informality has underpinned and facilitated egregious human rights and environmental violations.[18–20] For instance, ASGM miners are particularly vulnerable to extortion and arrest.[17,21–23] Of the many environmental issues arising from ASGM, policy makers and researchers have largely focused on mercury pollution.

Mercury use remains one of the simplest and most cost-effective ways to extract and concentrate gold by ASGM miners.[24,25] Miners use mercury to extract liberated gold particles in concentrates or whole ore. The mercury forms an amalgam that miners can heat to evaporate the mercury, leaving behind the gold.[24] Mercury lost when disposing of the amalgamating solution and mercury vaporized from the amalgam are the main sources of mercury emissions from ASGM activities. According to UNEP,[26] over 2,000 tonnes of mercury are emitted or released into the environment by ASGM miners worldwide. The inhalation of mercury vapor has negative health impacts on miners[27] and on people who live adjacent to gold workshops.[28] In aquatic ecosystems, mercury can form compounds with cyanide $Hg(CN)_2$, which can bioaccumulate.[29]

The 2013 Minamata Convention on Mercury seeks to reduce anthropogenic emissions of mercury (Box 1),[30] including from ASGM. As the environmental problems associated with ASGM have been primarily attributed to pervasive informality, policymakers have increasingly focused on formalization as the fundamental strategy to reform ASGM.[7] Researchers and policymakers have argued that formalization will not only stimulate economic growth and increase tax revenues by giving ASGM miners strong property titles, but will also improve working conditions and promote better environmental management.[31–35] The Minamata Convention therefore requires any Party where “artisanal and small-scale gold mining and processing in its territory is more than insignificant” to develop a National Action Plan (NAP) that includes steps towards ASGM formalization (Article 7.3).[36,37] By January 2022, sixteen countries had published NAPs: Burkina Faso,[38] Burundi,[39] Central African Republic,[40] Democratic Republic of Congo[41] (Box 2), Ecuador,[42] Guinea,[43] Laos,[44] Madagascar,[45] Mali,[46] Mongolia,[47] Nigeria[48], Republic of Congo,[49] Senegal,[50] Sierra Leone,[51] Uganda,[52] and Zimbabwe[53] (Figure 1).

This Perspective seeks to inform researchers and policymakers on how best to achieve the stated goals of the Minamata Convention as it relates to ASGM. We review previous attempts to reduce mercury emissions and releases from ASGM, and outline what successful reform will look like, how much it will cost, and who should pay for it. Previous approaches have largely failed. Comprehensive miner-centered approaches to formalization are needed but extending these approaches globally will be expensive. We argue that governments, consumers, and large corporations should fund such approaches.

## A brief history of controlling ASGM mercury emissions and releases

The nature of attempts to reduce mercury usage in ASGM, and the discourses used to underpin these reforms, has evolved over the past decades from isolated technical interventions to the full-scale formalization approaches mandated in the Minamata Convention.[54,55] The 1980s gold rush in the Amazon triggered a wave of baseline monitoring studies[56–58] that brought attention to mercury pollution as a consequence of ASGM. Subsequent research in the 1990s focused on building technical capacity.[55] In parallel, discourses on formalization in this period followed the more 'legalistic' lens popularized by De Soto, which emphasized the need to remove bureaucratic restrictions so that entrepreneurial small-scale miners could benefit from technical assistance and create more taxable revenue.[55,59,60]

The 2002-2007 GEF/UNEP/UNIDO Global Mercury Project (GMP), the most significant international effort before the Minamata Convention,[25,55] epitomized this period's framing of the problem as primarily one of awareness and technical capacity. The GMP aimed to educate ASGM miners and communities about the hazards of mercury and propose technical solutions to avoid mercury usage in six pilot countries (Brazil, Indonesia, Laos, Sudan, Tanzania, and Zimbabwe).[61] The project educated 300 trainers, who in turn trained an estimated 30,000 ASGM miners and community members.[61] Meanwhile, technical interventions included the introduction of relatively simple technologies and practices, such as burning amalgam in retorts and installing fume hoods in gold shops, which can reduce vapor emissions by 90%[61]. In parallel, other isolated projects funded by the Geological Survey of Denmark and Greenland introduced an alternative to mercury amalgamation using borax in the Philippines, Tanzania, and Bolivia.[62,63] Despite these efforts, interventions centered on awareness and technical capacity did not lead to lasting changes. As Veiga and Fadina noted, ‘At the end of six years of this multimillion dollar UN project [the GMP], not many miners continued with the methods they had learned’.[25]

As acknowledged in a post-project appraisal, the GMP encountered difficulties that stemmed from the fact that ASGM is largely poverty-driven, and that most ASGM miners lack the financial means to prioritize long-term health and environmental concerns over short-term economic considerations even with training and education.[61] Furthermore, some alternatives to mercury amalgamation are only economically viable with certain ores. For example, borax-treatment has been used for centuries, but requires ores with low sulfide concentrations[63] and high grades of gold due to the high rate of gold loss during the process.[64] Moreover, lack of trust by miners towards researchers and authorities, the low profitability of these gold extraction techniques, and the absence of trainers to help when the new equipment breaks down have all contributed to the widespread failure to change mining practices.[25] Beyond these financial constraints, the educational and technical focus of the GMP was ultimately unsuccessful because of poor knowledge of governance dynamics and an inability to tackle the structural issues that have created a widespread informal ASGM sector. Deep structural issues that have hindered ASGM reform include policy biases towards large-scale mining and the persistence of elite patronage networks, whereby corrupt government officials have an economic incentive to ensure revenue streams by maintaining informality.[54,55,65–67]

Increasing awareness of the poverty-driven nature of ASGM led to a phase of discourse in the 2000s centered around livelihoods'.[55] Recasting ASGM as not simply an environmental problem, but also a vital livelihood in low-income communities and rural areas, particularly as a complement to subsistence agriculture[68–71], has influenced policy discourse to emphasize the need to formalize the sector not only for tax revenue and/or environmental compliance, but also to protect livelihoods.

## An opportunity to develop better formalization approaches

Top-down, 'carrot and stick' approaches to formalization, in which miners have to jump through expensive bureaucratic hoops in order to achieve legal titles and access to technical and financial aid, have largely failed.[25,54,55] In Peru, slow permit allocation and weak enforcement undermined an attempt to formalize ASGM and restrict it to a 5,000 $km^2$ 'mining corridor', and failed to prevent a dramatic increase in deforestation for mining outside of the designated mining corridor, including in protected area buffer zones and indigenous territories.[72] A failure to adequately train artisanal miners in improved techniques has resulted in legal (pseudo-formalized) miners in Colombia polluting at equal rates to those of informal miners.[73] And even in rare cases that are considered to be successful, such as that of Guyana where 88% of ASGM is formalized, exclusionary dynamics and elite capture are prevalent.[73] The use of military and police violence to enforce restrictions on informal mining has led to human rights abuses[23] and failed to tackle environmental problems.[17,74] These examples show that a narrow focus on titling by no means guarantees that environmental regulations will be followed, as this requires money, training and incentives, and enforcement.[75] And even where formalization has occurred, formal ASGM operations are frequently found to rely on informal labour.[76]

There is widespread consensus in policy and academic circles that comprehensive bottom-up approaches are needed.[33,77] According to the International Institute for Sustainable Development (Winnipeg), bottom-up approaches are characterized by direct engagement with ASGM miners and tailoring the process to the specific complexities of each case.[77,78] For example, a formalization process in Mali started by recognizing traditional patterns of organizing gold miners instead of creating new cooperatives in a top-down manner, and making barriers low so that miners only had to apply for a $8 'gold-washing' (i.e. gold panning) card.[79] Formalization efforts in Mongolia have created space in the legal-regulatory framework for diverse institutional arrangements, recognizing not only registered companies, but also unregistered partnerships and miners' NGOs. [33]

In response to the failures of previous mercury reduction strategies, the Minamata Convention recognizes the need for a comprehensive approach to tackling mercury emissions that includes formalizing ASGM. While the process may appear bottom-up because each signatory country develops their own NAP, and the wording of the NAPs recognizes the need to include previously marginalized ASGM miners, the process of drafting and implementing the NAPs has echoed some of the previous problems with top-down approaches. The drafting of the NAPs has been delegated to consultants who may have consulted mining communities to a larger or lesser extent, but this does not mean that the mining communities have played an active role in drafting the NAPs. As such, the process has been driven by government agencies and consultants rather than mining communities.

In addition to the process being implemented *de facto* top-down by government ministries, implementation has been led by ministries lacking knowledge of and power over mining dynamics. While NAP implementation might ideally be a collaboration across multiple ministries, including the mining, environmental, labor, and health ministries, NAP implementation has mostly been delegated to environmental ministries that in some cases (e.g. Ghana and Sierra Leone) have little knowledge of informal mining dynamics, e.g. concerning the participation of women in the informal ASGM sector.[78,80] Furthermore, they typically have no power over permit allocation, inhibiting effective action and creating inter-ministerial conflict.[55]

Early indications from the development of NAPs offer warnings that strategic mistakes with previous formalization processes are being repeated, and in particular that structural barriers to formalization are not being eliminated. The aim to totally eliminate mercury instead of reducing mercury use where necessary is impractical in light of the economic constraints micro-ASGM miners face. A bias towards allocating the best and largest mining concessions to large-scale mining continues to be a problem in countries such as Cambodia and Ghana,[55,81] making it unclear where governments will allocate viable space for a formalized ASGM sector. In writing separate NAPs at a country-level, countries are missing opportunities for crossregional collaboration to tackle the illegal trade in gold and mercury.[55] Given the daunting scale of the challenge—in particular, the need to understand complex governance dynamics across vast scales—Hilson has proposed the 'formalization bubble' approach[54]. This strategy remains to be tested empirically, but would start with small, contained pilot sites, anchored around ASGM miners who are already licensed, as a way to effectively concentrate the spread of technical capacity and access to finance. By concentrating stakeholders, the strategy aims to generate accountability amongst stakeholders and thus reduce the risk of elite capture.[54]

**Comprehensive bottom-up approaches have a high price tag**

Comprehensive bottom-up ASGM formalization must deliver measures such as registration, environmental and social impact assessment, training and capacity building, monitoring, enforcement, and restoration needed to improve socio-environmental impacts. Since ASGM miners largely lack related financial and technical capacity,[33] assessment and compliance costs need to be funded from other sources. Up-front subsidies for replacement of equipment are also required. For example, a retort might cost US$5-50 and a shaking table US$1,000-10,000.[82] In many ASGM contexts, miners take their ore to independent processing centers for amalgamation and concentration. Developing cleaner processing facilities for these processors will require an investment of around US$10,000 per tonne of gold ore processed.[83] Similarly, site restoration is essential after the mine loses viability for ASGM. Woody biomass recovery rates on abandoned gold mining sites in Guyana were among the lowest ever recovered for tropical forests.[84] Restoration is thus also costly: restoration of gold mines in Peru cost an estimated $1,662–3,464 per hectare in the first year.[85] Unlike well-funded multinational companies with the legal obligations, resources, and expertise to restore large-scale mining sites, informal ASGM miners typically lack the capacity to successfully restore mining sites, leaving sites vulnerable to abandonment rather than rehabilitation.

The best available data sources for the likely active costs of this comprehensive global approach are the five-year budgets in the National Action Plans submitted by signatories to the Minamata Convention (Table 1). Actions taken to register and organize ASGM, interventions to eliminate the use of mercury in ASGM, and measures to promote public health and protect women of child-bearing age and children from the harmful effects of mercury are the dominant costs (Figure 2).

**Who should pay for reforming ASGM?**

Donor agencies and governments have identified the social and environmental costs of informal ASGM as major problems to tackle. Reforming ASGM to address these problems, whether through top-down or bottom-up formalization, presents significant new costs. There is increasing recognition that other stakeholders, particularly industry, governments, and consumers from the Global North, must assume greater financial responsibility for the impacts and regulation of ASGM activities.[86]

In 2019, the global gold market was dominated by jewelry (48.4%), investments (29.2%), central banks (14.9%) and technology (7.5%)[87]. Although the majority of global jewelry demand comes from China and India, and is driven partly by lack of access to banking, the top five per-capita gold-consuming countries for which data are available are Switzerland, UAE, Kuwait, Hong Kong SAR, and Germany[87]. There are significant opportunities to shift burdens onto donor countries, ASGM country governments, multinational mining corporations, and end consumers.

In principle, the revenue raised from royalties and taxes placed onto a new, large, formalized ASGM sector could stimulate economic growth and provide sufficient revenue to cover the costs of formalization. However, high up-front costs, taxes, and other fees could deter informal miners from engaging with the formalization process. Alternatively, governments could shift the financial burden onto other actors by taxing gold exports, raising taxes and royalties from the formal sector, using funds from the national budget (e.g. from the Ministry of Mines or equivalent), and encouraging partnerships between informal miners and large corporations.[33]

Corporate-ASGM partnerships are a potential mechanism by which corporations can help informal ASGM miners to reform their practices and use mercury-free techniques. For example, a Colombian mining company (Mineros S.A) operating on the Bonanza Gold Mine ran a partnership with 2,000 ASGM miners whereby the company instituted a mercury-free processing plant for them.[25] Cases in which informal ASGM activities occur on land on which formal leases have expired, as in Northern Myanmar, may be particularly suited to such an arrangement.[17] A possible policy tool for funding this arrangement might include an expansion of the fiduciary mechanisms currently used to guarantee successful post-mine restoration.[88] For example, in Western Australia, mining companies pay an annual levy to a publicly held Mining Restoration Fund, which is used to reclaim historic mine sites and pay for restoration if a company is unable to do so. These mechanisms could be extended to funding ASGM partnerships, requiring companies to pay into a central fund used to support ASGM formalization, and/or to postpone the restoration if ASGM occurs on the site after completion of the company's license.

Market incentives for miners who better comply with standards can also help to improve compliance. There exist several transnational governance schemes to regulate the global mining industry. Some focus on specific issues like transparency in revenue sharing (e.g., Extractive Industries Transparency Initiative) while others are concerned with a broad range of social and environmental sustainability issues (e.g., International Council on Mining and Minerals).[89] Fairtrade International (FLO) and Alliance for Responsible Mining (ARM) launched a 'Fairtrade and Fairmined Gold' Label in 2011,[90] but the two standards diverged from and competed with each other.[91] Risks involved in the implementation of such certification schemes include bureaucratic and technical barriers to participation, lack of enforcement and monitoring, no clear market for 'responsible' gold[91], and the passing of due diligence costs onto upstream actors.[92–94]

The difficulties encountered thus far in providing market incentives through certification suggest that tougher approaches may be needed to ensure that the high-income consumers, investors, and companies who ultimately benefit the most from global gold mining share the burden of paying for its environmental and social costs. Requiring the adoption of environmental and humanitarian standards by major importers through regulation, following the example of FLEGT for timber imports to the EU[95] and the Roundtable on Sustainable Palm Oil,[96] could be a step in the right direction. The main challenges lie in ensuring that the benefits of compliance outweigh the costs, particularly for the poor,[97] and that they are not undermined by market competition from miners operating under less stringent standards.[91] Further leverage points for enforcing greater environmental and social standards in publicly listed companies that mine, trade, or use gold could include pressure from lenders, sustainability reporting mechanisms in stock exchanges, and shareholder activism.[98]

International development funds could be used to provide support and environmental oversight for a formalized ASGM sector, analogous to the use of development funds to help exporting countries formalize their timber market in order to comply with the European Union Timber Regulation (EUTR).[99] Public subsidy through taxes and international development agencies may face challenges, since it could be seen as a public subsidy of private polluting enterprises, the costs of which the public bear. A complete financial accounting that takes into consideration not only the cost of formalization, but also the savings from avoiding future health and environmental costs, could make such investments more attractive.

Of the options discussed above, it is international development funding that has gathered the most traction so far, particularly through the Global Environmental Facility (GEF)[100,101]. The GEF-funded planetGOLD (US$ 180 million[102]) and GOLD+ (phase 2 of planetGOLD; US$ 417 million including co-financing[103]) have provided funds for countries to develop and implement their NAPs, including technical solutions to reduce mercury usage, formalize ASGM, and provide financial assistance and access to formal markets for formalized ASGM miners. Early achievements of planetGOLD (listed in the project’s 2019/20 annual progress report[100]) include designing a mercury-free processing plant in Burkina Faso, forming an agreement with the Alliance for Responsible Mining to carry out formalization activities in Colombia, training 70 women miners in mercury-free techniques in Ecuador, and obtaining certification for ‘El Dorado Gold’ for mercury-free gold in Guyana. As noted above, these steps are individually promising. But however effective they may be in isolation, if they are implemented unsystematically or inappropriately, these massive investments may not deliver the intended systematic reform, as happened with the 2002-2007 GEF/UNEP/UNIDO Global Mercury Project.

## Future Directions

Policy makers have made little progress in formalizing ASGM despite an increasing acknowledgement of its importance. Top-down command-and-control approaches to formalization are ineffective, and narrow approaches that focus on titling are insufficient to address the complex social and environmental concerns associated with informal ASGM. More comprehensive, bottom-up approaches to formalization are needed, but these require training, appropriate incentives, and monitoring and are thus costly. Moreover, such approaches risk placing undue burdens on poor miners in ways that are likely inequitable and undermining. Supporting a comprehensive, inclusive, and effective formalization strategy requires candidly confronting the financial and moral burdens of reforming ASGM. As it stands, upstream supply chain actors have borne not just the social and environmental costs of mining gold, but also the costs of formalization. We have approximated the scale of active costs to improve social and environmental standards in ASGM formalization strategies. The framing of the Minamata convention and the drafted National Action Plans suggest that policymakers will, at least on paper, heed these lessons.

However, the framing of planetGOLD and early experiences from drafting of NAPs in Cambodia, Sierra Leone, Ghana, and Mali[55] suggest that policy makers risk repeating the same mistakes: a bias towards large-scale mining, inadequate implementation, and one-size-fits-all technical solutions. It is encouraging that the political will in the Minamata Convention and GEF financing to back these reforms has been mobilized, but we urgently need to learn from past failures to ensure that we do not squander political will and money repeating similar mistakes.

## Experimental Procedures

### Resource Availability

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*Material availability*

Not applicable

*Data availability*

Data are available from: https://zenodo.org/record/5995951, and the R code is available at: https://zenodo.org/record/5996457.

Signatories to the Minamata Convention on Mercury with ‘more than insignificant’ artisanal and small-scale gold mining (ASGM) sectors are required to develop and implement National Action Plans (NAPs) to reform their ASGM sectors in line with Annexe C of the Convention. We compiled the budgets of available NAPs for reducing mercury emissions from ASGM sectors. As of 2021-12-31, these were available for 16 countries from: www.mercuryconvention.org/en/parties/national-action-plans. We used these data to estimate the approximate costs of expanding such approaches globally. In addition to compiling total costs, we coded items according to strategies corresponding to different elements according to Annexe C of the Minamata Convention to visualize budget breakdowns by country using the *tidyverse* R package[104] (Figure 2). We converted all costs to USD using the 2021-12-31 conversion rates provided by the US Treasury Department (https://fiscaldata.treasury.gov/datasets/treasury-reporting-rates-exchange/treasury-reporting-rates-of-exchange): 1 USD = 2848.63 MNT, 1 USD = 581.84 XOF, 1 USD = 581.84 XAF.

We extrapolated from the median costs per country for the available NAP budgets, and used the lower and upper quartile values of these costs (Tables 1–2) as lower and upper bounds on the global five-year cost to extend calculations to 64 countries with documented ASGM sectors (visualized using the *rworldmap* package[105]. Figure 1). We repeated the calculation on a per miner basis (Table 2), using bounded estimates of 20-30 million ASGM miners worldwide.[3,4] We estimate a total five-year active cost of $355 million USD (upper and lower estimate bounds: $213–742 million) if scaled per country, or $808 million USD ($248 million–$2.17 billion) if scaled per miner (Table 2). Since we only have data for 16 countries (out of 64 with significant ASGM sectors), and there are huge uncertainties about the number of ASGM miners worldwide due widespread informality, these estimates are necessarily crude. It is also important to note that there is substantial heterogeneity within the informal ASGM sector, and that the costs and challenges will not be evenly distributed per miner: micro- or small operations, which comprise the vast majority of the sector, lack the skills and capital needed to adopt new technology, and large and medium operations may have the means and incentives to resist reform. However, these numbers suggest the approximate scale of funding needed to implement comprehensive bottom-up approaches to reforming ASGM worldwide.

## Competing Interests

The authors declare no competing interests.

## Author contributions

Original conceptualization: GWP and ELW; Methodology: GWP; Writing: GWP, MB, SG, BN, JP, ELW; Visualization: GWP; Funding Acquisition: SG and ELW.

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## Box texts

Box 1. The Minamata Convention on Mercury

Mercury emissions have increased dramatically since the industrial revolution. Mercury concentration has doubled in the surface layers of the oceans and increased 12-fold in Arctic marine mammals.[106] Elemental mercury, emitted directly into water or deposited from the atmosphere, is converted by bacteria into methylmercury. An accumulation of methylmercury can cause severe neurological disorders. The Minamata Convention is named after a Japanese city where residents developed severe neurological disorders (now named Chisso-Minamata disease) after eating seafood that had accumulated mercury following decades of industrial emissions of mercury into the neighboring bay.

The Minamata Convention on Mercury[37] deals with all anthropogenic sources of mercury, including coal burning, cement production, and disposal of consumer products containing mercury (e.g., batteries, thermometers). The treaty aims to phase out the global trade in mercury; the manufacture, import and export of mercury-containing products (Annexe A); the elimination of mercury from several manufacturing processes (Annexe B); and to implement safer ways of disposing and storing of mercury. It also sets out to regulate ASGM (Annexe C), the largest anthropogenic mercury emission source, by educating mining communities about health risks, substituting mercury amalgamation-based gold extraction methods and, pertinently for our review, mandating ‘Steps to facilitate the formalization or regulation of the artisanal and small-scale gold mining sector’.[107,108]

Box 2. Case study: gold mining, mercury, and formalization in the Congo

The Democratic Republic of the Congo (DRC), as one of the signatories to the Minamata Convention, has developed a National Action Plan targeting ASGM formalization as one of the most important tools to curb mercury use.[41] Although the government has been involved in several formalization efforts before, the top-down approach and limited enforcement have rendered these barely effective.[60] The most extreme effort was the ban on all artisanal mining in the Eastern provinces in 2010-2011, which led to severe economic and social backlashes such as decreased income, school drop-outs, malnutrition, and untreated illnesses.[60] When ASGM activities were allowed again mid-2011, the requirement to group into cooperatives led to elite capture, leaving those at the bottom of the labour hierarchy worse off.[109] Meanwhile, non-governmental initiatives have been confronted with black market prices that are impossible to compete with.[110]

However, despite the limited formalization of ASGM, miners' commonly shared knowledge has significantly reduced mercury use. Indeed, techniques that are highly recommended by the Minamata convention are already widespread in DRC. These include using mercury on concentrates rather than whole ores and using leaves with trichomes to recapture mercury during the burning phase. Despite these techniques being less efficient than shaking tables and retorts, they have resulted in an average mercury-gold ratio of 1.8, which is one of the lowest in the world, totaling around 3 tonnes of mercury annually for 12 tonnes of artisanal gold production.[111] Adopting the more efficient shaking tables and retorts would require higher upfront costs and continued training. If not cared for by large-scale mining corporations and consumers from the Global North, these costs would be borne by individual ASGM miners and/or their already struggling cooperatives.

## Tables

Table 1 – National Action Plan budgets.

Total 5-year costs of National Action Plans (NAPs) to meet the Minamata Convention for countries with available budgets[38–53] (Figures 1–2). Estimates for size of the ASGM sector from Seccatore *et al.*,[2] except for Burkina Faso,[38] Democratic Republic of Congo,[41] Nigeria,[48] and Mongolia[47].

| Country | National Action Plan budget (USD) | ASGM miners | Cost per miner (USD) |
|---|---|---|---|
| Burkina Faso | 5'075'000.00 | 146'196.00 | 34.71 |
| Burundi | 3'327'000.00 | 91'000.00 | 36.56 |
| Central African Republic | 795'400.00 | 291'000.00 | 2.73 |
| Democratic Republic of Congo | 25'010'050.00 | 250'000.00 | 100.04 |
| Ecuador | 5'665'629.00 | 128'000.00 | 44.26 |
| Guinea | 2'798'000.00 | 250'000.00 | 11.19 |
| Laos | 5'805'000.00 | NA | NA |
| Madagascar | 7'019'000.00 | 437'000.00 | 16.06 |
| Mali | 2'420'800.00 | 361'000.00 | 6.71 |
| Mongolia | 5'170'550.30 | 65'000.00 | 79.55 |
| Nigeria | 47'177'681.95 | 259'012.00 | 182.14 |
| Republic of Congo | 5'444'523.11 | NA | NA |
| Senegal | 12'948'871.43 | 15'000.00 | 863.26 |
| Sierra Leone | 22'385'000.00 | 437'000.00 | 51.22 |
| Uganda | 11'145'785.94 | 218'000.00 | 51.13 |
| Zimbabwe | 3'328'000.00 | 509'000.00 | 6.54 |
| Grant Total | 165'516'291.73 | 3'457'208.00 | 47.88 |
| Median (per NAP) | 5'555'076.06 | 250'000.00 | 40.41 |

Table 2. Extrapolated 5-year global costs of meeting the Minamata Convention. NAP budget costs extrapolated to 58 countries included in a 2014 estimate of the size of the global ASGM sector[2], plus another 6 countries with documented ASGM sectors (Cambodia, Côte d'Ivoire, Lao PDR, Nigeria, Myanmar, Republic of Congo). Given the scarcity of data on both costs and the size of the ASGM sector (Table 1), these are necessarily imprecise estimates aiming to give an approximate sense of the possible scale of global costs for a concerted effort to formalize ASGM and mitigate the worst impacts of mercury. As the size of the global ASGM sector is unknown but estimated to be over 20 million[4], we estimated the cost for the lower bound of 20 million ASGM miners and the upper bound of 30 million ASGM miners.

| Summary statistic used | Cost per country (USD) | Multiplier | Multiplier value | Global Cost (USD) |
|---|---|---|---|---|
| Median | 5'555'076.06 | Countries | 64 | 355'524'867.52 |
| Lower Quartile | 3'327'750.00 | Countries | 64 | 212'976'000.00 |
| Upper Quartile | 11'596'557.31 | Countries | 64 | 742'179'668.00 |
| Median | 40.41 | Miners | 20'000'000 | 808'231'661.23 |
| Lower Quartile | 12.41 | Miners | 20'000'000 | 248'188'924.49 |
| Upper Quartile | 72.47 | Miners | 20'000'000 | 1'449'325'196.85 |
| Median | 40.41 | Miners | 30'000'000 | 1'212'347'491.84 |
| Lower Quartile | 12.41 | Miners | 30'000'000 | 372'283'386.73 |
| Upper Quartile | 72.47 | Miners | 30'000'000 | 2'173'987'795.27 |

## Figure legends

Figure 1. Worldwide distribution of documented ASGM sectors and countries with available National Action Plan budgets (as of January 2022) that we used to estimate the global costs of comprehensive formalization strategies[37] (Table 1). Legend: countries with documented ASGM sectors (yellow), countries with published NAP budgets (blue).

Figure 2. Breakdown of costs reported in the five-year budgets for National Action budgets[38–53] of sixteen countries (Table 1). 'Formalization' covers measures directly taken to organize and register informal ASGM miners, and to expand legal frameworks to include them.