# **Formalizing artisanal and small-scale gold mining: a grand challenge of the Minamata Convention**

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**Abstract**

Artisanal and small-scale gold mining (ASGM) employs millions in the Global South, but emits over 2,000 tonnes of mercury per year into land and water, with downstream negative health effects for humans and wildlife. The 2013 Minamata Convention on Mercury seeks to reduce anthropogenic emissions of mercury. As ASGM largely operates outside the law, its formalization is recognized as a necessary step for balancing emissions reduction with improved livelihoods. The Convention mandates formalization of the sector in National Action Plans but with little guidance. We argue that top-down approaches to formalization—involving centralized creation of permits and environmental mitigation requirements—are likely to exclude millions of miners. However, bottom-up approaches—working with existing miners to legitimise claims and improve practices—will require significant external investment to ensure positive health and environmental outcomes. Extrapolating from available budgets, the global five-year cost of this approach could be $314 million USD (upper and lower estimate bounds: $46.1 million– $1.30 billion) if scaled per country or $653 million USD ($44.2 million - $14.6 billion) if scaled per miner. These costs will need to be borne by consumers, large mining corporations, and/or governments.

## Introduction

Over the past three decades, the global appetite for gold has continued to grow, driven by increased demand from Asia and soaring investor demand following spiking gold prices.[1] An estimated ~16 million ASGM miners in 58 countries (Figure 1) extracted 380-450 tonnes of gold in 2010-2011, accounting for approximately 13-15% of total output.[2]

For millions of miners and their dependents, ASGM is the primary source of income.[3] For others, it is a complementary income source that helps them overcome periods of crisis or agricultural low seasons.[4] Scholars have long tried to understand miners' motivations in terms of push (poverty and lack of alternatives) or pull (quick earnings) factors,[5–7] often concluding that a combination of factors explains why ASGM activities have become so thoroughly embedded in regional economies.

ASGM remains largely informal globally, not officially recognized or registered, and neither regulated nor protected by state laws. As in other sectors, this informality is part of what has enabled such wide access and participation,[8] but it has also yielded grave consequences to people and the environment. The persistence of informality has been attributed to bureaucratic, financial, and legal barriers[9–11,] as well as the lack of incentives among ASGM miners to have their claims sanctioned by governments, as they commonly rely on traditional or customary land claims.[12–14] Taking a structuralist perspective on informality, others highlight that the cheap and flexible labour force provided by ASGM miners is extremely useful to global capital.[1]

The lack of oversight and protections arising from informality has underpinned egregious human rights and environmental violations.[15–17] For instance, ASGM miners are particularly vulnerable to extortion and arrest.[18–21] Of the environmental problems associated with ASGM, most research and policy attention has been paid to mercury pollution (Box 1).

Mercury remains one of the simplest and most cost-effective ways to extract and concentrate gold.[22,23] Liberated gold particles in concentrates or whole ore are usually extracted by artisanal miners using mercury, which forms an amalgam that is heated to evaporate the mercury leaving behind the gold.[22] The mercury lost when disposing the amalgamating solution and the mercury vaporized from the amalgam are the main sources of mercury emissions in ASGM activities. According to UNEP[24] over 2000 tonnes of mercury is annually lost by artisanal gold miners worldwide. Inhalation of mercury vapour has negative health impacts on miners[25] and in areas adjacent to gold workshops.[26] In aquatic ecosystems mercury can form compounds with cyanide $Hg(CN)_2$ which can bioaccumulate.[27]

Reducing emissions is thus central to the 2013 Minamata Convention on Mercury (Box 1).[28] Signatories have pledged to take tangible steps towards the reduction of mercury across the mining sector, including formalization of ASGM as a necessary precursor. As the environmental problems associated with ASGM have been attributed to pervasive informality, policymakers have increasingly focused on formalization as the fundamental strategy to reform ASGM.[11] Formalization, it is argued, will not only stimulate economic growth and increase tax revenues by giving ASGM miners strong property titles, but also improve working conditions and promote better environmental management.[29]

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).[30,31] By March 2021, eleven countries had published NAPs: Burkina Faso,[32] Burundi,[33] Central African Republic,[34] Ecuador,[35] Madagascar,[36] Mali,[37] Mongolia,[38] Senegal,[39] Sierra Leone,[40] Uganda,[41] and Zimbabwe.[42] Many others, such as the Democratic Republic of Congo[43] (Box 2), have already conducted assessments of the ASGM sector and developed NAPs to curb their mercury use.

In this article, we review the challenges of formalizing ASGM to reduce its environmental impacts and consider what a successful approach will likely entail. This includes consideration of how to incentivize and support informal miners to participate in a reformed ASGM sector. We discuss the need for considerable financial investment to accompany formalisation, for which a range of global stakeholders must bear increased responsibility.

## Challenges encountered in previous attempts to reform ASGM

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.[44,45] The 1980s gold rush in the Amazon triggered a wave of baseline monitoring studies[46–48] bringing attention to mercury pollution as a consequence of ASGM. There followed in the 1990s a phase that Hilson *et al.* have described as the 'Technical, Social and Environmental' approach focused on building technical capacity (including in the mining sector[45]. In parallel, discourses on formalization in this period followed the more 'legalistic' lens popularised by De Soto, which emphasised the need to remove bureaucratic restrictions to enable entrepreneurial small-scale miners to benefit from technical assistance and create more taxable revenue.[45,49,50]

The 2002-2007 GEF/UNEP/UNIDO Global Mercury Project (GMP), the most significant international effort before the Minamata Convention[23,45], epitomised the 'Technical, Social and Environmental' approach. The goal of the GMP was to educate ASGM miners and communities about the hazards of mercury and technical solutions to avoid mercury usage in six pilot countries (Brazil, Indonesia, Laos, Sudan, Tanzania, and Zimbabwe)[51]. The project educated 300 trainers who in turn trained an estimated 30,000 ASGM miners and community members.[51] Technical interventions included the introduction of relatively simple technologies and practices, such as burning amalgam in retorts and installing fume hoods into gold shops, which can reduce vapour emissions by 90%[51]. However, these interventions did not lead to lasting changes. Veiga and Fadina noted that 'At the end of six years of this multimillion dollar UN project, not many miners continued with the methods they had learned'.[23]

As acknowledged in a post-project appraisal, the GMP encountered difficulties stemming from the fact that ASGM is largely poverty-driven, and that even with training education most ASGM miners lack the means to prioritise long-term health and environmental concerns over short-term economic considerations.[51] ASGM miners often lack the capital and capacity to implement less-polluting techniques, such as gravity concentration and cyanidation.[52,53] Furthermore, some of these techniques are only economically viable with certain ores. For example, borax-treatment has been used for centuries but requires ores with low sulphide concentrations[54] and high grades of gold due to the high rate of gold loss during the .process.[55] 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 widespread failure to change mining practices.[23] Beyond these financial constraints, the educational and technical focus of the GMP was ultimately unsuccessful because of poor knowledge of governance dynamics and i inability to tackle the structural issues that have created a widespread informal ASGM sector, including policy biases towards large-scale mining and the persistence of elite patronage networks.[44,45,56–58]

Increasing awareness of the poverty-driven nature of ASGM led to a phase of discourse in the 2000s dominated by the 'Livelihoods Approach'.[45] 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[59–62], 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**

There is a broad consensus that top-down, 'carrot and stick' approaches to formalization, where miners have to jump through expensive bureaucratic hoops in order to achieve legal titles and access to technical and financial aid, have largely failed.[23,44,45] In Peru, an attempt to formalize ASGM and restrict it to a 5,000 $km^2$ 'mining corridor' was undermined by slow permit allocation and weak enforcement, 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.[63] A failure to adequately train artisanal miners in improved techniques has resulted in legal (pseudo-formalized) miners in Colombia polluting at equal rates to informal miners. 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.[65] The use of military and police violence to enforce these has led to human rights abuses[21] and failed to tackle environmental poblems.[20,67] Furthermore, a narrow focus on titling—the issuing of official mining permits to registered groups of ASGM miners, often organized in cooperatives—by no means guarantees that environmental regulations will be followed, as this requires money, training and incentives, and enforcement.[69] Even where formalization has occurred, formal ASGM operations are found to frequently rely on informal labour.[71]

The International Institute for Sustainable Development (Winnipeg) has stressed the importance of bottom-up approaches to formalization,[64] including direct work with miners and comprehensively integrating the specific complexities of each case, including the needs of marginalized groups.[66] For example, a formalization process in Mali started by recognising 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.[68] Providing geological maps and information on the location of gold deposits, and dedicated areas where ASGM miners can legally work, are also essential prerequisites.[70] Formalisation efforts in Mongolia have created space in the legal-regulatory framework for diverse institutional arrangements, recognising not only registered companies, but also unregistered partnerships and miners' NGOs.[72]

The Minamata Convention is a response to the failures of existing formalization strategy, and there is widespread consensus in policy and academic circles that comprehensive bottom-up approaches are needed. However, early indications from the development of NAPs offer warnings that strategic mistakes with previous formalization processes are being repeated. The aim to totally eliminate mercury instead of eliminating and reducing where necessary is impractical in light of economic constraints micro ASGM miners face.. A bias in allocating the best and largest mining concessions to large-scale mining continues to be a problem in Cambodia and Ghana[45,78], making it unclear where viable space for a formalized ASGM sector will be made. Gold and mercury are easily smuggled across borders, and the fact that each member country is writing a separate National Action Plan is a missed opportunity for cross-regional collaboration, particularly in West Africa[45]. Within each country, the implementation of an ambitious multi-sector plan would ideally be a collaboration across multiple ministries, including the mining, environmental, labour, and health ministries. However, it has mostly been delegated to environmental ministries which in some cases (e.g. Ghana and Sierra Leone) have little knowledge of informal mining dynamics and no power over permit allocation, inhibiting effective action and creating inter-ministerial conflict.[45] Given the daunting scale of the challenge—in particular the need to understand complex governance dynamics across vast scales—it may be more effective to start with small contained pilot sites. As a remedy to these challenges, the 'formalization bubble' approach[44] proposes to create decentralized platforms for formalization anchored around ASGM miners who are already licenced, as a more effective way to concentrate the spread of technical capacity and access to finance.

**Comprehensive bottom-up approaches are more likely to succeed but 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,[72] assessment and compliance costs will need to be funded from other sources. Up-front subsidies for replacement of equipment will also be required. For example, a retort might cost US$5-50 and a shaking table US$1,000-10,000.[73] In many ASGM contexts, miners take their ore to independent processing centres 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.[52] Similarly, restoration of the site 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.[74] Restoration is thus also costly: restoration of gold mines in Peru cost an estimated $1662–3464 per hectare in the first year.[75] 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 do this, leaving sites vulnerable to abandonment rather than rehabilitation.

The best available data source 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). These costs are dominated by 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 (Figure 2). We extrapolated from the median costs per country and per ASGM miner of the available budgets, and used the minimum and maximum values as lower and upper bounds on the global five-year cost to extend calculations to the ~16 million miners and 58 countries documented by Seccatore *et al.*[2] We estimate a total five-year active cost of $314 million USD (upper and lower estimate bounds: $46.1 million - $1.30 billion) if scaling per country, and $653 million ($44.2 million - $14.6 billion) if scaling per miner (Table 2). Since we only have data for 12 countries (out of 58 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 the costs and challenges will not be evenly distributed per miner: micro- or small operations (the vast majority) lack skills and capital 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.

**Who pays?**

Donor agencies and governments have identified the social and environmental costs of informal ASGM as major problems to tackle. Equally, the processes of formalization—whether top-down or bottom-up—present 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.[76]

The global gold market, as of 2019, was dominated by jewellery (48.4%), investments (29.2%), central banks (14.9%) and technology (7.5%)[77]. With the caveat that jewellery demand is higher in low income countries and driven partly by lack of access to banking, there are significant opportunities, if also clear constraints to shifting 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 taxes and fees could deter informal miners from engaging with the formalization process. Additionally, up-front costs would be required before taxation is possible. Alternatively, the tax burden could be shifted onto other actors, including taxes on gold exports, taxes and royalties from the formal sector, the national budget (e.g. from the Ministry of Mines or equivalent), or partnerships with large corporations.[72]

As larger corporations have greater capacity to use mercury-free gold mining processes, corporate-ASGM partnerships could be a potential solution. For example, a Colombian mining company (Mineros S.A) operating on the Bonanza Gold Mine ran a partnership with 2000 ASGM miners whereby the company instituted a mercury-free processing plant for them.[23] 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.[20] A possible policy tool for funding this arrangement might include an expansion of the fiduciary mechanisms currently used to guarantee successful post-mine restoration.[79] 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 formalisation, and/or to postpone the restoration if ASGM occurs on the site after completion of the company's licence.

Market incentives for minors who better comply with standards can also help to improve compliance. Several transnational governance schemes to regulate the global mining industry exist. Some focus on specific issues like transparency in revenue sharing (e.g., Extractive Industries Transparency Initiative) while others (e.g., International Council on Mining and Minerals) are concerned with a broad range of social and environmental sustainability issues.[80] Fairtrade International (FLO) and Alliance for Responsible Mining (ARM) launched a 'Fairtrade and Fairmined Gold' Label in 2011,[81] but the two standards diverged and competed with each other.[82] Risks involved in the implementation of such certification schemes include bureaucratic and technical barriers to participation, lack of enforcement and monitoring, the lack of a clear market for 'responsible' gold[82], and passing the due diligence costs onto upstream actors.[83–85]

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[86] and the Roundtable on Sustainable Palm Oil,[87] 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,[88] and that they are not undermined by market competition from less stringent standards.[82] 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.[89]

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).[90] 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 are borne by the public. However, a complete financial accounting could take into consideration not only the cost of formalization, but also the savings from avoiding future health and environmental costs.

Of the options discussed above, it is international development funding that has so far gathered the most traction, particularly through the Global Environmental Facility (GEF)[91,92]. The GEF funded planetGOLD (US$ 180 million[93]) and GOLD+ (phase 2 of planetGOLD; US$ 417 million including co-financing[94]) which has provided for countries to develop and implement their NAPS, including technical solutions to eliminate mercury usage, formalize ASGM, and to 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[91]) 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 good, but if implemented unsystematically or inappropriately there is the risk that these massive investments will not deliver the intended systematic reform (as happened with the 2002-2007 GEF/UNEP/UNIDO Global Mercury Project) .

**Future Directions**

Despite an increasing acknowledgement of the need to formalize ASGM, little progress has been made. Top-down command and control approaches to formalisation are ineffective, and narrow approaches that focus on titling are insufficient to address complex labour and environmental concerns. More comprehensive, bottom-up approaches to formalization are needed, but these are costly because they require training, appropriate incentives, and monitoring. Moreover, they 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. As it stands, upstream supply chain actors have not only borne the social and environmental costs of mining gold but also the costs of formalization. We approximate 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 these lessons will be heeded, at least on paper. However, the framing of planetGOLD and early experiences from drafting of NAPs in Cambodia, Sierra Leone, Ghana and Mali[45] suggest that there are risks of repeating the same mistakes - bias towards , inadequate implementation, one-size-fits-all technical solutions. It is encouraging that the political will in the Minamata Convention and financing through the GEF to back these reforms has been mobilised, but we urgently need to learn from past failures to ensure that the political will and money are not squandered repeating similar mistakes.

**Competing Interests**

The authors declare no competing interests.

**Author contributions**

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

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**References**

1. Verbrugge, B., and Geenen, S. (2020). Global Gold Production Touching Ground: Expansion, Informalization, and Technological Innovation (Springer Nature).
2. Seccatore, J., Veiga, M., Origliasso, C., Marin, T., and De Tomi, G. (2014). An estimation of the artisanal small-scale production of gold in the world. Science of The Total Environment *496*, 662–667.
3. McQuilken, J., and Perks, R. (2021). 2020 State of the Artisanal and Small Scale Mining Sector (World Bank).
4. Brugger, F., and Zanetti, J. (2020). “In my village, everyone uses the tractor”: Gold mining, agriculture and social transformation in rural Burkina Faso. The Extractive Industries and Society *7*, 940–953.
5. Verbrugge, B. (2014). Capital interests: A historical analysis of the transformation of small-scale gold mining in Compostela Valley province, Southern Philippines. The Extractive Industries and Society *1*, 86–95.
6. Bashwira, M.-R., and Haar, G. van der (2020). Necessity or choice: women’s migration to artisanal mining regions in eastern DRC. Canadian Journal of African Studies / Revue canadienne des études africaines *54*, 79–99.
7. Stoudmann, N., Reibelt, L.M., Rakotomalala, A.G., Randriamanjakahasina, O., Garcia, C.A., and Waeber, P.O. (2021). A double-edged sword: Realities of artisanal and small-scale mining for rural people in the Alaotra region of Madagascar. Natural Resources Forum *45*, 87–102.
8. Bryceson, D.F., and Geenen, S. (2016). Artisanal frontier mining of gold in Africa: Labour transformation in Tanzania and the Democratic Republic of Congo. Afr Aff (Lond) *115*, 296–317.
9. Van Bockstael, S. (2014). The persistence of informality: Perspectives on the future of artisanal mining in Liberia. Futures *62*, 10–20.
10. Salo, M., Hiedanpää, J., Karlsson, T., Cárcamo Ávila, L., Kotilainen, J., Jounela, P., and Rumrrill García, R. (2016). Local perspectives on the formalization of artisanal and small-scale mining in the Madre de Dios gold fields, Peru. The Extractive Industries and Society *3*, 1058–1066.
11. Hilson, G., and Maconachie, R. (2017). Formalising artisanal and small-scale mining: insights, contestations and clarifications. Area *49*, 443–451.
12. Verbrugge, B. (2015). The Economic Logic of Persistent Informality: Artisanal and Small-Scale Mining in the Southern Philippines. Development and Change *46*, 1023–1046.
13. Geenen, S. (2015). African Artisanal Mining from the Inside Out: Access, norms and power in Congo’s gold sector (Routledge).
14. Jonkman, J. (2019). A different kind of formal: Bottom-up state-making in small-scale gold mining regions in Chocó, Colombia. The Extractive Industries and Society *6*, 1184–1194.
15. Swenson, J.J., Carter, C.E., Domec, J.-C., and Delgado, C.I. (2011). Gold Mining in the Peruvian Amazon: Global Prices, Deforestation, and Mercury Imports. PLOS ONE *6*, e18875.
16. Gibb, H., and O’Leary, K.G. (2014). Mercury Exposure and Health Impacts among

Individuals in the Artisanal and Small-Scale Gold Mining Community: A Comprehensive Review. Environ Health Perspect *122*, 667–672.
17. Alvarez-Berríos, N.L., and Aide, T.M. (2015). Global demand for gold is another threat for tropical forests. Environ. Res. Lett. *10*, 014006.
18. Peluso, N.L. (2018). Entangled Territories in Small-Scale Gold Mining Frontiers: Labor Practices, Property, and Secrets in Indonesian Gold Country. World Development *101*, 400–416.
19. Zabyelina, Y., and Uhm, D. van (2020). Illegal Mining: Organized Crime, Corruption, and Ecocide in a Resource-Scarce World (Springer Nature).
20. Prescott, G.W., Maung, A.C., Zinmar, A., Carrasco, L.R., De Alban, J.D.T., Diment, A., Ko, A.K., Rao, M., Schmidt-Vogt, D., Soe, Y.M., et al. (2020). Gold, farms, and forests: enforcement and alternative livelihoods are unlikely to disincentivize informal gold mining. Conservation Science and Practice.
21. Hilson, G. (2017). Shootings and burning excavators: Some rapid reflections on the Government of Ghana's handling of the informal Galamsey mining 'menace.' Resources Policy *54*, 109–116.
22. Esdaile, L.J., and Chalker, J.M. (2018). The Mercury Problem in Artisanal and Small-Scale Gold Mining. Chemistry – A European Journal *24*, 6905–6916.
23. Veiga, M.M., and Fadina, O. (2020). A review of the failed attempts to curb mercury use at artisanal gold mines and a proposed solution. The Extractive Industries and Society *7*, 1135–1146.
24. UNEP (2021). Artisanal and Small-Scale Gold Mining (ASGM) | Global Mercury Partnership. https://www.unep.org/globalmercurypartnership/what-we-do/artisanal-and-small-scale-gold-mining-asgm.
25. Steckling, N. (2016). Mercury use in artisanal small-scale gold mining threatens human health: measures to describe and reduce the health risk.
26. Moody, K.H., Hasan, K.M., Aljic, S., Blakeman, V.M., Hicks, L.P., Loving, D.C., Moore, M.E., Hammett, B.S., Silva-González, M., Seney, C.S., et al. (2020). Mercury emissions from Peruvian gold shops: Potential ramifications for Minamata compliance in artisanal and small-scale gold mining communities. Environmental Research *182*, 109042.
27. Marshall, B.G., Veiga, M.M., da Silva, H.A.M., and Guimarães, J.R.D. (2020). Cyanide Contamination of the Puyango-Tumbes River Caused by Artisanal Gold Mining in Portovelo-Zaruma, Ecuador. Curr Envir Health Rpt *7*, 303–310.
28. Chen, C.Y., Driscoll, C.T., Eagles-Smith, C.A., Eckley, C.S., Gay, D.A., Hsu-Kim, H., Keane, S.E., Kirk, J.L., Mason, R.P., Obrist, D., et al. (2018). A Critical Time for Mercury Science to Inform Global Policy. Environ. Sci. Technol. *52*, 9556–9561.
29. Putzel, L., Kelly, A.B., Cerutti, P.O., and Artati, Y. (2015). Formalization as Development in Land and Natural Resource Policy. Society & Natural Resources *28*, 453–472.
30. Stylo, M., De Haan, J., and Davis, K. (2020). Collecting, managing and translating data into National Action Plans for artisanal and small scale gold mining. The Extractive Industries and Society *7*, 237–248.
31. UNEP (2013). Minamata Convention on Mercury.
32. Ministère de l'Environnement, de l'Économie Verte et du Changement Climatique (2020). Plan d'Action Nationale de réduction, voire d'élimination du mercure dans l'extraction minière artisanale et à petite échelle d'or conformément à la convention de Minamata sur le mercure [Burkina Faso].
33. Ministère de l'Environnement, de l'Agriculture et de l'Elevage (2019). Plan d´Action National pour réduire et / ou éliminer l'utilisation du mercure dans l'Extraction Minière Artisanale et à Petite échelle de l'or au Burundi (PAN) (Ministère de l'Environnement, de l'Agriculture et de l'Elevage).
34. Ministre de l'Environnement et du Développement Durable (2019). Plan d'Action Nationale: Pour réduire et si possible, éliminer l'utilisation du mercure dans l'extraction minière artisanale et à petite échelle de l'or (EMAPE) de la République Centrafricaine conformément à l'annexe C de la Convention de Minamata sur le Mercure.
35. Ministerio del Ambiente y Agua (2020). National Action Plan on the use of Mercury in

Artisanal and Small Scale Gold Mining in Ecuador, in accordance with the Minamata Convention on Mercury.
36. Ministère de l'Environnement, de l' Ecologies et des Forêts (2018). Plan d'Action National pour réduire et / ou éliminer l'utilisation du mercure dans l'Extraction Minière Artisanale et à Petite échelle de l'or MADAGASCAR, En conformité avec les dispositions de la Convention de Minamata sur le mercure.
37. Ministre de l'Environnement, de l'Assainissement et du Développement Durable (2020). Plan d'Action Nationale pour l'Extraction Minière Artisanale et à Petite Échelle d'Or au Mali Conformément à la Convention de Minamata sur le Mercure.
38. Ministry of Environment and Tourism of Mongolia (2020). The National Action Plan for reducing mercury pollution caused by artisanal and small-scale gold mining in Mongolia (Ministry of Environment and Tourism of Mongolia).
39. Anon (2019). Plan d'Action Nationale visant à réduire et éliminer l'usage du mercure dans l'extraction minière artisanale et à petite échelle d'or au Sénégal.
40. Environment Protection Agency-Sierra Leone (2019). National Action Plan for Reducing Mercury Use in the Artisanal and Small-scale Gold Mining (ASGM) Sector in Sierra Leone (Environment Protection Agency-Sierra Leone).
41. National Environment Management Authority (2019). The National Action Plan for artisanal and small-scale gold mining in Uganda, in accordance with the Minamata Convention on Mercury (National Environment Management Authority (Uganda)).
42. Ministry of Environment, Tourism, and Hospitality Industry (2019). National Action Plan for artisanal and small-scale gold mining in Zimbabwe in accordance with the Minamata Convention on Mercury.
43. Nkuba, B., De Haan, J., Kamundala, G., and Bagaya Ciyoka, J. (2020). Plan d'Action National pour réduire et si possible, éliminer l'utilisation du mercure dans l'Extraction Minière Artisanale et à Petite Échelle de l'or (EMAPE) en République Démocratique du Congo (RDC) (CEGEMI-UCB, ACE & UNITAR).
44. Hilson, G. (2020). 'Formalization bubbles': A blueprint for sustainable artisanal and small-scale mining (ASM) in sub-Saharan Africa. The Extractive Industries and Society *7*, 1624–1638.
45. Hilson, G., Zolnikov, T.R., Ortiz, D.R., and Kumah, C. (2018). Formalizing artisanal gold mining under the Minamata convention: Previewing the challenge in Sub-Saharan Africa. Environmental Science & Policy *85*, 123–131.
46. Pfeiffer, W.C., Drude de Lacerda, L., Malm, O., Souza, C.M.M., da Silveira, E.G., and Bastos, W.R. (1989). Mercury concentrations in inland waters of gold-mining areas in Rondônia, Brazil. Science of The Total Environment *87–88*, 233–240.
47. Martinelli, L.A., Ferreira, J.R., Forsberg, B.R., and Victoria, R.L. (1988). Mercury Contamination in the Amazon: A Gold Rush Consequence. Ambio *17*, 252–254.
48. Malm, O., Pfeiffer, W.C., Souza, C.M.M., and Reuther, R. (1990). Mercury pollution due to gold mining in the Madeira River basin, Brazil. Ambio *19*, 11–15.
49. ILO (1999). Social and labour issues in small-scale mines. Report TMSSM/1999.
50. Geenen, S. (2012). A dangerous bet: The challenges of formalizing artisanal mining in the Democratic Republic of Congo. Resources Policy *37*, 322–330.
51. McDaniels, J., Chouinard, R., and Veiga, M.M. (2010). Appraising the Global Mercury Project: an adaptive management approach to combating mercury pollution in small-scale gold mining. International Journal of Environment and Pollution *41*, 242–258.
52. Veiga, M.M., Angeloci-Santos, G., and Meech, J.A. (2014). Review of barriers to reduce mercury use in artisanal gold mining. The Extractive Industries and Society *1*, 351–361.
53. Zolnikov, T.R., and Ramirez Ortiz, D. (2018). A systematic review on the management and treatment of mercury in artisanal gold mining. Science of The Total Environment *633*, 816–824.
54. Appel, P.W.U., and Na-Oy, L. (2013). How to Mitigate Mercury Pollution in Tanzania. *2013*.
55. Veiga, M.M., and Gunson, A.J. (2020). Gravity Concentration in Artisanal Gold Mining. Minerals *10*, 1026.

56. Hirons, M. (2020). How the Sustainable Development Goals risk undermining efforts to address environmental and social issues in the small-scale mining sector. Environmental Science & Policy *114*, 321–328.
57. Maconachie, R., and Conteh, F.M. (2020). Artisanal mining and the rationalisation of informality: critical reflections from Liberia. Canadian Journal of Development Studies / Revue canadienne d'études du développement *41*, 432–449.
58. Clifford, M.J. (2014). Future strategies for tackling mercury pollution in the artisanal gold mining sector: Making the Minamata Convention work. Futures *62*, 106–112.
59. Lahiri-Dutt, K. (2018). Between the Plough and the Pick: Informal, Artisanal and Small-scale Mining in the Contemporary World (ANU Press).
60. Lahiri-Dutt, K., Alexander, K., and Insouvanh, C. (2014). Informal Mining in Livelihood Diversification: Mineral Dependence and Rural Communities in Lao PDR. South East Asia Research *22*, 103–122.
61. Hilson, G. (2016). Farming, small-scale mining and rural livelihoods in Sub-Saharan Africa: A critical overview. The Extractive Industries and Society *3*, 547–563.
62. Okoh, G., and Hilson, G. (2011). Poverty and Livelihood Diversification: Exploring the Linkages Between Smallholder Farming and Artisanal Mining in Rural Ghana. Journal of International Development *23*, 1100–1114.
63. Alvarez-Berríos, N.L., L'Roe, J., and Naughton-Treves, L. (2021). Does formalizing artisanal gold mining mitigate environmental impacts? Deforestation evidence from the Peruvian Amazon. Environ. Res. Lett.
64. IISD (2017). Global trends in Artisanal and Small-scale mining (ASM): a review of key numbers and issues.
65. Veiga, M.M., and Marshall, B.G. (2019). The Colombian artisanal mining sector: Formalization is a heavy burden. Extractive Industries and Society *6*, 223–228.
66. Hilson, G., Hu, Y., and Kumah, C. (2020). Locating female 'Voices' in the Minamata Convention on Mercury in Sub-Saharan Africa: The case of Ghana. Environmental Science & Policy *107*, 123–136.
67. Spiegel, S.J. (2015). Shifting Formalization Policies and Recentralizing Power: The Case of Zimbabwe's Artisanal Gold Mining Sector. Society & Natural Resources *28*, 543–558.
68. Maconachie, R., and Hilson, G. (2011). Safeguarding livelihoods or exacerbating poverty? Artisanal mining and formalization in West Africa. Natural Resources Forum *35*, 293–303.
69. Hook, A. (2019). Fluid formalities: Insights on small-scale gold mining dynamics, informal practices, and mining governance in Guyana. Resources Policy *62*, 324–338.
70. Hilson, G., and Maponga, O. (2004). How as a shortage of census and geological information impeded the regularization of artisanal and small-scale mining? Natural Resources Forum *28*, 22–33.
71. Geenen, S., and Verbrugge, B. (2020). Theorizing the Global Gold Production System. In Global Gold Production Touching Ground: Expansion, Informalization, and Technological Innovation, B. Verbrugge and S. Geenen, eds. (Springer International Publishing), pp. 17–52.
72. UNITAR & UN Environment (2018). Handbook for developing National ASGM Formalization Strategies within National Action Plans (UNITAR & UN Environment).
73. UNEP (2012). Analysis of formalization approaches in the artisanal and small-scale gold mining sector based on experiences in Ecuador, Mongolia, Peru, Tanzania and Uganda A compendium of case studies June.
74. Kalamandeen, M., Gloor, E., Johnson, I., Agard, S., Katow, M., Vanbrooke, A., Ashley, D., Batterman, S.A., Ziv, G., Holder-Collins, K., et al. (2020). Limited biomass recovery from gold mining in Amazonian forests. Journal of Applied Ecology *57*, 1730–1740.
75. Román-Dañobeytia, F., Huayllani, M., Michi, A., Ibarra, F., Loayza-Muro, R., Vázquez, T., Rodríguez, L., and García, M. (2015). Reforestation with four native tree species after abandoned gold mining in the Peruvian Amazon. Ecological Engineering *85*, 39–46.
76. USAID (2017). USAID Global Environmental Management Support (GEMS) Sector Environmental Guideline: Artisanal and Small-scale Mining (USAID).

77. World Gold Council (2020). World Gold Council.
78. Spiegel, S. (2016). Land and ‘space’ for regulating artisanal mining in Cambodia: Visualizing an environmental governance conundrum in contested territory. Land Use Policy *54*, 559–573.
79. Gerard, D. (2000). The law and economics of reclamation bonds. Resources Policy *26*, 189–197.
80. Auld, G., Betsill, M., and VanDeveer, S.D. (2018). Transnational Governance for Mining and the Mineral Lifecycle. Annual Review of Environment and Resources *43*, 425–453.
81. Sippl, K.L. (2018). Golden Opportunity? Voluntary Sustainability Standards for Artisanal Mining andthe United Nations Sustainable Development Goals. (Harvard University).
82. Sippl, K. (2020). Southern Responses to Fair Trade Gold: Cooperation, Complaint, Competition, Supplementation. Ecological Economics *169*, 106377.
83. Cook, R., and Mitchell, P. (2014). Evaluation of Mining Revenue Streams and Due Diligence Implementation Costs along Mineral Supply Chains in Rwanda (Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources, BGR)).
84. Sarfaty, G.A. (2015). Shining Light on Global Supply Chains. Harv. Int’l L.J. *56*, 419.
85. Solidaridad (2020). Changing Gear; Accelerating Inclusive and Sustainable Production Through a New European Regulatory Framework (Solidaridad Europe).
86. Lesniewska, F., and McDermott, C.L. (2014). FLEGT VPAs: Laying a pathway to sustainability via legality lessons from Ghana and Indonesia. Forest Policy and Economics *48*, 16–23.
87. Cattau, M.E., Marlier, M.E., and DeFries, R. (2016). Effectiveness of Roundtable on Sustainable Palm Oil (RSPO) for reducing fires on oil palm concessions in Indonesia from 2012 to 2015. Environ. Res. Lett. *11*, 105007.
88. Ruysschaert, D., and Salles, D. (2014). Towards global voluntary standards: Questioning the effectiveness in attaining conservation goals: The case of the Roundtable on Sustainable Palm Oil (RSPO). Ecological Economics *107*, 438–446.
89. Jouffray, J.-B., Crona, B., Wassénius, E., Bebbington, J., and Scholtens, B. (2019). Leverage points in the financial sector for seafood sustainability. Science Advances *5*, eaax3324.
90. Hansen, C.P., Rutt, R., and Acheampong, E. (2018). ‘Experimental’ or business as usual? Implementing the European Union Forest Law Enforcement, Governance and Trade (FLEGT) Voluntary Partnership Agreement in Ghana. Forest Policy and Economics *96*, 75–82.
91. GEF (2020). planetGOLD 2019/2020 Annual Progress Report.
92. GEF About the Programme. planetGOLD. https://www.planetgold.org/about.
93. $180 million investment to tackle the hidden cost of gold (2019). Global Environment Facility. https://www.thegef.org/news/180-million-investment-tackle-hidden-cost-gold.
94. Global Opportunities for Long-term Development of artisanal and small-scale gold mining ASGM) Sector Plus - GEF GOLD + (2020). Global Environment Facility. https://www.thegef.org/project/global-opportunities-long-term-development-artisanal-and-small-scale-gold-mining-asgm-sector.
95. UNEP (2013). Global Mercury Assessment 2013 (UNEP, Division of Technology, Industry and Economics (DTIE) Chemicals Branch).
96. Spiegel, S., Keane, S., Metcalf, S., and Veiga, M. (2015). Implications of the Minamata Convention on Mercury for informal gold mining in Sub-Saharan Africa: from global policy debates to grassroots implementation? Environ Dev Sustain *17*, 765–785.
97. Bank, M.S. (2020). The mercury science-policy interface: History, evolution and progress of the Minamata Convention. Science of The Total Environment *722*, 137832.
98. de Haan, J., and Geenen, S. (2016). Mining cooperatives in Eastern DRC The interplay between historical power relations and formal institutions. The Extractive Industries and Society *3*, 823–831.
99. Reuters (2020). Gold smugglers in Congo hobble legal trade by buying at a premium, report says. Reuters.

100. Nkuba, B., Zahinda, F., Chakirwa, P., Murhi, I., De Haan, J., and Bashwira, M.-R. (2018). L'or Artisanal Congolais: Analyse socio-économique et de l'utilisation du mercure (Centre d'Expertise en Gestion du secteur Minier, Université Catholique de Bukavo).

## 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.[95] 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 neighbouring bay.

The Minamata Convention on Mercury[31] 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, 'Steps to facilitate the formalization or regulation of the artisanal and small-scale gold mining sector'.[96,97]

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.[43] Although the government has been involved in several formalization efforts before, the top-down approach and limited enforcement have rendered these barely effective. 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.[50] When ASGM activities were allowed again mid-2011, the requirement to group into cooperatives gave rise to elite capture, leaving those at the bottom of the labour hierarchy worse off.[98] Meanwhile, non-governmental initiatives are confronted with black market prices that are impossible to compete with.[99]

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, totalling around 3 tons of mercury annually for 12 tons of artisanal gold production.[100] Adopting the more efficient shaking tables and retorts would require higher upfront costs and continued training. If not cared for by LSM corporations and consumers from the Global North, these costs would be borne by ASGM miners through their already struggling cooperatives.

## Tables

Table 1. Total 5-year costs of National Action Plans (NAPs) to meet the Minamata Convention for countries with available budgets[32–43] (Figure 2). Estimates for size of the ASGM sector from Seccatore *et al.*[2], except for Burkina Faso[32], Democratic Republic of Congo[43], and Mongolia[38].

| Country | National Action Plan budget (USD) | ASGM miners | Cost per miner (USD) |
|---|---:|---:|---:|
| Burkina Faso | 5,075,000.00 | 146,196 | 34.71 |
| Burundi | 3,327,000.00 | 91,000 | 36.56 |
| Central African Republic | 795,400.00 | 291,000 | 2.73 |
| Democratic Republic of Congo | 19,660,000.00 | 250,000 | 78.64 |
| Ecuador | 5,665,629.00 | 128,000 | 44.26 |
| Madagascar | 7,019,000.00 | 437,000 | 16.06 |
| Mali | 2,420,800.00 | 361,000 | 6.71 |
| Mongolia | 5,170,550.29 | 65,000 | 79.55 |
| Senegal | 13,561,508.43 | 15,000 | 904.10 |
| Sierra Leone | 22,385,000.00 | 437,000 | 51.22 |
| Uganda | 11,145,785.94 | 218,000 | 51.13 |
| Zimbabwe | 3,328,000.00 | 509,000 | 6.54 |
| MEDIAN | 5,418,089.65 | 234,000.00 | 40.41 |
| MEAN | 8,296,139.47 | 245,683.00 | 109.35 |

Table 2. Extrapolated global costs of meeting the Minamata Convention over the next 5 years in the 58 countries included in the estimate of the size of the global ASGM sector[2], using the mean estimate of 16,177,000 ASGM miners worldwide. 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.

| Summary statistic used | Value (USD) | Multiplier | Multiplier value | Global Cost (USD) |
|---|---|---|---|---|
| Median | 5,418,089.65 | Countries | 58 | 314,249,199.41 |
| Mean | 8,296,139.47 | Countries | 58 | 481,176,089.37 |
| Min | 795,400.00 | Countries | 58 | 46,133,200.00 |
| Max | 22,385,000.00 | Countries | 58 | 1,298,330,000.00 |
| Median | 40.41 | Miners | 16,177,000 | 653,738,179.19 |
| Mean | 109.35 | Miners | 16,177,000 | 1,768,975,559.88 |
| Min | 2.73 | Miners | 16,177,000 | 44,217,133.33 |
| Max | 904.10 | Miners | 16,177,000 | 14,625,634,791.47 |

**Figure legends**

Figure 1. Worldwide distribution of documented ASGM sectors[2] and countries with available National Action Plan budgets that we used to estimate the global costs of comprehensive formalization strategies[31] (Table 1).

Figure 2. Breakdown of costs reported in the five-year budgets for National Action Plans[32–43] of twelve countries (Table 1). ‘Formalization’ covers measures directly taken to organise and register informal ASGM miners, and to expand legal frameworks to include them.