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Artisanal and small-scale gold mining and biodiversity: a global literature review

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Abstract

Artisanal and small-scale gold mining (ASGM) is crucial to the livelihoods of close to 20 million people in over 80 countries, including 4-5 million women, mainly in rural areas with limited alternative economic prospects, particularly in developing countries. ASGM is largely informal, which can add to the challenge of addressing negative social and environmental effects including impacts on biodiversity. However, with proper guidance, ASGM can operate in a responsible manner, using cleaner production methods that minimize impacts on human health and the environment. This study presents and analyzes the interactions between ASGM and biodiversity based on new findings from 27 ASGM National Action Plans (NAPs) developed within the framework of Article 7 and Annex C of the Minamata Convention on Mercury, as well as a global literature review of more than 100 publications. In terms of key findings according to the literature reviewed, alongside other human occupation such as agriculture and industrial activities, ASGM also has an impact on the environment and biodiversity. The interrelationship between ASGM and biodiversity, including protected areas, is pervasive at every stage of ASGM operations, from extraction to mine closure, and generates significant impacts on the surrounding ecosystems. These impacts include, in descending order of most reported impacts: deforestation, soil degradation, chemical contamination of aquatic and terrestrial systems, and changes to the turbidity of watercourses. Tropical regions and key species such as amphibians and freshwater fish are among the most affected. Singly or combined, these environmental stressors lead to loss or deterioration of habitat and, by extension, indigenous biodiversity and ecosystem services. In addition, legal, institutional, and regulatory frameworks and related measures, inadequate or non-existent in some cases, may not necessarily support sustainable practices, often resulting in exploited sites abandoned without remediation, reclamation, rehabilitation, or restoration measures. To mitigate such impacts a key recommendation arising from the literature review is to strengthen the integration of the interrelationship between ASGM and biodiversity in the implementation of existing relevant national strategies, including those developed under the NAPs. The global literature review also highlights the importance of a multi-stakeholder, systemic approach combining the use of geospatial analysis, scientific and local knowledge, as well as the adaptation of the relevant frameworks, capacity building, and awareness raising. This approach can inform decision making with a view to developing sustainable initiatives that prevent and reduce the impacts of artisanal and small-scale gold mining on ecosystems, and that preserve biodiversity.

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Background

Artisanal and small-scale gold mining (ASGM) has been practised for hundreds of years. This practice currently takes place primarily in Latin America, Africa, and Southeast and Central Asia (Grasmick et al. 1998, Babut et al. 2003, Veiga et al. 2006, Spiegel et al. 2014, Martinez et al. 2018, Pascal et al. 2020, UNEP 2021, Yao and Ahoussi 2021, Gerson et al. 2022, Keane et al. 2023), where local communities are engaged to extract environmental resources. Twenty percent of annual gold production is estimated to come from

ASGM, with an estimated workforce of nearly 20 million miners, including about 5 million of women and children (Keane et al. 2023). Given the potential to generate quick revenues, the recently rising price of gold, and availability of rudimentary practices, ASGM constitutes a considerable source of employment, income, and poverty reduction, especially in remote rural areas with limited alternative livelihoods. It is a direct source of income for nearly 20 million people and an indirect driver for improving the living conditions of more than one hundred million people (Macdonald et al. 2014, Keane et al. 2023).

However, despite the potential economic benefits of ASGM, it poses a significant risk to human health and to ecosystems and biota, even if of lesser importance than other anthropological activities. The use of chemicals, including mercury and cyanide, to extract the gold is a common practice in ASGM (Grasmick et al. 1998, Babut et al. 2003, Veiga et al. 2006, Spiegel et al. 2014, UNEP 2021, Yao and Ahoussi 2021, Gerson et al. 2022, Keane et al. 2023). In parallel to its natural occurring sources (such as volcanic activities, erosion and evaporation), in the ASGM operations, liquid mercury is added to the gold ore to form a mercury-gold amalgam, which is then burned to vaporize the mercury leaving the gold behind. This gaseous form of mercury is emitted into the atmosphere from where it can be deposited in terrestrial and aquatic ecosystems (Gerson et al. 2022). Once deposited, mercury can be sequestered in sediments in its inorganic form. When it enters into aquatic environments with the right conditions, inorganic mercury can be converted by microbial activity into methylmercury (MeHg). Easily soluble in lipids and possessing bioaccumulation and biomagnification properties in the food web, the organic form of mercury can easily cross biological membranes (Martinez et al. 2018, Pascal et al. 2020).

People can be exposed to mercury primarily through breathing mercury vapor and to MeHg by eating fish or other animals. MeHg, a potent neurotoxin, bioaccumulates in aquatic and terrestrial species. MeHg bioaccumulation can affect the central nervous system, and lead to adverse behavioral, neurological, physiological, and reproductive effects on contaminated wildlife (Evers 2018). Consuming fish and other animals with elevated MeHg levels is therefore hazardous to humans. Based on a global analysis of mercury in freshwater fish, 45% of fish families include individuals that exceed the U.S. established human health safety threshold of 0.46 ug/g, wet weight ($n = 312{,}335$ individual fish representing 131 families) (Evers et al. 2024). Many species of fish families are from tropical regions and commonly exceed this health threshold (e.g., 16 of 30 fish families in South America) (Evers et al. 2024). Therefore, there is a growing risk to mining communities in tropical regions that consume freshwater fish from surrounding waterbodies. Pregnant women and their fetuses are particularly vulnerable (Markham and Sangermano 2018, Cabeza et al. 2019, Omara et al. 2019, Schön-Blume et al. 2021).

The Minamata Convention on Mercury, which entered into force in August 2017, aims to protect human health and the environment from the adverse effects of mercury and mercury compounds. As a legally binding instrument, the Convention requires parties with more than insignificant ASGM activity that uses mercury to develop a National Action Plan (NAP) to reduce and, when feasible, eliminate mercury use in the sector. The NAP must also include strategies for promoting the reduction of emissions and the release of, and exposure to, mercury.

ASGM miners frequently work without any prior knowledge of environmental contamination and mitigation measures (Mawala and Merket 2019). Biological diversity (or biodiversity) is defined by the Convention on Biological Diversity (CBD) as "the variety of life on Earth and the natural patterns it forms." The term biological diversity therefore includes all living species, their ecosystems, and their overall interactions. The actions of miners sometimes have irreversible impacts on biodiversity and surrounding ecosystems, contributing to the triple planetary crisis of climate change, nature and biodiversity loss, and pollution. ASGM is linked to, among others, deforestation, land degradation, chemical pollution, and deterioration of water quality (Villegas et al. 2012, Hinton and Hollestelle 2012, Niane et al. 2014, Asner and Tupayachi 2017, Espejo et al. 2018, Atangana 2019, UNEP. 2021, UNEP 2021). Moreover, lack of protective measures around mercury amalgamation and limited management of tailings from gold mining lead to contamination of air, water, and soil, which further endangers ecosystem integrity (Macdonald et al. 2014).

While the mining communities and a broader group of stakeholders generally recognize the links between ASGM and biological diversity, as well as the importance of the ecosystem services nature provides, these stakeholders perceive the protection of biodiversity, and the sustainability of ecosystem services to be favored at the expense of the socio-economic development of targeted populations. Given the growth of ASGM and the threats this sector poses to the preservation of biodiversity and ecosystem services, the global literature review has been undertaken to document current knowledge about the relationship between ASGM and biodiversity. This paper presents key findings gathered from the existing literature, such as: (1) reported interactions among ASGM, wildlife, and surrounding environments; (2) socio-economic, legal, regulatory aspects; and (3) monitoring and mapping capacities for sound management of ASGM sites. This paper also includes recommendations drawn from the literature for possible

Table 1 Predefined criteria used for the global literature review

Period to be covered	• Publishing dates between 1990 to 2023
Geographic coverage	• All geographical and climatic regions
Language of the documentation	• English, French, and Spanish
Key words	• Artisanal and small-scale gold mining, ASGM, mining activities, ASM, mercury, gold mining
	• Aquatic ecosystems, water, sediment, terrestrial ecosystems, soil, biodiversity, biota, protected areas, biodiversity hotspots, forests, wildlife, ecosystems services, ecosystems accounting
	• Threats, contamination risks and ecosystem sensitivity
Type and form of documents	• Theoretical, empirical, historical, statistical, scientific, and technical and/or popular
	• Archives, newspaper articles, periodicals, audio-visual and/or cartographic sources, manuals, laws and regulations, monographs, reports, government publications, statistical series, theses, and memoirs

future action to reduce adverse impacts on biodiversity, including, where feasible, closure of the mining sites as initiatives towards, protection, conservation, and rehabilitation of ecosystem services.

Methodology

The global literature review consisted of a screening, extraction, compilation, and analysis of existing and accessible literature according to predefined criteria (Table 1). A total of 116 resources were reviewed, including articles, reports from international and non-governmental organizations, guides and methodologies, toolkits, and academic theses. The literature was assessed and key information extracted.

In addition, information of reported impacts on the environment, including linkages with biodiversity, wildlife, and ecosystem services, were also extracted from the 27 NAPs submitted to the Secretariat of the Minamata Convention as of July 2023.

The data on ASGM locations produced as part of the NAP projects, together with the information available on biodiversity hotspots, protected areas (including national parks) have been used to map the interaction between identified ASGM activities and important biodiversity areas.

The ASGM sites have been identified and added to the geodatabase as follows:

- Coordinates of the sites were listed in the NAP report or the NAP field report, or were shared by a relevant national stakeholder. All the coordinates were converted into decimal degrees for latitude and longitude. The sites were entered into a standardized EXCEL table and added to QGIS. The EXCEL table records mercury uses for each site as indicated in the NAP report as Yes, No or No data.
- In CAR, DRC and Tanzania the sites were taken from IPIS online database, saved as csv and added as new layer in QGIS. In Zimbabwe, some of the sites were taken from IPIS online database and some coordinates from the NAP report.
- In countries where the NAP report only has an image map showing location of the sites with no associated coordinates, the sites' locations were digitized from that map. The map was georeferenced into QGIS using 4 known points then each site was manually added and recorded with also the name of the region within boundaries of which it fell.
- For some NAP countries (Ecuador, Kenya, Kyrgyzstan, Mali, Mongolia), it was not possible to get ASGM site coordinates and it was not possible to digitize site locations based on maps in the NAP.
- The ASGM regions have been manually recorded in QGIS using as a base layer the gadm admin_1 or admin_2 layer for each country. The ASGM regions are either named in the NAP and/or are selected because there is a site falling within the boundaries.
- Compiled ASGM sites were overlaid over Key Biodiversity Areas (KBAs; BirdLife International 2023) and Protected Areas classified as IUCN Protected Area Management Categories I-IV (PA, UNEP-WCMC and IUCN 2023).
- Distance from the ASGM sites to the closest KBA or PA was calculated. All sites that intersected or were within 5 km of a KBA or a PA were identified and aggregated by country.

Results and discussion

More than 80% of the reviewed documents, alongside the 27 NAPs published, were peer-reviewed scientific articles or reports from intergovernmental and nongovernmental organizations. Most documents were published between 2015 and 2023 and mainly covered Sub-Saharan Africa, Latin America, or mining regions around biodiversity hotspots and protected areas (Table 2). Only five resources were found that covered Asia (primarily Southeast

Table 2 Overall characterization of consulted documents

Type of documents	Number
Scientific Article	65
Report	30
Other (Press releases, methodologies, policy brief among others)	11
Thesis	5
Guide	5
Period Coverage	**Number**
1995–2000	4
2000–2005	7
2005–2010	9
2010–2015	8
2015–2020	47
2020–2023	41
Geographic Coverage	**Distribution**
Global coverage	43
Sub-Saharan Africa	40
Latin America	28
Asia	5

Asia), although this region is well known for its mining activities.

From Latin America to Asia to Sub-Saharan Africa, the assessed literature globally reported the existence of dozens of mining regions, often near or within biodiversity hotspots and, in some cases, protected areas. All 27 submitted NAPs (Table 3) expressed growing concern about observed impacts of ASGM on the surrounding environment and biodiversity.

ASGM, key biodiversity areas and protected areas

Many of the countries known to have a high incidence of ASGM activities, including those in Africa (Congo, Côte d'Ivoire, Ghana, Guinea, Kenya, Madagascar, Nigeria, Tanzania, the Democratic Republic of Congo, Uganda, Zambia, Zimbabwe), Asia (Cambodia, Indonesia, Mongolia), and South America (Ecuador, Guyana, Paraguay), also have some of the highest levels of biological diversity identified globally, resulting in observed ASGM practices in and/or within the vicinity of Key Biodiversity Areas (KBAs, Fig. 1). In fact, Eswatini, the Republic of the Congo, the Lao Peoples Democratic Republic and Madagascar respectively include up to 75%, 38%, 32% and 26% of ASGM sites in and/or within 5 km of their KBAs (Table 4).

All 27 NAPs identify relationships between ASGM operations and the loss of biodiversity. ASGM was reported in these NAPs as one of the key drivers for biodiversity loss and impact on ecosystem services in mining areas due to deforestation, land degradation, and chemicals pollution of aquatic and terrestrial systems (Obeng et al. 2019). Nine out of the 27 submitted NAPs explicitly reported ASGM activities happening inside or in the vicinity of protected areas (Table 5). For example, the Democratic Republic of the Congo reported ASGM presence in almost 40% of protected areas. Lao People's Democratic Republic noted that hard rock mining and processing with mercury occurs within the boundaries of the Nakai-Nam Theun National Biodiversity Conservation Area. Niger reported that ASGM is practiced in some protected areas, such as in the Reserve Naturelle National de l'Air et du Ténéré. Mali and Mongolia highlighted the link between ASGM activities and excessive poaching of the wildlife and disruption of migration routes of protected species in the vicinity of or inside protected areas.

Similarly, more than 20% of reviewed documents highlight ASGM activities near or in the premises of biodiversity hotspots and protected areas leading to habitat and wildlife disappearance. ASGM activities near or within biodiversity hotspots and protected areas were reported, among others, in the Amazon region in Madre de Dios (Espinosa and Beyeler 2021, Cuya et al. 2021, Markham and Sangermano 2018), the Tapajos River Basin (Malm 1998, Espinosa and Beyeler 2021), the Guiana Forest (Rahm et al. 2017, Espinosa and Beyeler 2021), as well as in the Choco biogeographic region, a global biodiversity hotspot located at the Colombian Pacific (Palacios-Torres et al. 2018). In the Democratic Republic of Congo, ASGM was identified in almost 40% of protected areas (NAP Democratic Republic of Congo 2020) Cabeza et al. (2019) and Puluhulawa and Harun (2020) reported gold mining in Ranomafana (Madagascar) and Taman Nasional Bogani Nani Wartabone (Indonesia) National Parks, respectively.

According to the World Wildlife Fund (WWF) report on "Artisanal and Small-scale Mining in Protected Areas and Critical Ecosystems Programme" (2012), mining in protected areas may be favored as they are generally perceived as the property of the community and therefore would not require any prior exploitation authorization. Moreover, protected areas often lack monitoring and can therefore be easily exploited. The use of protected zones may be a default alternative in some cases. For example, investigations in Ghana, Liberia, the Democratic Republic of Congo, Sierra Leone, and Tanzania concluded that exploiting protected areas is a result of territorial conflicts with large-scale mining industries that often hold exploitation permits and push artisanal miners to look for other sites to continue their activity. Protected areas are also of interest to mining communities because they provide a number of ecosystem services, including food and charcoal production (Villegas et al. 2012).

Table 3 Observed impacts of ASGM on biodiversity that were reported in the National Action Plans*

Deforestation (19 countries)	Land degradation and loss of habitat (18 countries)	Chemicals pollution (19 countries)	Physical impacts on water (14 countries)
• Burkina Faso	• Burundi	• Burkina Faso	• Central African Republic
• Central African Republic	• Chad	• Burundi	• Guyana
• Chad	• Eritrea	• Congo	• Indonesia
• Democratic Republic of the Congo	• Guyana	• Chad	• Kyrgyzstan
• Ecuador	• Indonesia	• Eritrea	• Lao Peoples Democratic Republic
• Ghana	• Kyrgyzstan	• Guinea	• Mali
• Guinea	• Lao Peoples Democratic Republic	• Guyana	• Niger
• Guyana	• Madagascar	• Indonesia	• Nigeria
• Indonesia	• Mali	• Kenya	• Paraguay
• Mali	• Niger	• Madagascar	• Senegal
• Niger	• Nigeria	• Mali	• Sierra Leone
• Nigeria	• Senegal	• Nigeria	• Uganda
• Senegal	• Sierra Leone	• Paraguay	• Zambia
• Sierra Leone	• eSwatini	• Senegal	• Zimbabwe
• eSwatini	• Tanzania	• Sierra Leone	
• Tanzania	• Uganda	• Tanzania	
• Uganda	• Zambia	• Uganda	
• Zambia	• Zimbabwe	• Zambia	
• Zimbabwe		• Zimbabwe	

*Note that only countries that completed their project on National Action Plan and submitted their report to the Secretariat of the Minamata Convention are mentioned.

Furthermore, the importance of interaction between artisanal and small-scale gold mining and biodiversity conservation becomes apparent when overlapping the distribution of ASGM mining regions as reported in NAPs with the Key Biodiversity Areas (KBAs) (Fig. 1).

ASGM, biodiversity, and ecosystem services

The global literature review has confirmed that the expansion of ASGM activities in recent decades is often coupled with adverse impacts to the surrounding environment, fish and wildlife, and ecosystem services (Malm 1998, Markham and Sangermano 2018, Obeng et al. 2019, Cuya et al. 2021, Espinosa and Beyeler 2021, NAPs). Nearly 70% of the documents studied and more than 90% of finalized NAPs acknowledge various effects of ASGM practices on ecosystems and wildlife, the main ones highlighted by the literature include: deforestation, land degradation and loss of habitat, chemical pollution of terrestrial and aquatic ecosystems, and physical impacts on water.

Deforestation

Although the extent of deforestation varies depending on the region and type of forest cutting, mining activities are reported to be a major driver for deforestation, after other human occupations such as agriculture, infrastructure, and urban expansion in terms of importance. With the increase in mining activities in recent decades, Kramer et al. (2023) points out that globally, "almost 63% (approximately 8600 km^2) of deforestation caused by the expansion of global mining activities in the past 20 years took place after 2010 and only 37% in the period 2001 to 2010." For example, Guyana reported more than 9182 hectares were cleared for ASGM operations between 2004 and 2021 based on studies in four key ASGM locations. In French Guiana, the proportion is even higher, with 90% of deforestation caused by gold mining, with no less than 1,000 hectares of forest destroyed every year since 2012 (Melun and Bihan 2020).

More than half of the submitted NAPs reported deforestation, loss of vegetation, and loss of forest cover as key impacts of ASGM activities. Documents reviewed also identified deforestation, vegetation clearing, and related phenomena as being the most visible and most documented of the main impacts of ASGM on surrounding ecosystems

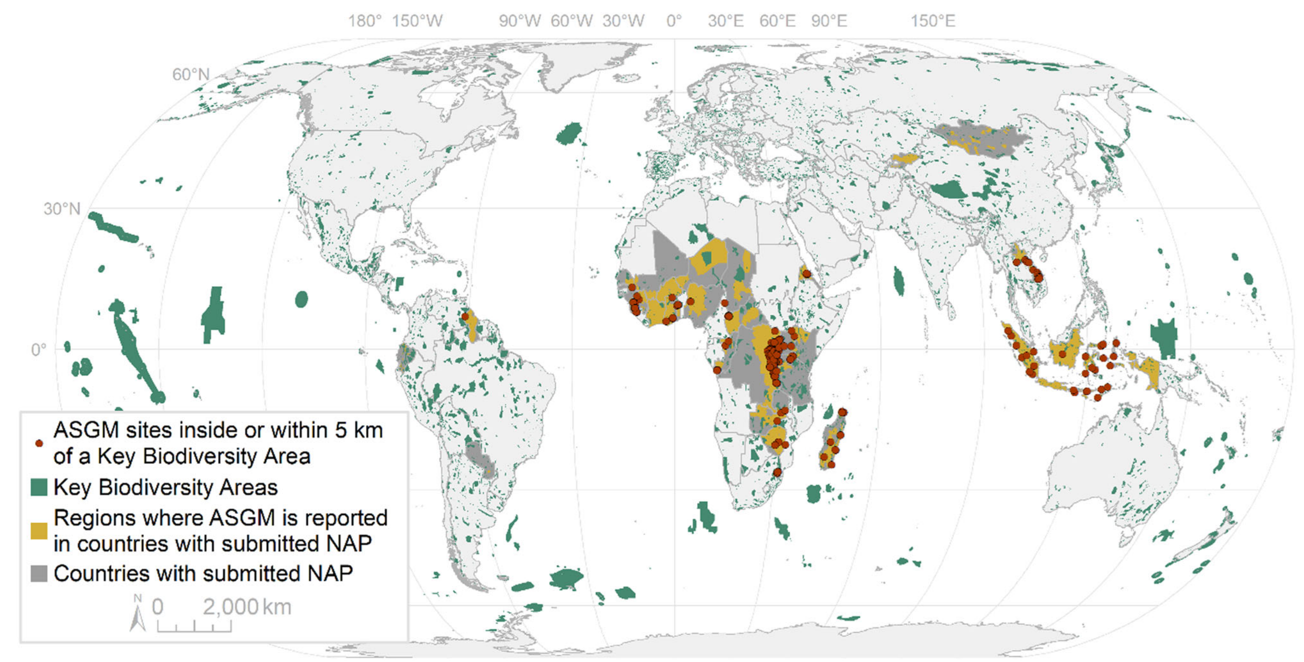

Fig. 1 Map of ASGM sites reported in NAPs that intersect or are within 5 km of Key Biodiversity Areas (KBAs)

and biota (Laperche et al. 2008, Villegas et al. 2012, Espejo et al. 2018, Ngom et al. 2022). Nearly three quarters of the documents and NAPs, covering mainly Latin America and Sub-Saharan Africa, report deforestation, loss of vegetation, and loss of forest cover as key impacts of ASGM activities, resulting in loss of habitats and, therefore, disappearance of related biodiversity.

In the context of the mining sector, direct causes of deforestation mainly take the form of the conversion of forests and/or agricultural areas into mining sites (Ngom et al. 2022). According to the WWF report on deforestation (Kramer et al. 2023), tropical forests are home to the greatest biological diversity (80% of amphibian species, 75% of birds, 68% of mammals, and 60% of vascular plants), and are the most exposed to mining-related deforestation, including from ASGM activities. Over the last 20 years, 84% of the deforestation resulting directly from mining activities have been concentrated in only ten countries, including countries with reported widespread ASGM activities, such as Indonesia, Brazil, Ghana, Peru, Myanmar, and Suriname (Kramer et al. 2023). ASGM-linked deforestation in these countries often affects the habitats of endemic species (Cabeza et al. 2019).

In addition, other practices related to mining activities can indirectly lead to deforestation. For example, support activities such as transport or energy infrastructure may induce forest clearing (Kramer et al. 2023). Deforestation in ASGM areas may also result from the proliferation of wood fires, the removal of trees to gain access to gravel for the construction of makeshift dwellings (NAP Burundi. 2019, NAP Central African Republic. 2019), or in some cases to strengthen road access to mining sites (NAP Tanzania. 2020). Certain tree species are used to construct the shafts for underground extraction, to create barriers on the rivers in the case of alluvial extraction, or to make charcoal for cooking (NAP Democratic Republic of Congo. 2020). The Central African Republic and, further south, the Democratic Republic of Congo report in their NAPs that miners not only cut down trees for mining exploration, but also use these trees to build temporary settlements or protect excavated pits. In Kenya (Figs. 2, 3), felled trees are used to build sheds for machinery, covers for dug shafts, shelters, or even houses on site for the miners (East Africa ASGM Study Tour in Kenya, 2023).

Beyond that, mining activities often attract people, leading to migration. The result is the emergence of other parallel activities, such as agriculture, which further contribute to the increase in deforestation. Considering that the indirect effects of mining activities are difficult to quantify, it is likely that the importance of mining as a cause of deforestation is largely underestimated (Kramer et al. 2023). Deforestation, in turn, also has other effects such as the disappearance of fauna and flora, soil erosion, and the alteration of watercourses around sites, as well as an increase in water turbidity. In some cases, deforestation can even lead to an increase in the temperature of aquatic systems (Laperche et al. 2008).

Intense deforestation in the areas exploited for gold panning in French Guyana has led to the destruction and sometimes even complete loss of habitats (Ngom et al.

Table 4 Number of ASGM sites reported in NAPs that are inside, within 5 km, and outside Key Biodiversity areas by country

Country	Number of KBAs				% of ASGM sites in KBAs	% of ASGM sites in 5 km buffer of KBAs	% of ASGM sites in/within 5 km of KBAs
	In	Within 5 km	Outside	Total			
Democratic Republic of the Congo	229	226	1669	2124	10.8%	10.6%	21.4%
Sierra Leone	19	7	109	135	14.1%	5.2%	19.3%
Central African Republic	13	1	247	261	5.0%	0.4%	5.4%
Indonesia	10	17	127	154	6.5%	11.0%	17.5%
Lao Peoples Democratic Republic	10	3	28	41	24.4%	7.3%	31.7%
Uganda	8	9	62	79	10.1%	11.4%	21.5%
Madagascar	5	9	40	54	9.3%	16.7%	25.9%
Republic of the Congo	5	3	13	21	23.8%	14.3%	38.1%
Eritrea	5	0	19	24	20.8%	0.0%	20.8%
Zimbabwe	3	7	310	320	0.9%	2.2%	3.1%
eSwatini	3	6	3	12	25.0%	50.0%	75.0%
Tanzania	2	6	329	337	0.6%	1.8%	2.4%
Zambia	2	1	13	16	12.5%	6.3%	18.8%
Togo	1	4	79	84	1.2%	4.8%	6.0%
Ghana	1	4	12	17	5.9%	23.5%	29.4%
Burundi	0	11	43	54	0.0%	20.4%	20.4%
Nigeria	0	2	77	79	0.0%	2.5%	2.5%
Guinea	0	2	40	42	0.0%	4.8%	4.8%
Guyana	0	1	291	292	0.0%	0.3%	0.3%
Chad	0	1	58	59	0.0%	1.7%	1.7%
Senegal	0	1	52	53	0.0%	1.9%	1.9%
Burkina Faso	0	0	180	180	0.0%	0.0%	0.0%
Paraguay	0	0	43	43	0.0%	0.0%	0.0%
Niger	0	0	18	18	0.0%	0.0%	0.0%
Total	316	321	3862	4499	7.0%	7.1%	14.2%

2022). The same phenomenon is observed in the protected areas of Madre de Dios (Espejo et al. 2018), the Tapajos River, and in the forest shared by the nine countries of the Amazon region (Bolivia, Brazil, Colombia, Ecuador, French Guiana, Guyana, Peru, Suriname and Venezuela). In Sub-Saharan Africa as well, Burkina Faso (Ngom et al. 2022), Ghana (Obeng et al. 2019, Ngom et al. 2022), Ivory Coast (Affessi et al. 2016; Ngom et al. 2022), Madagascar (NAP Madagascar. 2018), Mali (Ngom et al. 2022), Niger (Grégoire and Gagnol 2017), and Tanzania (Mawala and Merket 2019) are witnessing increasing deforestation as a result of ASGM and/or related activities, leading to the destruction of pastureland, loss of vegetation and forest cover, as well as soil degradation. In Indonesia, deforestation is accompanied by the decrease of organic soil and aquatic habitats (UNITAR. 2016). Notably, due to the inaccessibility and/or lack of preliminary geological data and site characteristics, pits dug by miners can be quickly abandoned when no mineral deposits are found. In the absence of environmentally sound rehabilitation or restoration measures, abandoned pits are left open, not only altering the surrounding landscape, but also posing a danger to miners and wildlife.

Land degradation and loss of habitat

Land degradation and loss of habitat are other key impacts of ASGM that have been reported in the consulted resources. In remote rural areas, any individual wishing to engage in ASGM may relatively easily find a site or join an existing team of miners, with little or no preliminary site

Table 5 Overview of National Action Plans reporting ASGM activities in protected areas

	Country	Impacts on biodiversity
5	**Congo**	• Possible contamination of water bodies and sediment with mercury as mining waste are released directly into the environment • **Existence of ASGM sites in the vicinity of protected areas**
6	**DRC**	• Deforestation • Loss of biodiversity • Decrease in land useable for agriculture • **Mining in protected areas**
14	**Lao Peoples Democratic Republic**	• Water pollution and siltation • Negative impacts to aquatic animals • **Mining activities in protected areas**
15	**Madagascar**	• Land degradation • Contamination of water and soils • **Sites using mercury in vicinity of protected areas**
17	**Mongolia**	• Severely eroded land • Large amount of solid waste generated • Rangeland degradation • Unrehabilitated mine pits, causing animals and people fall into pits/shafts • Excessive use of wood and bushes for shaft pillars in Khangai region, and destroying topsoil and plant cover • Water and soil contamination • **Excessive poaching of wildlife and presence of ASGM in vicinity or inside protected areas**
18	**Niger**	• Damage to ecosystems, namely the abusive cutting of trees on the sites leading to the destruction of flora and habitat for fauna • Disappearance of certain animal species • Wind and water erosion, leading to soil degradation in these areas • **ASGM practiced in some protected areas, such as in the Reserve Naturelle National de l'Air et du Ténéré (RNNAT) in the Agadez region**
23	**eSwatini**	• **ASGM operations within the country's major national park (Malolotja Nature Reserve)** • Impacts on protected plant species • Roads created in the reserve by gold ore smugglers through the South African fence has resulted in an impact in the spatial distribution of wild animals • Rehabilitation non existent • Rubble and waste not managed properly • local land degradation and deforestation due to panning
25	**Uganda**	• **Operational gold mining and exploration licenses in protected areas and forest reserves** • No deliberate efforts to carry out active restoration as required by the Ugandan environmental laws were observed
26	**Zambia**	• Land degradation • Deforestation • Contamination of surface and groundwater • Siltation of water bodies • Water stagnation in abandoned mine pits • Pollution from mercury use in gold amalgamation • Dust and noise pollution • **ASGM activities near protected areas negatively impacted wildlife population due to migration and poaching**

investigation, geological explorations, or environmental impact assessment (Mawala and Merket 2019; West Africa ASGM Study Tour, Togo, 2023), instead relying on historical knowledge passed down from generation to generation to determine the sites to be exploited (West Africa ASGM Study Tour, Togo, 2023).

Fig. 2 Deforestation to accommodate the mine site, Narok County, Kenya (East Africa ASGM Study Tour, Kenya, 2023)

Fig. 3 Cutting down trees to build makeshift housing, Migori County, Kenya (East Africa ASGM Study Tour, Kenya, 2023)

Consequently, in the hard rock context, the depth of shafts dug may vary from a few meters (West Africa ASGM Study Tour, Togo, 2023) to several meters (O'Neill (2017); East Africa ASGM Study Tour, Kenya, 2023). In both cases, entire areas may thus be altered, and sometimes permanently destroyed, including in protected areas or biodiversity hotspots. The first layers of soil, humus, and topsoil (or surface soil) consisting mainly of organic matter and plants are altered and moved to reach the eluvial horizon and subsoil where the mineral deposits are located.

In Northern Tanzania, for example, miners have reported nonexistence and/or inaccessibility of geological data as well as the high cost of adequate geological surveys. To partially compensate for this, miners rely on "artisanal" sampling, which allows them to characterize the nature of the soils in order to direct the digging operations, however this does not prevent mining in protected areas such as in the Biharamulo (Geita) and Makere (Kigoma) forest reserves (Mawala and Merket 2019). In French Guyana similar concerns about insufficient preliminary prospecting are leading to the excavation of large areas of land to find gold deposits.

ASGM activities are regularly located in riparian and floodplain areas that are important habitats for a broad diversity of fish and wildlife (NAP Burundi 2019). Whether or not minerals are found, little or no action is taken to close the pits and rehabilitate the mined site and surrounding landscape. Abandoned ASGM sites might leave behind mercury-containing waste and tailings, making the area even more dangerous for associated biota and human communities. For example, in the Central African Republic, birds on mining sites are forced to move away due to the destruction of their habitat and noise pollution from mining activity, resulting in a long-term decline in their populations and diversity (NAP Central African Republic, 2019). Markham et al. (2018) and Cabeza et al. (2019) have also mentioned the exposure or outright disappearance of amphibians in Peru and Madagascar because of alteration of the surrounding soils and mercury contamination of aquatic systems. In Ecuador, the lack of an adequate mining model for alluvial mining results in the alteration of riverbeds caused by digging. This disruption of the local ecosystem leads to species migration and loss of biodiversity, landslides, and eutrophication of waters (NAP Ecuador 2021).

Chemical pollution

Nearly 70% of NAPs and 50% of documents reviewed mention the contamination of terrestrial and aquatic ecosystems by chemicals as one of the main consequences of ASGM activities. Pollution is understood as the introduction of chemical elements external to ecosystems, leading to environmental contamination of air, soils, and water. As such, chemical pollution is considered by the Convention on Biological Diversity (CBD) as one of the main drivers of biodiversity loss (BRS 2021). Mercury and cyanide are the main pollutants used and released into the environment through ASGM activities (Grasmick et al. 1998, Veiga et al. 2006, Donkor et al. 2009, Villegas et al. 2012, Yao and Ahoussi 2021, NAPs). For mercury, it is the amalgamation process to extract relatively pure gold that is reported by all the documents and NAPs on the subject (Veiga et al. 2006, Donkor et al. 2009, Yao and Ahoussi 2021, NAPs). The inorganic mercury emissions released to air, water, and soil from the amalgamation process can be transformed into methylmercury (MeHg) when suitable conditions are achieved (e.g., microbial activity, particulate organic matter, and concentration of dissolved organic carbon). The physico-chemical characteristics of MeHg (solubility in lipids, protein binding properties) favor its passage through biological membranes, as well as bioaccumulation and biomagnification in the aquatic food web, thus contaminating wildlife (Evers et al. 2007, Donkor et al. 2009, Evers 2018, Markham and Sangermano 2018, Cabeza et al. 2019, Gerson et al. 2022, Sayers et al. 2023, Evers et al. 2024). For example, when considering certain investigations conducted in the

Amazon, particularly in the southeast of the Peruvian Amazon basin, high concentrations of atmospheric mercury are reported in areas where Hg-gold amalgam burning takes place, compared with lower concentrations at non-mining sites (Melun et al. 2020, Gerson et al. 2022). Gerson et al. (2022) also highlights that mercury from ASGM activities is deposited in terrestrial ecosystems, including the forests neighboring the mining sites, which therefore become hotspots for the bioaccumulation of MeHg in the terrestrial food web. If the forests are subsequently cleared to expand mining activities, mercury can pass into aquatic systems, where MeHg would biomagnify and bioaccumulate in the aquatic food web – especially in favorable conditions (Gerson et al. 2022). However, the magnitude of adverse impacts is relatively unknown for the tropical biomes that harbor most of the ASGM activities in the world because of the poor characterization of mercury exposure in upper trophic level biota (Evers et al. 2024).

Cyanidation is commonly considered either as an alternative or a complementary process to mercury amalgamation worldwide. Several countries in Africa (such as Burkina Faso, Côte d'Ivoire, Ghana, Zimbabwe), Asia (Indonesia) and South America (Venezuela) can be cited among the long list of countries where the tailings, whether treated with mercury or not, are reprocessed with cyanide (Veiga et al. 2006).

The lack of environmentally sound management practices also leads to the release of mercury-containing residues and waste. Sound management of tailings is often neglected in ASGM settings. Many NAPs, including those of Congo, Ecuador, Guyana, Niger, and Zambia, reported that tailings are either directly released into the environment or left behind without proper stabilization or containment measures after the operations cease or move to new locations. Furthermore, Zimbabwe's NAP highlighted that all reported gold processing sites had tailings from milling and cyanidation ponds that were not lined and were, in some cases, located close to rivers and water reservoirs. According to the governments of Guinea and Kyrgyzstan, tailings are also used to build barriers for tailings ponds or used as construction material contributing to the spread of potentially contaminated materials.

Cyanide leaching in tailings to which mercury has been added without first removing the mercury is one of the worst practices as defined by Annex C of the Minamata Convention because it leads to generation of mercury-cyanide complexes that are highly mobile in the environment and bioavailable (Keane et al. 2023). The mercury cyanide complexes, which are often discharged in untreated form into local drainage have been recently shown to bioaccumulate in zebrafish and induce systemic metabolic damage (da Silva et al. 2023). As reported earlier, 16 out of 27 submitted NAPs explicitly reported the presence of this worst practice within their territories.

Furthermore, in Guinea for example, ore-washing water is directly deposited into rivers, contributing to the considerable degradation of water quality and the water tables. Riverbanks around Lake Victoria, a source of fishing for nearly 40 million people between Kenya, Tanzania, and Uganda, are under increasing pollution threats by mining activity, with locals complaining that drinking the river water makes them and their domesticated animals ill (Mawala and Merket 2019). The Mara River, from Kenya to Tanzania, is also impacted by pollution from gold mining along its banks, putting the biodiversity of the Serengeti and Masai Mara at risk (Mawala and Merket 2019).

Gold mining and the associated release of Hg, including mercury-cyanide complexes from Artisanal Gold Mining in the Portovelo-Zaruma area in Ecuador severely impacted water quality, aquatic ecosystem structure, and contamination of biota and human communities in the Puyango river catchment as well as downstream in the Tumbes Delta in Peru (Marshall et al. 2020). The construction of adequate impoundments for the confinement of mining and processing waste was proposed as a measure to reduce environmental impacts (Tarras-Wahlberg et al. 2001). Gold mining activities in the small streams of the Nouragues Nature Reserve (French Guiana) affected the functional structure of fish assemblages, favoring smaller and more ubiquitous fish at the expense of larger, habitat specialist species. In addition, the site resilience was incomplete after the activities ended (Brosse et al. 2011). Review of the existing studies in Ghana revealed that the water quality parameters near ASGM sites show impairment, with some samples exceeding guidelines for acidity, turbidity, and nitrates.

Physical impacts on water

ASGM influences the quality and availability of water resources, which in turn has impacts on biodiversity. One particularly common impact is the increase in water turbidity. Since mining activities often take place around watercourses, there is a constant discharge of sediment from the pits into the riverbeds, increasing the amount of suspended matter. The result is increased turbidity in the water, which reduces light in the water column and oxygen levels in the water, leading to a decline in aquatic life in the areas affected (Laperche et al. 2008, Ngom et al. 2022).

ASGM occurring upstream of, adjacent to, or near aquatic systems may result in the sedimentation of particles from discarded mining waste, and the increase of water turbidity. Alluvial mining especially has a direct impact on watercourses due to the use of dredges in riverbeds (NAP Madagascar). For example, in Mali (Sissoko 2019, Maiga et al. 2022), Niger (Grégoire and Gagnol 2017), and

Senegal (Niane et al. 2014), gold panning by dredging has been practiced for more than a decade and is progressively leading to polluted rivers, pressure on aquatic species, destruction of fishing equipment, and reduced fishing catches (Maiga et al. 2022).

The Burundi NAP (2019) refers to the destruction of water resources and their biodiversity as a result of the relocation of riverbeds, the destruction of riverbanks and cultivated wetlands, as well as the sedimentation of rivers. The mining regions are facing the disappearance of indigenous species of *Cyperus papyrus* (paper reed) or *Cyperus latifolus* (sedges), especially in the swamps and wetlands of the catchment areas. In some mining areas in Zimbabwe and around the Mar, Ou, and Xékong rivers in Lao People's Democratic Republic, local communities witness the decline in natural water quality due to the use of chemicals in ASGM, causing the death of aquatic species and making the water unusable.

Information gathered demonstrates that the interaction of ASGM practices with the surrounding environment and biodiversity is indeed visible at all stages of the mining process (Table 6), through the observed impacts on nature (Villegas et al. 2012).

Socio-economic, policy, regulatory, and institutional frameworks

Nearly all documents that refer to the socio-economic dimension of the sector portray ASGM as a considerable source of income for the communities concerned. In all three main ASGM regions, ASGM activities are often either main sources of livelihoods (Cuya et al. 2021) or a complementary source of revenues to agricultural activities for which incomes and benefits might not be sufficient for the local community to survive (Bohbot. 2017, Obeng et al. 2019, Omara et al. 2019, Sissoko 2019).

At the same time, direct and indirect negative consequences of ASGM on the surrounding ecosystems and the services they provide to communities (Obeng et al. 2019, Martinez et al. 2018, Babut et al. 2003), which are in diverse forms, including provisioning, regulation, support, and cultivation, become increasingly visible (Table 7; Obeng et al. 2019).

The increase of the ASGM sector in recent decades has been identified as a main driver of the reduction of these ecosystem services in mining areas. For instance, recent studies in Ghana (Obeng et al. 2019), Indonesia (Puluhulawa and Harun 2020), Mali (Sissoko 2019, Maiga et al. 2022), and Peru (Cuya et al. 2021) documented a tension between employment and improved living conditions on the one hand, and the preservation of nature and ecosystem services on the other. The communities that were approached in the mining regions of western Ghana (Obeng et al. 2019), Madre de Dios in Peru (Cuya et al. 2021), and the Taman Nasional Bogani Nani Wartabone National Park in Indonesia (Puluhulawa and Harun 2020) generally recognize the importance of preserving nature after observing the harmful effects of gold mining on the environment. The same communities point to the current dilemma: preserving the environment and wildlife or favoring socio-economic development. Indeed, ASGM has become one of the main sources of income for local communities in many regions, however its current practice is generally contrary to the conservation of biological diversity. In interviews in Ghana, people recognized the importance of the various ecosystem services that nature provides to their communities; in particular, they realized the impacts of mining practices on nontimber forest products, since the availability of snails, widely used in Ghanaian cuisine, has drastically decreased as a result of mining activities (Obeng et al. 2019).

Across the main regions concerned, the legal, institutional, and regulatory frameworks can also be an impediment to the conservation of ecosystems and biological diversity. The consulted resources also highlight the inadequacy, insufficiency, or outright absence of legal, institutional, and regulatory frameworks to manage the mining sector and protect the environment and wildlife. Where directives do exist, enforcement and control measures are lacking. In Ghana, despite the existence of the Minerals and Mining Act 2006 (Act 03) on environmental protection and the preservation and rehabilitation of mined areas, implementation and monitoring remain a concern (Obeng et al. 2019, Macdonald et al. (2014)). In Indonesia as well, according to Macdonald et al. (2014), despite the existence of the Indonesian Mineral and Coal Law (2009), ASGM continues to operate informally and even illegally, mainly due to a lack of institutional and technical capacity for enforcement and regular assistance at regional and local levels.

As the situation is similar for most of the countries that have reported the existence of ASGM in their country, the NAPs and the investigations carried out in the sector all converge on the need to optimize the legal, institutional, and regulatory frameworks, while building the capacities required for measures to enforce the laws (Macdonald et al., (2014), Sundseth et al. 2017, Obeng et al. 2019, Puluhulawa and Harun 2020).

Mapping and monitoring ASGM impacts on biodiversity

Nearly all documents consulted on geospatial analysis of ASGM impacts on the environment and biodiversity identify remote sensing as an effective tool for detecting and monitoring changes in the physical characteristics of mined areas. According to Planque et al. (2022), remote sensing

Table 6 Interactions between ASGM processing steps and biological diversity

Observed effects	ASGM steps	Envisaged and/or observed effects on biological diversity
	**Site exploration and preparation** • Clearing of vegetation and forest for a better access to sediments for mining, and for wood, firewood collection, bark removal to fabricate pans for minerals washing, and uses of specific plants for medicinal purposes. • Physical removal of soils and rocks to access the deposits, often using tools such as spades, backhoes, and dredges. • Insufficiency and/or absence of closure measures after site exploration and exploitation.	• Deforestation, leading to the direct loss of habitat and biodiversity. • Reduction of nutritive sources, including fruit trees and consumable vegetation. • Soil degradation, including erosion, landslides. sedimentation, siltation, and alteration of the vegetation. • Reduction or disappearance of migration paths for animals. • Vulnerability and reduction of capacities to recover original ecosystem. • Release of dust • Alteration of riverbanks and riverbeds, as well as impacts on hydrological systems and aquatic wildlife. • Lack of backfilling of dug pits increases erosion and limits the rehabilitation of the original vegetation. • Increase of species migration to other habitats.
 	**Mining: minerals extraction** • In alluvial mining, redirection of waterways to facilitate access to deposits. • Use of machines, especially pumps for water removal before the digging in riverbanks. • Unsound displacement of soils and dumping of wastes and effluents in terrestrial and aquatic systems.	• Siltation, causing the reduction of light penetration into the water, which may adversely impact biodiversity. • Chemicals (mercury, cyanide, other chemicals) pollution of aquatic systems, including drinking water. • Landslides, sedimentation, riverbanks, and riverbeds alteration, causing the modification of hydrological systems.
	**Ore processing, tailings management** • Uncontrolled use of hazardous chemicals such as mercury and cyanide for amalgamation and cyanidation. • Unsound dumping and lack of proper management of polluted waste, tailings, and effluents in aquatic systems.	• Appearance of areas with increased exposure of mercury and cyanide contamination to biota. • Bioaccumulation and biomagnification of Hg in the food web. High trophic level fish consumed by mining communities are mostly affected.

Table 6 (continued)

Observed effects	ASGM steps	Envisaged and/or observed effects on biological diversity
	**Additional support activities** • Hunting of surrounding animals for trade and communities' consumption. • Construction of shelters, and sometimes even temporary or permanent camps and villages.	• Further stressing sustainable fish and wildlife populations. • Alteration of wildlife habitats, notably due to noise, space conflict between human and wildlife. • Reduction of migration routes for animals.

Table 7 Overview of identified goods and services provided by ecosystems

Type	Benefits
Provisioning Services	• Provision of food, fuel, and fibre • Generation and renewal of soil fertility, including nutrient cycling
Regulating Services	• Purification of air and water • Prevention of rivers drying • Detoxification and decomposition of wastes • Stabilization and moderation of the Earth's climate • Moderation of floods, droughts, temperature extremes, and the forces of wind • Pollination of plants, including many crops • Control of pests and diseases
Supporting Services	• Provision of shelter and building materials • Habitats for plants and animals • Maintenance of genetic resources as key inputs to crop varieties and livestock breeds, medicines, and other products
Cultural Services	• Cultural and aesthetic benefits • Scientific Research • Cultural and spiritual believes

uses sources of energy and predefined sensors to collect data on observed characteristics and activities at the surface of the earth. Information gathered may then be associated with geographical data, as well as soil and water physical properties to map and assess land uses, changes in land cover, deforestation, or physical alteration of aquatic systems such as turbidity to identify changes in land cover and water dynamics (UNITAR. 2016, Espejo et al. 2018, The Cadmus Group LLC (2019), Ngom et al. 2022, Planque et al. 2022).

According to Ngom et al. (2022), Almeida-Filho and Shimabukuro presented the first studies on early uses of remote sensing in Brazil in the 2000s for the observation of areas impacted by gold mining activities. More recently, various studies also concluded to the relevance of combining geographical, spatial-temporal, and other data gathered on the surrounding ecosystem at gold mining sites to characterise landscape transformations following mining activities through:

- The production of structural and geological maps that allow the identification of mineral deposits;
- Detection and analysis of the dynamics of pollution of terrestrial ecosystems, in particular: deforestation to convert forests into mining sites (UNITAR. 2016, Espejo et al. 2018, The Cadmus Group LLC (2019)); soil degradation (Ngom et al. 2022) such as acidification, erosion or compaction, alteration of humus, variation in vegetation, or reduction in the organic matter present, and pollution by chemical products); and habitat loss (The Cadmus Group LLC (2019));
- The representation of deforestation and land degradation as a result of alluvial and hard rock mining activities (The Cadmus Group LLC (2019));
- Assessment of water pollution due to mercury discharges in rivers through the detection of turbidity variations in rivers, or sediment discharge in rivers (The Cadmus Group LLC (2019); Ngom et al. 2022);
- Estimates of the evolution of ASGM activities (Espejo et al. 2018) and related wastes (The Cadmus Group LLC (2019)).

Ngom et al. (2022) identifies effective uses of remote sensing capabilities to describe the interactions between mining and deforestation, land degradation, and water turbidity alteration, among others, in West Africa and thereafter monitor changes in land degradation, deforestation, and water turbidity over time. In Niger, the Koma Bangou site has been monitored for 40 years using spectral indices reacting to minerals potentially present in tailings and waste to characterize the extent of mine waste dispersion and cyanide pollution. The impacts of gold mining on agricultural cocoa areas were also observed in southern Ghana between 2011 and 2015 to conclude that mined areas tripled around the Offin, Ankora, Birim, Anum, and Tano rivers (Ngom et al. 2022).

In the Madre de Dios region of the Peruvian Amazon, the use of remote sensing (using Landsat 5 data through an ISODATA unsupervised classification approach) determined that between 2003 and 2009, 6600 hectares of primary rainforest and wetlands were transformed into mining areas and tailings dumps, first at a rate of 292 hectares per year between 2003 and 2006, and then at a rate of 1915 hectares per year between 2006 and 2009. These transformations have been proportional to the increase in the price of gold in the region. Also in the same region, a combination of CLASlite and Global Forest Change (Cuya et al. 2021), reported estimated deforestation due to gold mining at 100,000 hectares over a period of 34 years (between 1984 and 2017), with a peak in 2011 when almost 53% of the deforestation took place.

In Indonesia, spatial observation of mining regions has made it possible to visualize the decrease in agricultural activities in favor of gold mining, and consequently the reduction in vegetation and forest covering in three areas of the Kalimantan region (Table 8; UNITAR. 2016).

During the development of the Sierra Leone NAP, geospatial data obtained using GPS, satellite images, and drones were also used to assess the extent of gold mining activities and the visible impacts on ecosystems. As part of its strategy to formalise the sector, the country is also stressing the importance of using remote sensing to monitor ASGM practices and their impacts in areas that are difficult to access.

In Suriname, ASGM sites in the Amazonian rainforest have been monitored using the ASMSpotter[1] tool that leverages machine learning to localize ASM sites using satellite imagery. The tool provides local authorities a map of where artisanal mining is occurring to prioritize controls and therefore increases the effectiveness of local initiatives to transform the ASGM sector.

Although remote sensing can be a powerful tool for identifying ASGM and its impact on biodiversity, there are limitations. Certain types of ASGM activity, such as underground hard-rock mining may not be easily detected from satellite imagery. Likewise, ASGM might be harder to detect in certain environments, such as arid or heavily disturbed landscapes. Ideally remoted sensing would be combined with ground truthing to increase confidence in the interpretations (Planque et al. 2022).

[1] https://business.esa.int/projects/asmspotter

Table 8 Overview of the vegetation and forest loss in Indonesia between 2002 and 2015

Area of Kalimantan	Time Period	Percentage (%) of vegetation and forest lost
Upper Kahayan Catchment Area	2005–2015	16.2
Kapuas Catchment Area	2005–2015	13.6
Galangan Site and Katingan Catchment Area	2002–2014	31.4

Remediation, reclamation, and restoration

ASGM sites are often abandoned without adequate measures to close the pits and shafts and to restore the site to a condition suitable for another use. Countries, notably in Eastern and Western Africa, generally point out the absence and need for appropriate measures for site closure in terms of remediation, reclamation, rehabilitation, and restoration (East Africa ASGM Study Tour, Kenya, 2023 - West Africa ASGM Study Tour, Togo, 2023). Documents that do address the issue identify factors and approaches that can encourage initiatives to preserve and protect biodiversity. Also, none of the NAPs describe current practices for mine closure and a limited number of NAPs propose specific strategies for mine closure (remediation, restoration, among others).

Conversely, the challenges identified in documents consulted and discussions during the ASGM study tours in Eastern and Western Africa include: (1) insufficient knowledge and awareness of the importance of preserving biodiversity, (2) the cost and/or inaccessibility of training and more sustainable extraction alternatives, (3) the accessibility of mercury and other chemicals, and (4) the inadequacy of the legal, institutional, and regulatory frameworks that do not encourage the adoption and implementation of measures. In this regard, participants to the East Africa study tour highlighted the need to amend the NAP reports to integrate specific strategies for mine closure as a key priority for future action.

Further, investigations into approaches that could increase the interest of mining communities in appropriate site closure have concluded that a multistakeholder approach is needed. Such an approach should combine scientific knowledge, local knowledge of the sector, and the involvement of all relevant stakeholders and decision-makers to define the needs, priorities, and appropriate actions to be implemented (Macdonald et al. 2014, Asian Foundation. 2016, Atangana 2019, Mawala and Merket 2019, Obeng et al. 2019, O'Brien et al. 2021, IUFRO 2022). O'Brien et al. (2021) proposes an approach based on the design of site models that integrate technical data, stakeholder involvement, and local knowledge for informed site remediation.

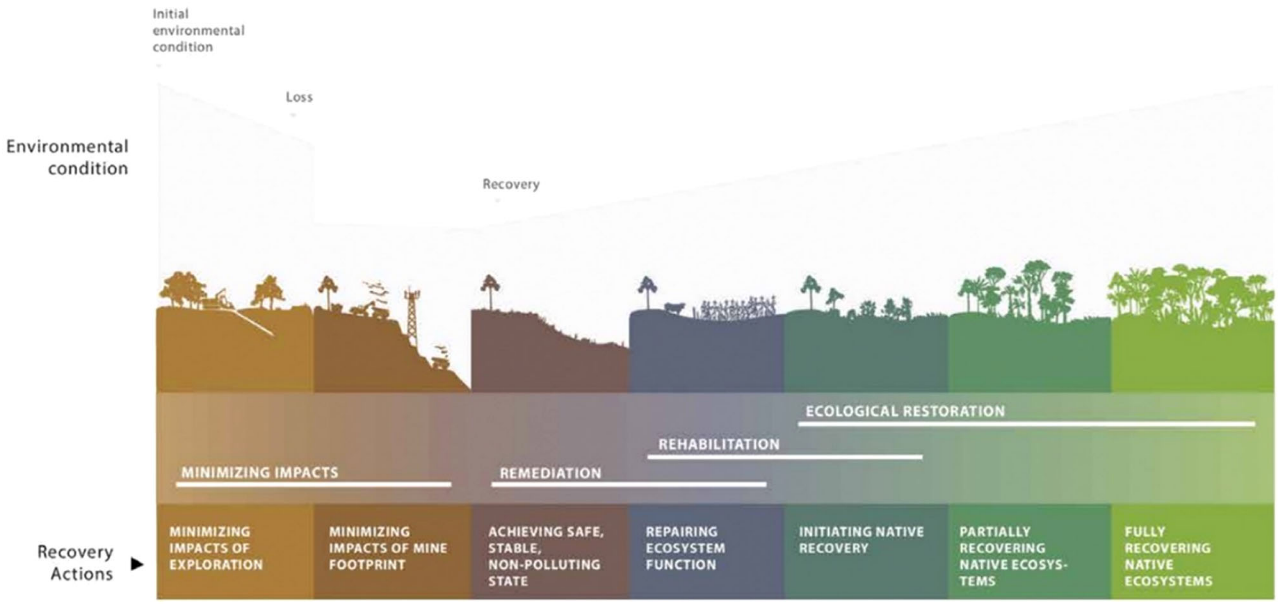

Fig. 4 Overview of existing options for mines closure (Source: Society for Ecological Restoration 2022)

In Ghana (Obeng et al. 2019), a study found that three communities (Ntakam, Asawinso No.1, and Nkatieso) realized the importance of the forest, particularly for its environmental services, but are faced with a conflict of interest between socio-economic prosperity and biodiversity protection. To overcome this, the article proposes Payment for Ecosystem Services (PES) systems based on compensation to reduce any loss of earnings associated with a contribution to preserving ecosystem services. In terms of practical solutions, Otchere et al. (2004) has proposed aquaculture as an option for rehabilitating mined sites, given the benefits that the activity could offer in terms of income, jobs, and food for mining communities, provided that the approach is adapted to the context of the site identified (physico-chemical characteristics and heavy metal contamination, as well as the long-term viability of the planned habitat).

In the conception of initiatives towards wildlife and ecosystem preservation, several stages can be distinguished when talking about reducing the impacts of gold panning and preserving biodiversity. First, prevention should be the priority, in the sense that any action aimed at avoiding harmful impacts on ecosystems and wildlife should be encouraged. Secondly, the approach of reducing the damage caused to ecosystems, in particular through the adoption of sustainable practices, should be emphasized. When, as reported by several countries, mining activity is already operational and effects are observed, the closure of sites that have already been mined should be considered in four distinct stages: remediation, reclamation, rehabilitation, and restoration (Fig. 4).

For example, for eastern Cameroon, Atangana (2019) proposed a process for reducing impacts on biodiversity and/or fencing off and rehabilitating sites according to their status, distinguishing between sites still in operation and abandoned sites. For the former, the use of more sustainable and environmentally friendly techniques and technologies would be recommended. The rehabilitation of abandoned sites would involve mechanical work to fill in the holes and level the site before applying biological methods such as phytoremediation. For mercury, Atriplex *canescens* and *Lupinus* are the species and genera identified for phytoremediation, due to their ability to accumulate mercury (Atangana 2019).

In Mongolia, the relevance of applying the Frugal Rehabilitation Methodology (FRM) for economically and ecologically viable, as well as socially acceptable, rehabilitation and restoration of land degraded by gold mining has been demonstrated through the second phase of the "Engaging Stakeholders in Environmental Conservation" projects (ESEC II) in the country. By proposing a systemic approach combining mechanical and biological rehabilitation techniques, as well as stakeholder consultation and a training process lasting several years, frugal rehabilitation appears to have brought together the key aspects required for environmental responsibility and the rehabilitation of land degraded by gold mining (Asia Foundation 2016).

In Peru, Madre de Dios region, Pure Earth and CINCIA proposed and undertook five steps to a sustainable rainforest rehabilitation in ASGM context: mapping; selection of species to be planted, their transport and planting, and documentation/monitoring. Teams from the two organizations were able to restore the Paolita II and Fortuna Milagritos mining concessions (Pure Earth, 2019). The promising results achieved are the fruit of inclusive collective initiatives involving all relevant stakeholders, including local players and the mining communities themselves.

Conclusions and recommendations

The number of documents addressing interactions between ASGM and biodiversity has increased over time, especially during the period of 2015 to 2023, suggesting growing attention to potential impacts of ASGM on biodiversity. Each stage of the gold mining process has its own effects on biodiversity and ecosystem services. Key highlights extracted from the review include the following:

- **ASGM in protected areas**: ASGM is taking place in various protected areas worldwide (Canavésio et al. 2010, Villegas et al. 2012, Weinberg et al. 2013, Asner and Tupayachi 2017, Espejo et al. 2018, Puluhulawa and Harun 2020, Verweijen et al. 2022). Nine out of 27 submitted NAPs explicitly reported ASGM activities happening inside or in the vicinity of protected areas. Similarly, more than 20% of reviewed documents highlight mining activities near or in the premises of biodiversity hotspots and protected areas. Visible impacts on the surrounding environment as well as on fish and wildlife populations were notably reported in all countries around the Amazon Basin, the Democratic Republic of Congo, Indonesia, and Madagascar – regions that are known for their rich and unique biodiversity (NAP Democratic Republic of Congo. 2020; UNITAR. 2016; Cabeza et al. (2019); Puluhulawa et al. 2020). In South America, recognized for its numerous biodiversity hotspots including protected areas, ASGM sites often overlap with biodiversity hotspots, alluvial gold mining being the source of large-scale land transformation and deforestation in the region. In 2014, 31% of the deforestation occurring in the region were located within 10 km of 32 protected areas, mainly in Brazil, Peru and Colombia (USAID, 2019).
- **Tropical regions of greatest concern**: Reported impacts of ASGM on biodiversity and ecosystem services in the literature and NAPs reviewed suggest that the threats to wildlife in the tropical zone are often the most pronounced. Malm Olaf (1998) emphasized the greater sensitivity of the tropical zone to the impact of mining activities. More recently, various studies (Donkor et al. 2009, Villegas et al. 2012, Rahm et al. 2017, Barkdull et al. 2019, Ngom et al. 2022, Kramer et al. 2023), Cabeza et al. (2019) made a similar observation, implying also that tropical areas may be the most documented with regards to their sensitivity to ASGM activities. In an article discussing ASGM as a source of mercury exposure in the Brazilian Amazon, Cabeza et al. (2019) concluded that there was a high level of methylation in the sediments of the Madeira and Tapajos rivers, with the highest values detected in tropical aquatic environments.
- **Key species affected**: According to the literature review heavily affected species include amphibians, freshwater fish birds, and bats as particularly sensitive to water contamination from mining waste (Markham and Sangermano 2018, Cabeza et al. 2019, Cirimwami et al. 2021, Pisconte et al. 2023, Portillo et al. 2023). South America has the most biodiverse countries in the world, particularly Brazil, Colombia and Peru, with the largest numbers of plants, amphibians and primate species in the world, some being affected by mining activities (USAID, 2019). Evers et al. (2024) identified species of greatest concern are high trophic level organisms (i.e., trophic level index >3.5) associated with waterbodies and wetland habitats in tropical as well as temperate biomes across the world.
- **Insufficiency and/or lack of adequate policy frameworks**: The literature review indicates shortcomings in the legal, institutional, and regulatory frameworks to manage the ASGM sector to prevent and reduce adverse effects on the environment as well as to fish and wildlife.
- **Mapping ASGM impacts on the environment**: Remote sensing is identified as a promising tool to map and monitor the extent of ASGM operations and its overlap with biodiversity hotspots, in particular to demonstrate the interactions between mining and deforestation, land degradation, and physical alterations of aquatic systems.
- **Limited adequate initiatives for mine closure:** Although existing methods and concepts were mentioned, less than 10% of the resources consulted proposed applicable strategies for the sustainable and environmentally friendly closure of abandoned sites. None of the NAPs reported successful decontamination, remediation, rehabilitation, and/or restoration initiatives for closed sites.
- **Need for improving communication and awareness raising:** Further education and awareness is critical to highlight the impacts of ASGM on biodiversity and ecosystem services, and on the existence of and access to more efficient and cleaner extraction techniques and equipment that as essential to reduce ASGM impacts on biodiversity (Aldous et al. 2023).

The findings are multifaceted and therefore require cross-sectoral and multistakeholder action. In an international context of binding legal instruments, the ratification of the Minamata Convention on Mercury is crucial. Implementation of the Convention would include, among others, the formalization of the ASGM sector, and the development and delivery of training and awareness campaigns on the use and management of mercury, contaminated sites, and mercury-free alternatives. At the same time, linkages with the implementation of the Convention on Biological Diversity and the new 2030 targets of the Kumming-Montreal Global Biodiversity Framework, with a focus on target 7 on pollution, should be explored. Recommendations include the implementation of conventions on chemicals that aim to protect human health and the environment, namely the Stockholm Convention (Persistent Organic Pollutants), the Rotterdam Convention (Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade), and the Basel Convention (Control of Transboundary Movements of Hazardous Wastes and their Disposal) as they provide key guidance for safely managing hazardous substances and their wastes.

Better understanding the science behind the behavior of mercury from its use in gold amalgamation to its entry into the environment, wildlife, and the food chain remains a priority to support effective and systemic implementation of binding instruments. Further in-depth research suggested in documents reviewed (Omara et al. 2019; Rahm et al. 2017; Espinosa and Beyeler 2021; Schön-Blume et al. 2021) notably include:

- A better understanding of the biogeochemical cycle of mercury in tropical ecosystems, including the physico-chemical (pH, organic carbon, conductivity, etc.), geochemical, and biological processes and factors governing the transformation of elemental mercury (Hg0) into its inorganic and organic forms and their bioaccumulation, is fundamental to further characterize mercury speciation in the ASGM sector. This is a prerequisite to better understand methylation and demethylation processes, elemental mercury dispersion, transformations and bioaccumulation which in turn will contribute to improved approaches for preventing pollution of ecosystems and contamination of the food chain.
- Where relevant, analysis of the effects of the presence of trace elements (lead and arsenic, among others) in the premises of ASGM sites on mercury fluxes in water, sediments, and soils can increase information on the reactions between these different chemical elements in the environment.
- More data are needed on the concepts of sensitivity, risk, and threats of contamination to aquatic and terrestrial species by mercury from gold mining (Aldous et al. 2024). This knowledge would contribute to better preservation of protected areas and regular, targeted monitoring of the state of ecosystems, ASGM activities, and the introduction of appropriate monitoring and control measures to the national, regional, and local context to reduce the direct and indirect impacts of ASGM practices on ecosystems as well as fish and wildlife. Identification of key biotic indicators by biome and geographic area of interest will improve assessment and monitoring cost efficiencies (Evers et al. 2024).
- Improved research, dissemination, and large-scale implementation of economically viable and sustainable best practices and concepts for decontamination, reclamation, rehabilitation, and restoration of sites abandoned after the extraction of gold.

Particularly with regard to the Minamata Convention, concerned Parties are encouraged to develop and implement their NAPs that should consider: (1) the legal and regulatory framework, including enforcement of application measures and possible sanctions; (2) the formalization of the ASGM sector, along with the planetGOLD Criteria for Environmentally and Socially Responsible Operations (planetGOLD. 2021) to assess the feasibility of sustainable formalization of the ASGM sector according to the characteristics and context of each country, region, and locality; (3) the adoption of sustainable alternatives and practices for the use of hazardous chemicals such as mercury; (4) the implementation of appropriate remediation methods and techniques; and (5) reclamation and restoration of degraded sites due to mining activities.

Promoting a multistakeholder approach would enable the technical, scientific, socio-economic, and legal aspects necessary for the greening of the ASGM sector to be considered. Each identified stakeholder should have defined roles and responsibilities to ensure inclusive initiatives towards a sustainable reduction of the impacts of ASGM on biodiversity. Figure 5 summarizes key recommendations extracted from the review.

Summary

ASGM is widely practiced in rural areas of developing countries. Although this activity does not generate the most significant impacts compared to other anthropogenic activities, it does considerably affect the environment, biodiversity and, by extension, ecosystem services. As such, the future of ASGM and that of the surrounding ecosystems and wildlife appear to be closely linked, even more so now that mining activities represent a considerable source of income

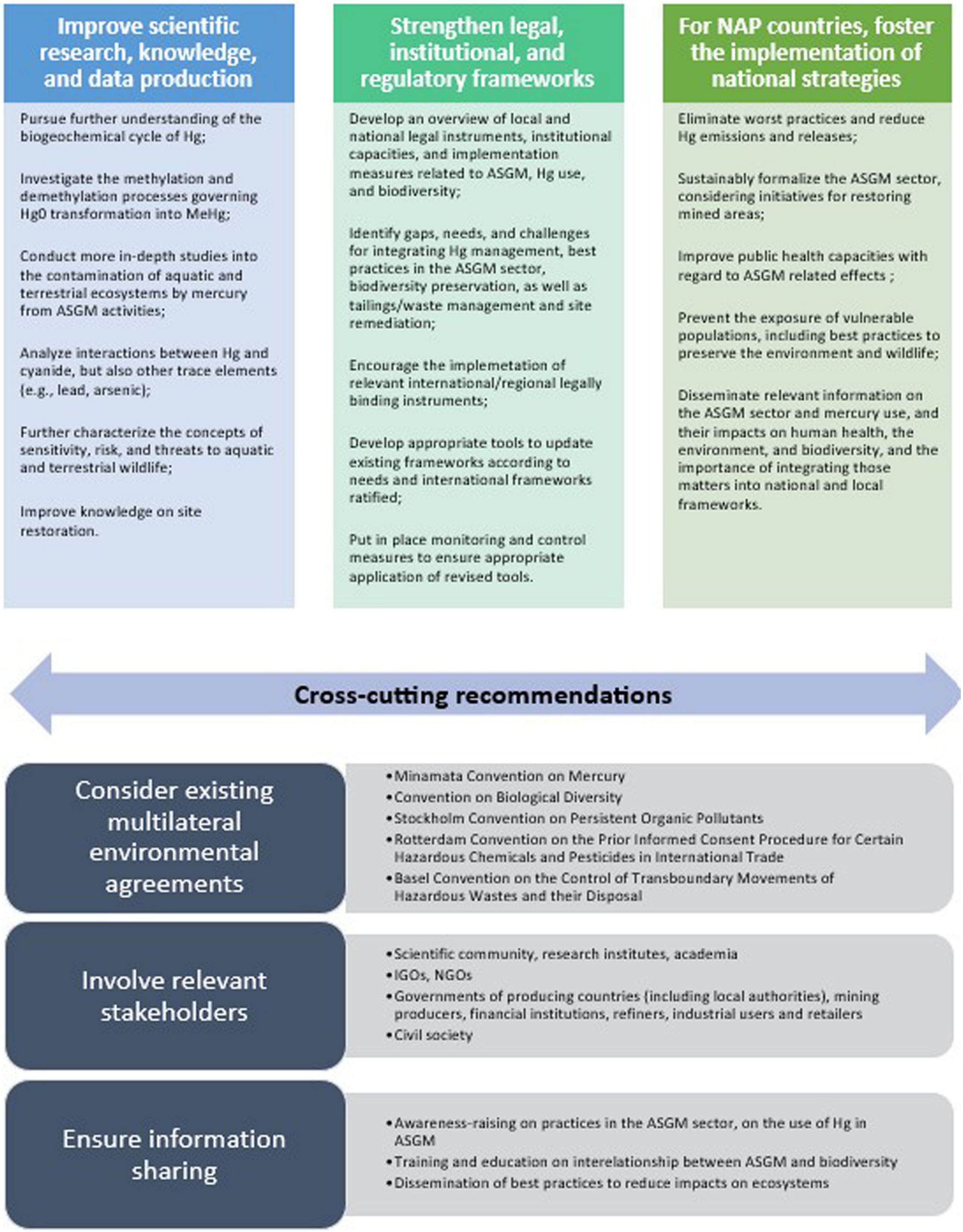

Fig. 5 Overview of recommendations extracted from the global literature review

for rural communities. For multiple reasons including improved living conditions and complementarity with agricultural activities, people are turning to mining, often to the detriment of the environment and biodiversity. As a result, deforestation, soil degradation, loss of habitats, contamination of soils and waters by chemicals including mercury, and changes to the turbidity of aquatic systems lead to the loss of biodiversity and ecosystem services. Additionally, legal, and institutional frameworks in place, and the lack of knowledge and pertinent capacities for sound mining activities are not conducive to preventing and reducing above-reported adverse effects.

As such, this literature review highlights the importance of informed initiatives to preserve the environment and wildlife where possible, and otherwise reduce and/or remedy the impacts of gold mining on associated ecosystems. In the context of ongoing and future actions, the ratification and application of relevant MEAs, particularly the Minamata Convention on Mercury and the Convention on Biological Diversity (CBD) is crucial. In doing so, the implementation of national strategies through a multi-stakeholder approach combining scientific and local knowledge, as well as visualization tools, awareness raising, and capacity building would be key drivers towards minimizing biodiversity loss resulting from ASGM activities.

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Author contributions IDE conducted the literature review, and wrote the main text. MS contributed to the literature review and data collection in the National Action Plans reports, and provided substantial inputs to the structure and content of the main text. KD. provided substantial contributions to the structure and content of the main text, the data collection in the National Action Plans reports, and supported the development of Figure 1 and Table 4. DE provided substantial contributions to the main text, and supported the development of Figure 1 and Table 4. VS provided substantial inputs to sections related to chemical pollution. MB and CW developed Figure 1 and Table 4. All authors reviewed the manuscript.

Compliance with ethical standards

Conflict of interest The authors declare no competing interests.

References

Affessi AS, Koffi KGJC, Sangaré M (2016) Impacts sociaux et environnementaux de l'orpaillage sur les populations de la region duBounkani (Cote d'Ivoire). Eur Sci J, ESJ 12(26):288. https://doi.org/10.19044/esj.2016.v12n26p288

Aldous A, Fernandez L, Tear T (2023) The global challenge of reducing mercury contamination from artisanal and small-scale gold mining (ASGM): Evaluating solutions using generic theories of change. Ecotoxicology 32(9). https://doi.org/10.21203/rs.3.rs-3399501/v1

Aldous AR, Tear T, Fernandez LE (2024) The global challenge of reducing mercury contamination from artisanal and small-scale gold mining (ASGM): evaluating solutions using generic theories of change. Ecotoxicology. https://doi.org/10.1007/s10646-024-02741-3

Asner GP, Tupayachi R (2017) Accelerated losses of protected forests from gold mining in the Peruvian Amazon. Environ Res Lett 12(9):094004. https://doi.org/10.1088/1748-9326/aa7dab

Atangana MSB (2019) Travail de fin d'études: "REHABILITATION D'UN SITE MINIER DEGRADE DU SECTEUR DE BETAR-EOYA (EST CAMEROUN)." MatheO. https://matheo.uliege.be/handle/2268.2/8406

Babut M, Sekyi R, Rambaud A et al. (2003) Improving the environmental management of small-scale gold mining in Ghana: a case study of Dumasi. J Clean Prod 11(2):215–221. https://doi.org/10.1016/S0959-6526(02)00042-2

Barkdull NM, Carling GT, Rey KA, Yudiantoro DF (2019) Comparison of mercury contamination in four Indonesian watersheds affected by artisanal and Small-Scale gold mining of varying scale. Water Air Soil Poll 230(9). https://doi.org/10.1007/s11270-019-4271-1

BirdLife International (2023). The World Database of Key Biodiversity Areas. Developed by the KBA Partnership: BirdLife International, International Union for the Conservation of Nature, Amphibian Survival Alliance, Conservation International, Critical Ecosystem Partnership Fund, Global Environment Facility, Re:wild, NatureServe, Rainforest Trust, Royal Society for the Protection of Birds, Wildlife Conservation Society and World Wildlife Fund. Available at www.keybiodiversityareas.org

Bohbot J (2017) L'orpaillage au Burkina Faso: une aubaine économique pour les populations, aux conséquences sociales et environnementales mal maîtrisées. EchoGéO. (42). https://doi.org/10.4000/echogeo.15150

Brosse S, Grenouillet G, Gevrey M, Khazraie K, Tudesque L (2011) Small-scale gold mining erodes fish assemblage structure in small neotropical streams. Biodiversi Conserv 20(5):1013–1026. https://link.springer.com/article/10.1007/s10531-011-0011-6

Burundi. (2019) Plan d'Action National pour réduire et/ou éliminer l'utilisation du mercure dans l'Extraction Minière Artisanale et à Petite Echelle de l'Or. https://minamataconvention.org/sites/default/files/documents/national_action_plan/Burundi-ASGM-NAP-2019.pdf

Cabeza M, Terraube J, Burgas D, Temba EM, Rakoarijaoana M (2019) Gold is not green: artisanal gold mining threatens Ranomafana National Park's biodiversity. Animal Conserv 22(5):417–419. https://doi.org/10.1111/acv.12475

Central African Republic. (2019) Plan d'Action National pour réduire et, si possible, éliminer l'utilisation du mercure pour l'Extraction Artisanale et à Petite Echelle de l'Or (EMAPE) de la République Centraficaine conformément à l'Annexe C de la Convention de Minamata sur le mercure. https://minamataconvention.org/sites/default/files/documents/national_action_plan/Central-African-Republic-ASGM_NAP-2019-FR.pdf

Cirimwami L, Baguma G, Mushagalusa O (2021) Exploitation minière et biodiversité : cas de Twangiza Mining dans l'Est de la RDC. https://www.researchgate.net/publication/356253963_Exploitation_miniere_et_biodiversite_cas_de_Twangiza_Mining_dans_l'Est_de_la_RDC

Cuya A, Glikman JA, Groenendijk J, Macdonald DW, Swaisgood RR, Barocas A (2021) Socio-environmental perceptions and barriers to conservation engagement among artisanal small-scale gold mining communities in Southeastern Peru. Glob Ecol Conserv 31:e01816. https://doi.org/10.1016/j.gecco.2021.e01816

Da Silva HAM, Kasper D, Marshall BG, Veiga MM, Guimaraes JRD(2023) Acute ecotoxicological effects of Hg(CN)2 in Danio rerio (zebrafish) Ecotoxicology 32(4):429–437. https://doi.org/10.1007/s10646-023-02651-w

Democratic Republic of Congo. (2020) Plan d'Action National pour réduire et si possible, éliminer l'utilisation du mercure dans l'Extraction Minière Artisanale et à Petite Echelle de l'Or (EMAPE) en République Démocratique du Congo (RDC). https://minamataconvention.org/sites/default/files/documents/national_action_plan/RDC-NAP-2021-FR.pdf

Donkor A, Nartey V, Bonzongo JC, Adotey D (2009) Artisanal Mining of Gold with Mercury in Ghana. West African J Appl Ecol 9: https://doi.org/10.4314/wajae.v9i1.45666

East Africa ASGM Study Tour in Kenya (2023) https://www.unep.org/globalmercurypartnership/news/story/towards-mercury-free-asgm-africa-turning-strategies-actions

Espejo JC, Messinger M, Román-Dañobeytia F, Ascorra C, Fernandez LE, Silman MR (2018) Deforestation and forest degradation due to gold mining in the Peruvian Amazon: A 34-Year Perspective. Remote Sens 10(12):1903. https://doi.org/10.3390/rs10121903

Espinosa C, Beyeler K (2021) Tracking Amazon Gold, Part 1: On-The-Ground Impacts and Solutions. Amazon Aid Foundation. https://amazonaid.org/wp-content/uploads/2021/05/Tracking-Amazon-Gold.pdf

Evers DC, Han YJ, Driscoll CT, Kamman NC, Goodale MW, Lambert KF, Holsen TM, Chen CY, Clair TA, Butler T (2007) Identification and Evaluation of Biological Hotspots of Mercury in the Northeastern U.S. and Eastern Canada. Bioscience 57:29–43

Evers, DC (2018) The Effects of Methylmercury on Wildlife: A Comprehensive Review and Approach for Interpretation. In: Dellasala, DA, Goldstein, MI (eds) Encyclopedia of the Anthropocene. Elsevier 181–194. https://doi.org/10.1016/B978-0-12-809665-9.09985-7. (http://www.sciencedirect.com/science/article/pii/B9780128096659099857)

Evers, DC et al. (2024) Global mercury concentrations in biota: Their use as a basis for a global biomonitoring framework. Ecotoxicology 33

Gerson JR, Szponar N, Zambrano AA, et al. (2022) Amazon forests capture high levels of atmospheric mercury pollution from artisanal gold mining. Nat Commun 13(1). https://doi.org/10.1038/s41467-022-27997-3

Grasmick C, Cordier S, Fréry N, Boudou A, Maury-Brachet R (1998) La pollution mercurielle liée à l'orpaillage en Guyane: contamination des systèmes aquatiques et impact sanitaire chez les Amérindiens du Haut-Maroni. J D'Agri Traditionnelle Et De Botanique Appliquée 40(1):167–179. https://doi.org/10.3406/jatba.1998.3667

Grégoire E, Gagnol L (2017) Ruées vers l'or au Sahara : l'orpaillage dans le désert du Ténéré et le massif de l'Aïr (Niger). EchoGéo, mai. https://doi.org/10.4000/echogeo.14933

Hinton J, Hollestelle MR (2012) *Artisanal and Small-Cale mining in Protecting Areas and Critical Ecosystems Programme (ASM-PACE): methodological toolkit For Baseline Assessments And response strategies to Artisanal And small-scale mining in Protected Areas And critical ecosystems*. © Estelle Levin Limited and WWF. June 30, 2012. https://www.profor.info/sites/profor.info/files/MethodologicalToolkit.pdf

Keane SE, Bernaudat L, Davis KJ et al. (2023) Mercury and artisanal and small-scale gold mining: Review of global use estimates and considerations for promoting mercury-free alternatives. AMBIO: J Hum Environ 52(5):833–852. https://doi.org/10.1007/s13280-023-01843-2

Kramer M, Kind-Rieper T, Munayer R, Giljum S, Masselink R et al. (2023) Extracted Forests: Unearthing the role of mining-related deforestation as a driver of global deforestation. Climate-Diplomacy [WWW Document]. URL https://climate-diplomacy.org/magazine/environment/extracted-forests-unearthing-role-mining-related-deforestation-driver-global

Laperche V, Nontanovanh M, Thomassin JF (2008) Synthèse critique des connaissances sur les conséquences environnementales de l'orpaillage en Guyane - *Rapport BRGM/RP-56652-FR* - Décembre 2008, 73 pages, 19 illustrations et 12 tableaux. http://infoterre.brgm.fr/rapports/RP-56652-FR.pdf

Macdonald KF, Lund MA, Blanchette ML, McCullough CD (2014) Regulation of artisanal small scale gold mining (ASGM) in Ghana and Indonesia as currently implemented fails to adequately protect aquatic ecosystems. IMWA. Published online January 1:2014, http://ro.ecu.edu.au/ecuworkspost2013/863

Madagascar. (2018) Plan d'Action National pour réduire et/ou éliminer l'utilisation du mercure dans l'Extraction Minière Artisanale et à Petite Echelle de l'Or à Madagascar, en conformité avec les dispositions de la convention de Minamata sur le mercure. https://minamataconvention.org/sites/default/files/documents/national_action_plan/Madagascar-ASGM-NAP-Dec2018-FR.pdf

Maiga F, Oumarou Touré A, Diya A, Ouattara I, Doumbia S (2022) Les effets de l'orpaillage par drague sur la biodiversité aquatique de l'affluent Baoulé dans la commune rurale de Kémékafo, région de Dioila. RASP 4(1):38–47. https://www.revue-rasp.org/index.php/rasp/article/view/155

Malm O (1998) Gold mining as a source of mercury exposure in the Brazilian Amazon. Environ Res 77(2):73–78. https://doi.org/10.1006/enrs.1998.3828

Markham K, Sangermano F (2018) Evaluating Wildlife Vulnerability to Mercury Pollution From Artisanal and Small-Scale Gold Mining in Madre de Dios, Peru. Trop Conserv Sci https://doi.org/10.1177/1940082918794320

Marshall BG, Veiga MM, da Silva HAM et al. (2020) Cyanide Contamination of the Puyango-Tumbes River Caused by Artisanal Gold Mining in Portovelo-Zaruma, Ecuador. Curr Envir Health Rpt 7:303–310. https://doi.org/10.1007/s40572-020-00276-3

Martinez G, McCord SA, Driscoll CT et al. (2018) Mercury Contamination in Riverine Sediments and Fish Associated with Artisanal and Small-Scale Gold Mining in Madre de Dios, Peru. Int J Environ Res Public Health 15(8):1584. https://doi.org/10.3390/ijerph15081584

Mawala E, Merket H (2019) Mapping Artisanal and Small-Scale Mining in Northwest Tanzania. s. d. IPIS (blog). https://ipisresearch.be/publication/mapping-artisanal-small-scale-mining-northwest-tanzania/

Melun G, Bihan ML (2020) Histoire et impacts environnementaux de l'orpaillage en Guyane. *ResearchGate*. Office français de la biodiversité. Collection Comprendre pour agir. 100 pages. https://www.researchgate.net/publication/344097645_Histoire_et_impacts_environnementaux_de_l%27orpaillage_en_Guyane

Ngom NM, Baratoux D, Bolay M, et al. (2022) Artisanal exploitation of mineral resources: remote sensing observations of environmental consequences, social and ethical aspects. Surveys Geophys 44(1):225–247. https://link.springer.com/article/10.1007/s10712-022-09740-1

Niane B, Moritz R, Guédron S et al. (2014) Effect of recent artisanal small-scale gold mining on the contamination of surface river sediment: Case of Gambia River, Kedougou region, southeastern Senegal. J Geochem Explor 144:517–527. https://doi.org/10.1016/j.gexplo.2014.03.028

O'Brien RM, Smits KM, Smith N, Schwartz M, Crouse D, Phelan T (2021) Integrating scientific and local knowledge into pollution remediation planning: An iterative conceptual site model framework. Environ Dev 40:100675. https://doi.org/10.1016/j.envdev.2021.100675

O'Neill JD (2017) Estimating Mercury Use and Documenting Practices in Artisanal and Small-scale Gold Mining (ASGM)-Methods and Tools Version 1.0. https://artisanalgold.org/wp-content/uploads/2022/11/ASGM_toolkit_eguide_en.pdf

Obeng EA, Oduro KA, Obiri BD et al. (2019) Impact of illegal mining activities on forest ecosystem services: local communities' attitudes and willingness to participate in restoration activities in Ghana. Heliyon 5(10):e02617. https://doi.org/10.1016/j.heliyon.2019.e02617

Omara T, Karungi S, Kalukusu R, Nakabuye B, Kagoya S, Musau B (2019) Mercuric pollution of surface water, superficial sediments, Nile tilapia (Oreochromis nilotica Linnaeus 1758 [Cichlidae]) and yams (Dioscorea alata) in auriferous areas of Namukombe stream, Syanyonja, Busia, Uganda. PeerJ 7:e7919. https://doi.org/10.7717/peerj.7919

Otchere FA, Veiga MM, Hinton J, Farias R, Hamaguchi R (2004) Transforming open mining pits into fish farms: Moving towards sustainability. Nat Res Forum 28(3):216–223. https://doi.org/10.1111/j.1477-8947.2004.00091.x

Palacios-Torres Y, Caballero-Gallardo K, Olivero-Verbel J (2018) Mercury pollution by gold mining in a global biodiversity hotspot, the Choco biogeographic region, Colombia. Chemosphere 193:421–430. https://doi.org/10.1016/j.chemosphere.2017.10.160

Pascal N, Dieudonné, M, Mputu Kanyinda, Jean-noel. (2020) Evaluation of the level of mercury pollution in the sediments of the rivers draining the gold panning sites in the territory of Fizi, eastern Democratic Republic of Congo. J Geosci Environ Protec 08(02):97–111. https://doi.org/10.4236/gep.2020.82007

Pisconte JN, Vega1 CM, Pillaca-Ortiz JM, Quispe E, Sevillano-Ríos CS, Tejeda V, Ascorra C, Silman MR, Fernandez LE (2023) Elevated mercury exposure to bird communities inhabiting Artisanal and Small-Scale Gold Mining landscapes of the southeastern Peruvian Amazon. Ecotoxicology. PREPRINT (Version 1) available at Research Square https://doi.org/10.21203/rs.3.rs-3318605/v1

Planque M, Benvenuti A, Moomen AW, Lacroix P (2022) How can remote sensing support artisanal and small-scale gold mining policy development, implementation and evaluation? Global Mercury Partnership [WWW Document], n.d. URL https://owncloud.unepgrid.ch/index.php/s/0cuN7cEgfaWKepb-pdfviewer

Portillo A, Vega CM, Mena JL, Bonifaz E, Ascorra C, Silman MR, Fernandez LE (2023) Mercury bioaccumulation in bats in Madre de Dios, Peru: implications for Hg bioindicators for tropical ecosystems impacted by artisanal and small-scale gold mining. Ecotoxicology. https://doi.org/10.1007/s10646-023-02719-7

Puluhulawa F, Harun AA (2020) Biodiversity Protection from the Impact of Illegal Gold Mining for Sustainability. IOP Conference Series 519:012031. https://doi.org/10.1088/1755-1315/519/1/012031

Pure Earth (2019) Rainforest reforestation brings degraded mining sites back to life, provide models of hope. https://www.pureearth.org/rainforest-reforestation-brings-degraded-mining-sites-back-to-life-in-peru-provide-models-ofhope/

Rahm M, Thibault P, Shapiro A, Smartt T, Paloeng C, Crabbe S, Farias P, Carvalho R, Joubert P (2017). Monitoring the impact of gold mining on the forest cover and freshwater in the Guiana Shield. 2015. pp.20. https://www.bio-plateaux.org/sites/default/files/documents/Gold_mining_impact_2015_GS_FINAL.pdf

Ruby Weinberg et al. (2013) Rapport d'activités et recommendations mises à jour : Exploitation minière artisanale dans la réserve naturelle d'Itombwe, République Démocratique du Congo. © Estelle Levin Limited &4 WWF. https://www.levinsources.com/assets/pages/Itombwe-FR.pdf

Schön-Blume N, Dolega P, Buchert M, Bodenmüller B, Meyer M (2021) The Impact of Gold: Sustainability aspects in the Gold supply-chains and Switzerland's role as a gold hub. https://www.oeko.de/fileadmin/oekodoc/The-Impact-of_Gold.pdf

Sissoko MF (2019) Double rationalité sur l'orpaillage traditionnel au Mali. Revue Africaine Des Sciences Sociales Et De La Santé Publique 1(2):101–115. http://revue-rasp.org/index.php/rasp/article/view/15

Spiegel SJ, Keane SE, Metcalf S, Veiga MM, Yassi A (2014) The Minamata Convention on Mercury: Time to Seek Solutions with Artisanal Mining Communities. Environ Health Persp 122(8). https://doi.org/10.1289/ehp.1408514

Sundseth K, Pacyna JM, Pacyna EG, Pirrone N, Thorne RJ (2017) Global Sources and Pathways of Mercury in the context of Human Health. Int J Environ Res Public Health 14(1):105. https://doi.org/10.3390/ijerph14010105

Tarras-Wahlberg H, Flachier A, Lane SN, Sangfors O (2001) Environmental impacts and metal exposure of aquatic ecosystems in rivers contaminated by small scale gold mining: the Puyango River basin, southern Ecuador. Sci Tot Environ 278(1-3):239–261. https://doi.org/10.1016/S0048-9697(01)00655-6

The Asian Foundation. (2016) Engaging Stakeholders in Environmental Conservation Project. https://asiafoundation.org/wp-content/uploads/2016/09/MG-ESEC-II-2016-ENG.pdf

The Cadmus Group LLC. (2019) "Small-scale & artisanal mining: impacts on biodiversity in Latin America". March 2019. https://www.land-links.org/wp-content/uploads/2019/10/ASM_White-Paper_USAID_FINAL_21March2019Final.pdf

UNEP-WCMC and IUCN (2023), Protected Planet: The World Database on Protected Areas (WDPA) [Online], March 2023, Cambridge, UK: UNEP-WCMC and IUCN

UNITAR's Operational Satellite Applications Programme. s. d. (2016) Satellite Mapping of Artisanal and Small-Scale Gold Mining in Central Kalimantan, Indonesia.UNOSAT_Central_Kalimantan_Report_Feb2016o (2). https://wedocs.unep.org/20.500.11822/11526

United Nations Environment Programme, Economy Division (2021) Chemicals, Wastes and Climate change: Interlinkages and Potential for Coordinated Action https://wedocs.unep.org/20.500.11822/36396

United Nations Environment Programme, Ecosystems Division (2021) Interlinkages between the Chemicals and Waste Multilateral Environmental Agreements and Biodiversity: Key Insights. https://wedocs.unep.org/20.500.11822/36088

United Republic of Tanzania. (2020) National Action Plan for Artisanal and Small-scale Gold Mining 2020–2025. https://minamataconvention.org/sites/default/files/documents/national_action_plan/TANZANIA-NAP-EN-2020.pdf

Veiga MM, Maxson PA, Hylander LD (2006) Origin and consumption of mercury in small-scale gold mining. J Clean Produc 14(3-4):436–447. https://doi.org/10.1016/j.jclepro.2004.08.010

Verweijen J, Schouten P, O'Leary SF et al. (2022) Conservation, conflict and semi-industrial mining: the case of eastern DRC. IOB Analyses & Policy Briefs, IOB Analyses & Policy Briefs. https://ideas.repec.org/p/iob/apbrfs/2022006.html

Villegas C, Weinberg R, Levin E, Hund K (2012) Artisanal and Small-Cale mining in Protecting Areas and Critical Ecosystems Programme (ASM-PACE) https://www.profor.info/sites/profor.info/files/MethodologicalToolkit.pdf

West Africa ASGM Study Tour in Togo (2023) https://www.unep.org/globalmercurypartnership/news/story/voyage-detude-sur-lextraction-artisanale-et-petite-echelle-de-loremape-dor-en-afrique

Yao KSA, Ahoussi KE (2021) Assessment of Mercury (Hg) and Cyanide (CN) Pollution in Surfacewaters, Groundwaters and Sediments around Industrial Mining Sites in the Department of Divo (Ivory Coast). J Water Res Protect 13(02):75–91. https://doi.org/10.4236/jwarp.2021.132005