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Review

From Stockholm to Minamata and beyond: Governing mercury pollution for a more sustainable future

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SUMMARY

The 50th anniversary of the 1972 United Nations Conference on the Human Environment provides an opportunity to reflect on mercury pollution as a sustainability issue past, present, and future. Scientists and policymakers recognize that mercury is connected to multiple sustainability challenges, but a more comprehensive understanding of global mercury governance in the context of sustainability is needed. Here, in this Review, we synthesize the existing literature and evaluate the global governance of mercury pollution in relation to sustainability. We find that global 50-year trends in mercury production, consumption, and discharges are mixed, but mercury governance has expanded; mercury discharges from coal-fired power plants and artisanal and small-scale gold mining, two leading sectors of mercury pollution, are increasingly connected to sustainability challenges; a global-scale indicator of mercury discharges can provide policy-relevant information, but cannot capture local variations; and long-term interventions addressing mercury use and pollution are part of broader sustainability transitions.

INTRODUCTION

The global sustainable development agenda is large, multifaceted, and critical to ensuring human well-being for both current and future generations. A key sustainability challenge involves how to further advance the assessment and governance of hazardous substances that cause environmental and human health problems.[1] Hazardous substances, as part of a focus on novel entities, have also been identified as a major global issue for which some scientists have attempted to classify a planetary-level boundary to inform policy making and management.[2] Among a large group of hazardous substances, mercury is of much concern.[3–5] The two largest contemporary sources of anthropogenic discharges of mercury to the environment are coal-fired power plants and artisanal and small-scale gold mining (ASGM), and these sources of mercury pollution are also linked to issues of energy production, air and water pollution abatement, climate change mitigation, and poverty eradication. For people who are not working in or affected directly by mercury-using sectors, most contemporary human mercury exposure is to methylmercury, a powerful neurotoxin, from eating contaminated fish and other aquatic foods.[6]

Global assessment reports over the past two decades have synthesized scientific knowledge of the environmental behavior of mercury and its impact on human health, also informing international cooperation. The first global mercury assessment, completed in 2002, identified mercury as a global pollutant due to long-range atmospheric transport that warranted international action.[3] Voluntary partnerships aiming to reduce mercury use and pollution under the United Nations Environment Programme (UNEP) started in the mid-2000s, and UNEP's Governing Council decided in 2009 to launch negotiations on a global mercury treaty.[7,8] A second global mercury assessment report—finalized in 2013 and focusing on anthropogenic sources, emissions, releases, and environmental transport—re-confirmed the global scale of the mercury issue, as countries adopted the Minamata Convention on Mercury that same year.[7,9] The Minamata Convention entered into force in 2017.[10] The most recent global mercury assessment report, including updated information on mercury discharges from different sectors and regions, was completed in 2018.[4] By 2022, 136 countries and the European Union were parties to the Minamata Convention. In addition to the global assessments, the Arctic Monitoring and Assessment Programme produced a series of Arctic-focused reports beginning in the 1990s identifying mercury as an environmental pollutant and human health problem.[11–19]

Much natural science research centers on the biogeochemical cycling of mercury, often focusing on atmospheric transport.[20,21] Previous studies provide estimates of mercury concentrations in the atmosphere and terrestrial and aquatic ecosystems as well as exchange processes between them.[20,22,23] A few studies have estimated the importance of mercury releases to land and water to global biogeochemical cycling.[24,25] Mercury in land and water can pose local contamination problems, and much research has focused on localized human health risks from mainly methylmercury exposure.[26] Researchers have increasingly studied mercury biogeochemical cycling and risks to wildlife and humans in the context of major global change drivers.[26] Previous work found that many individual, environmental, and societal drivers of the distribution and health effects of mercury are broader in scope than the mercury issue alone.[27] A smaller set of social science literature has focused on mercury policy and institution building, including the Minamata Convention.[7,9,28–32] However, there is a need for additional scientific information to inform policy making aimed at further protecting people from adverse effects of mercury exposure. Despite an increasing scientific and societal realization that mercury pollution is linked to a broad range of sustainability issues,[30,33,34] a more comprehensive understanding of mercury pollution as a sustainability governance challenge is needed.

In this review—50 years after the United Nations Conference on the Human Environment in Stockholm and 5 years after the entry into force of the Minamata Convention—we examine connections between major aspects of the mercury issue and the global sustainable development agenda, over a centruy-long time frame (1972–2072). The analysis focuses on mercury discharges from the two largest sources globally: coal-fired power plants and the ASGM sector. We draw from a literature review of international reports, synthesis articles, and a large number of natural and social sciences articles focusing on mercury and coal burning and ASGM, respectively. We highlight four points related to mercury science and governance in the context of sustainability. First, 50-year trends in mercury production, use, emissions, and releases are uncertain and mixed, but national and international efforts addressing mercury-related environmental and human health problems have increased in scope and stringency. Second, over the past 50 years, coal burning and ASGM have become increasingly linked to sustainability challenges due to complex production and consumption patterns and an expansion of international policy. Third, a global indicator of total cumulative anthropogenic discharges can provide useful information on the status of the mercury problem for global policy making, but such an indicator cannot provide sufficient insight on mercury's localized impacts on human well-being. Fourth, looking forward, many necessary long-term interventions to address mercury pollution are connected with broader policy debates and actions on sustainability transitions.

GLOBAL MERCURY TRENDS SINCE 1972

The human fingerprint on mercury's global biogeochemical cycle has been summarized in prior literature and assessments, which largely focus on human-induced mercury emissions to the atmosphere, atmospheric transport, and deposition to ecosystems where methylmercury is formed in aquatic environments. To review the mercury pollution problem and how it has changed since 1972, we take a broader approach by synthesizing existing data on global trends in mercury production, consumption, and anthropogenic emissions and releases in the context of sustainable development. Consistent with Minamata Convention language, we use the term emissions to mean mercury emissions to the air, releases refer to mercury releases to land and water, and discharges include both emissions and releases of mercury. Related to our first point, while total primary mercury mining has declined and mercury uses in products and industrial manufacturing processes have been reduced over the past five decades, estimates of global emissions trends provide conflicting data, and the one estimate of global releases indicates no change. Taken together, these estimates provide a mixed overall picture of how global mercury pollution has changed since the Stockholm Conference. At the same time, policy interventions to address mercury pollution have expanded dramatically, including under the Minamata Convention.

Mercury is emitted and released to the environment both by natural processes (such as volcanic eruptions and weathering of rocks) and by anthropogenic activities. The human contribution is far larger than emissions and releases from natural processes.[20] Human activities mobilize mercury through mining of mercury, other mining processes, and the burning of fossil fuels (largely coal) where mercury is a contaminant. Figure 1 shows a summary of available data on global trends over the past 50 years in mercury production (primary mining) and consumption, anthropogenic emissions, anthropogenic releases, and key milestones on global mercury policy and sustainability. Figure 1 also shows available emissions projections over the next 50 years. Both production and consumption of mercury were much higher at the time of the Stockholm Conference than they are today. Over the past five decades, there has been a steep decline in primary mercury mining, which is reflected in Figure 1 in trends in production. Related changes in commercial mercury consumption, including information on fluctuations in mercury prices, are summarized in Box 1. The production, consumption, emissions, and releases of mercury are closely linked to one another through the biogeochemical cycle. Both new mercury discharges and historically emitted legacy mercury are involved in global atmospheric transport and environmental cycling.

Prior scientific estimates have mainly focused on quantifying anthropogenic mercury emissions to air in the context of global biogeochemical cycling.[37,38,45,46] This focus is in part due to a lack of reliable data on human-induced releases, but studies are also underpinned by an assumption that emissions are of greater global-scale concern than releases due to their long-range atmospheric transport. Mercury releases are accounted for in the global biogeochemical cycle when they enter the atmosphere from land and water, and are typically quantified through modeling or emissions constraints.[47,48] Global biogeochemical cycle analyses have found that human activities have enhanced the amount of mercury in the atmosphere by about an order of magnitude over natural levels. Recent work suggests this factor is much greater in the Northern Hemisphere (16×) than in the Southern Hemisphere (4×).[49] This enrichment happened mainly before 1972. About a third of the mercury emitted to air in the present day is from primary anthropogenic sources. The majority of the remaining emissions consist of the re-volatilization of historical mercury from land and oceans. As a result of this re-volatilization, mercury depositing to ecosystems from the atmosphere today reflects a combination of recently emitted mercury and mercury that was discharged decades to centuries ago from both anthropogenic and natural sources.[50]

Global trends in anthropogenic mercury discharges

Separate global emissions inventories report very different trends in primary anthropogenic emissions since 1972, with the most recent data from 2015. Figure 1 shows the range of these estimates. Data from different emission inventories show varying estimates and differ even as to whether global mercury

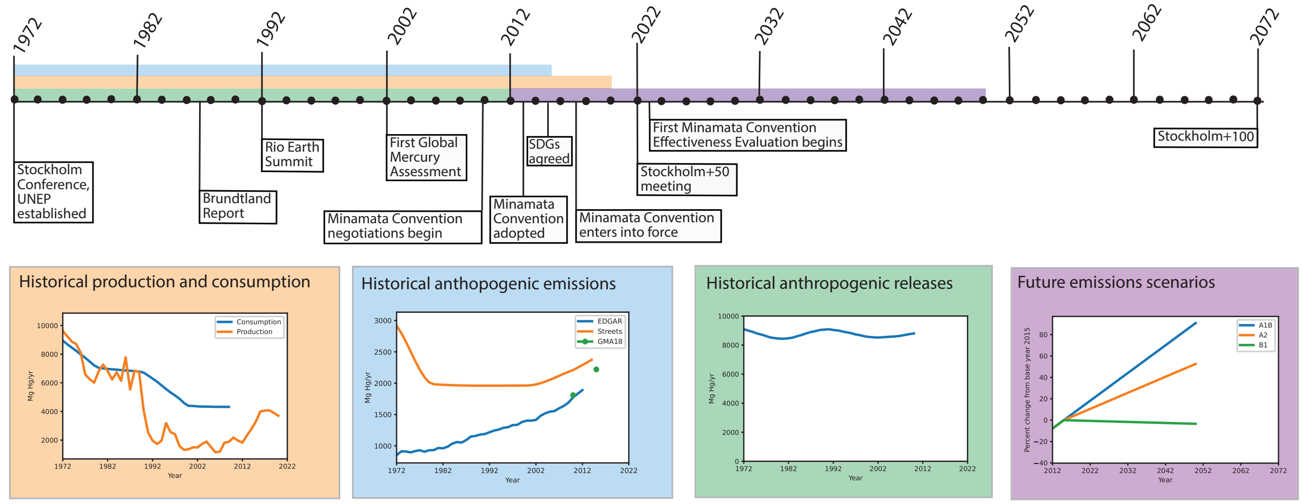


Figure 1. Historical trends in mercury production and consumption, emissions, releases, and future scenarios from 1972 to 2072

Colored bars on timeline indicate data availability, noting key milestones on global mercury policy and sustainability. Production figures are from US Geological Survey (USGS) mineral commodity statistics.[35] Consumption data are from Horowitz et al.[36] Emission data are from Muntean et al. (EDGAR),[37] Streets et al.,[38,39] and the 2018 Global Mercury Assessment.[4] Release data are from Streets et al.[39] Normalized emissions scenarios were compiled by Schartup et al.[40] For future emissions scenarios, A1B, A2, and B1 refer to mercury scenarios based on underlying socio-economic assumptions from the Intergovernmental Panel on Climate Change's Special Report on Emissions Scenarios, and are described further in Schartup et al.[40]

emissions have declined or increased over the past five decades. Muntean et al. estimate that mercury emissions more than doubled, from roughly 850 Mg to nearly 1,900 Mg in the four decades following the Stockholm Conference.[46] In contrast, trend estimates by Streets et al. show mercury emissions peaking at roughly 3,000 Mg around the time of the Stockholm Conference, declining rapidly during the 1970s, remaining roughly steady from 1980 to 2000, and then increasing again slightly from 2000 to 2010.[39] Overall, Streets et al. estimate about a 25% decrease in emissions from 1972 to 2010. They credit the initial decline in mercury emissions in the 1970s a result of phase-outs of mercury uses in products and processes. From 2010 to 2015, Streets et al. estimate that global emissions grew by about 1.8% per year, driven by emissions from coal-fired power plants and industrial metals production in emerging economies in Asia as well as the ASGM sector globally.[38] The most recent global mercury assessment estimated that mercury emissions increased by 20% between 2010 and 2015, as coal burning and ASGM were responsible for almost 60% of global mercury emissions to air in 2015.[4]

Different estimates of global mercury emissions trends remain uncertain and conflicting because environmental measurements provide limited constraints. The variability and sparsity of atmospheric concentration measurements make it difficult to evaluate the emissions trajectories shown in Figure 1, which also differ based on the forms of mercury released, in particular the fraction of shorter-lived forms of mercury (gaseous oxidized mercury or particulate-bound mercury) versus the more long-lived form of gaseous elemental mercury.[37] The few reliable measurements of atmospheric mercury concentrations from the 1970s, largely in the Northern Hemisphere, are in general higher than today's concentrations.[51] More measurements are available since 1990, but there remain gaps in global coverage, especially in developing regions and in the Southern Hemisphere. Many stations in North America and Europe see declines in atmospheric concentrations or deposition over the past 30 years, but those at a few stations have increased.[51–53] Much of this variability is due to the fact that emissions in some places have decreased, but have increased in others. In the last decade, constant or increasing trends in atmospheric mercury concentrations have been observed at Southern Hemisphere sites.[54] Data from environmental archives such as sediments and peat cores provide a more comprehensive record of mercury deposition over time than atmospheric concentrations, although they provide coarser time resolution. These show that mercury deposition peaked in the mid-twentieth century, although peat records imply a greater decline than sediment records.[47]

Few studies have calculated the global amount of anthropogenic mercury releases to land and water. There is only one comprehensive historical inventory available, which estimates that mercury releases are generally much larger than mercury emissions to air.[39] As shown in Figure 1, that estimate shows little change in global mercury releases since 1972, as total releases for the year 2010 were estimated at more than twice the amount of mercury emissions to air.[39] The limited scientific data on global mercury releases are likely more uncertain than existing data on atmospheric mercury emissions, as there are even fewer ways to constrain estimates of discharges with environmental measurements. Further, top-down estimates quantified by a mass balance approach may overestimate environmental releases, as some mercury can remain in forms that may be effectively immobile for longer timescales. Regardless, the global release estimate suggests that a large amount of mercury is entering the environment in particular places all around the world. It is unclear how much of the mercury that is released to land and water stays locally, and what fraction enters the pool of mercury that cycles globally through land, water, and air. If a greater fraction of this mercury than is frequently assumed is subject to global

Box 1. Mercury, mining, and uses over the past 50 years

Mercury is a naturally occurring chemical element in the Earth's crust. It is the only metal in the periodic table that is liquid at room temperature, and different organic and inorganic mercury compounds are found in solid and gaseous forms. Some mercury compounds have been synthesized in laboratories and these can also end up being discharged into the environment.[34] World mercury production from mining in 1972 was roughly 9,500 Mg, or 279,508 flasks, a unit of measure specifically used for mercury and equivalent to 34 kg.[41] This represented about a 10% decrease from the all-time global peak at 298,552 flasks in 1971. Several historically dominant mercury mines have been shut down since the Stockholm Conference, including the ones in Huancavelica, Peru (1974), Idrija, Slovenia (1995), and Almadén, Spain (2002), but mining continued in a few other places, including China (however, mercury mining in Wanshan, going back thousands of years, ended in 2003).[42] Much commercial mercury has been recycled and used in multiple manufacturing processes and products over time as well as traded internationally.[43]

The international price of mercury has fluctuated substantially over the past 50 years. In 1972, the average price of mercury was $41,175 per Mg (in year 2021 US dollars), down from a peak price of over $141,000 (year 2021 US dollars) in 1965.[44] The mercury price declined until the early 2000s, then increased again to a peak value of about $115,000 per Mg (in year 2021 US dollars) in 2013.[44] This more recent price increase was largely due to a growing demand for mercury for use in the expanding ASGM sector even as some countries restrict mercury import and use in ASGM.[43] The mercury price declined again after 2013, but illegal extraction in previously closed mercury mines in Mexico and Indonesia together with undocumented exports provided increased supply internationally.[43] Because the United States and the European Union adopted mercury export bans starting in the 2000s, and a growing number of other countries also introduced export and import restrictions, there is no longer a global commercial commodity price for mercury, but prices vary across regional and domestic markets based on demands and controls.[34] Some places, including Hong Kong and the United Arab Emirates, continue to be important nodes in the international mercury trade.[43]

Global mercury use peaked around 1970, about the same time as primary mercury mining hit an all-time high, at near 10,000 Mg per year.[36] Many industrial uses of mercury expanded during much of the twentieth century, but global demand began to decline around the time of the Stockholm Conference. Mercury in 1972 was used in a variety of consumer products (including electronic goods, thermometers and other measuring and control devices, batteries, and paints) as well as multiple chemical manufacturing processes, including chlorine and caustic soda production.[41] Mercury was also frequently used in dental amalgam. Roughly two-thirds of global mercury consumption in the early 1970s was in industrialized countries.[36] Uses in the these countries declined dramatically in the decades following the Stockholm Conference, and contemporary mercury consumption is predominantly in developing countries.[36] UNEP estimated that global demand for commercial mercury in 2015 was 4,720 Mg.[43] This mercury was almost evenly used in consumer products (31%), production processes (32%), and ASGM (37%).

transport, it would affect the accuracy of existing biogeochemical cycling studies and estimates of historical emissions.

Data limitations on anthropogenic mercury emissions and releases coupled with a variety of assumptions about future energy use and the application of emission control technologies mean that the future trajectory of global mercury discharges is highly uncertain. Existing scenarios of future global human-induced mercury emissions, which are shown in Figure 1, involve a large range of potential trajectories.[40] The range of emissions estimates is summarized by Schartup et al.[40] Estimates to 2050 under the highest emission assumptions project more than a doubling of mercury emissions relative to 2015 levels.[55] In contrast, the maximum feasible reduction scenarios show reduced mercury emissions to near zero.[45] Corresponding comprehensive scenario projections of future anthropogenic releases of mercury are unavailable at global scale. It is possible, however, that ongoing international collaborative efforts to implement the Minamata Convention together with expanded national reporting under the treaty can provide more data that, alongside further scientific research, will help improve future global estimates of mercury emissions and releases.

Mercury governance and the Minamata Convention

Global patterns of human exposure to mercury, and associated health risks, have changed since the Stockholm Conference.[34] People who have come in direct contact with elemental mercury, including miners and workers in manufacturing sectors, have suffered serious illness and fatalities for millennia. As much primary mercury mining and mercury uses in consumer products and industrial processes have been phased out over the past 50 years (as reflected in overall consumption trends in Figure 1), occupational exposure has been significantly reduced, with the exception of the ASGM sector where high-dose exposure to mercury vapor remains problematic. Use in medicine is another way in which people have been exposed to different forms of mercury for centuries with negative health consequences, but such use has also largely stopped. In 1972, the US Food and Drug Administration proposed banning mercury in most cosmetics due to mercury's known hazards, and phase-outs of mercury use in medicine and beauty products have since been expanded in countries all over the world (but mercury in some skin-lightening creams continues to pose risks).[34] Methylmercury exposure from dietary intake of predominantly fish together with other aquatic animals from oceans and freshwater lakes and rivers, however, remains a concern worldwide.[56]

The extent of domestic and international interventions to address different aspects of the mercury problem has grown considerably since 1972. Key milestones on global mercury policy and sustainability are shown in Figure 1. Discussions at the Stockholm Conference included how to advance abatement of transboundary air and water pollution, of which discharges of mercury and other heavy metals were an important part.[28] Mercury pollution gained widespread international attention after methylmercury poisoning was identified in Minamata, Japan, in the 1950s, and people affected by the disease were present in Stockholm in 1972. Countries have introduced increasingly stringent domestic regulations on mercury mining, uses, and discharges in the decades following the Stockholm Conference. Internationally, regional water pollution agreements in Europe and North America included expanding controls on mercury releases starting in the 1970s, the global 1989 Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal included a focus on mercury wastes, and a 1998 Heavy Metals Protocol to the regional Convention on Long-Range Transboundary Air Pollution covering North America and Europe identified mercury as a priority substance.[19,28] The UNEP Global Mercury Partnership starting in 2005 created a multi-stakeholder platform for addressing different aspects of the mercury issue, and the Minamata Convention has been a global focal point for life-cycle mercury abatement since treaty negotiations began in 2010. The Minamata Convention is also an important institutional part of the 2030 Agenda for Sustainability, for which the Sustainable Development Goals (SDGs) —agreed in 2015 with 2030 target dates—are central.[57]

The Minamata Convention sets out to protect human health and the environment from anthropogenic emissions and releases of mercury (Article 1). The control provisions (detailed in Articles 3–12) specify measures that parties must take to address the supply, trade, use, emissions, and releases of mercury as well as manage mercury wastes and contaminated sites. Box 2 provides a summary of these control provisions. The Minamata Convention aims to eliminate mercury mining and China, currently the world's largest producer of mined mercury, has stated that all domestic mercury mines will be closed down no later than 2032. The treaty also introduces trade-related provisions and targets phase-outs and reductions in mercury uses in consumer products, industrial processes, and ASGM (but with some remaining medical uses in dental amalgam and vaccines still permitted).[58] The Minamata Convention stipulates mainly technology-based measures for controlling anthropogenic mercury emissions and releases, and parties must take steps to ensure environmentally sound storage and waste management of discarded mercury and remediate contaminated sites. Parties to the Minamata Convention continue to work to develop guidance on best available techniques (BATs) and best environmental practices (BEPs) associated with these technology-based measures. International partnerships and civil society organization provide additional efforts to address mercury-related problems, including in ASGM.

MERCURY AS A SUSTAINABILITY CHALLENGE

Efforts to address mercury pollution over the past 50 years have occurred in the context of a broader global sustainable development agenda that has emerged over that period. Related to our second point, coal burning and mercury use in ASGM, the two largest contemporary sources of mercury discharges, are increasingly intertwined with broader challenges related to sustainability.[59] Figure 2 summarizes and compares the issues of mercury in coal burning and ASGM, illustrating central areas of major mercury emissions to air, key regions, Minamata Convention provisions, and connections with relevant SDGs.

Mercury discharges from coal burning

The total amount and geographical distribution of coal burning have changed dramatically over the past 50 years, and this in turn has changed levels and locations of associated mercury discharges to the environment. Since 1972, global coal consumption has increased by nearly 150%, as human demand for energy grew during that time, but coal nevertheless remained a similar fraction of the world's energy mix, comprising between 25% and 30%.[62] All forms of coal contain trace amounts of mercury that are mobilized when coal is burned.

In 1972, consumption of coal in Europe was 5,294 TWh (equivalents), while in the US it was 3,362 TWh. European consumption peaked in the mid-1980s at just over 7,000 TWh, while US consumption peaked in the 2000s at around 6,400 TWh. Today, coal consumption in both regions is below 3,000 TWh.[62] In contrast, in China and India, coal consumption was 2,353 TWh and 468 TWh in 1972, respectively, and had grown to 22,853 TWh and 4,871 TWh in 2020.[62] China and India have driven most of the global growth in coal power since 2000. In 2018, 60% of China's primary energy consumption came from coal. Eighty percent of China's coal capacity in 2019 was from power plants built after 2000.[63] As a result, China was responsible for 51.7% of global coal consumption in 2019.[64] India has also increased domestic investments in coal-fired power plants, and its share of the world's coal consumption was 11.8% in 2019. This puts India ahead of the United States (at 7.2%) and the European Union (at 4.9%). Other Asian countries with a relatively high portion of global coal consumption include Japan (3.1%), Indonesia (2.2%), South Korea (2.2%), and Vietnam (1.3%), with all of Asia responsible for 77.4% of world consumption.[64]

Changes in the magnitude and location of coal burning have altered the geographical distribution of major sources of mercury emissions to air from energy production. In 2015, 13.1% of global mercury emissions to air came from stationary coal-fired power plants.[4] In addition, 5.7% came from other kinds of industrial coal combustion. By 2015, the European Union and North America contributed only 6% and 2%, respectively, of global mercury emissions from coal burning. Because China and India are leading users of coal, the majority of mercury emissions from coal burning originate from these two countries. By 2010, 72% of global mercury emissions from coal combustion came from Asia. Africa and the Middle East were responsible for 9%, and Russia and other countries formerly part of the Soviet Union contributed just under 4%.[61] Streets et al. calculate that coal combustion in the early 1970s resulted in just over 200 Mg of mercury emitted to air.[61] Estimates vary about the amount of mercury emitted from coal for the present day; the same Streets et al. study estimated for 2010 a median value of 561 Mg and an uncertainty range of 221 to 1,473 Mg.[61]

In the past five decades, many efforts to address mercury emissions from coal burning have focused on the application of end-of-pipe emissions control technology, which has advanced significantly in the past 50 years through the development of technology as well as better knowledge and practices. The efficiency of different mercury capture technologies varies, but the most efficient ones currently on the market can capture up to 98% of all mercury in coal.[65,66] Different emission control technologies, however, vary with respect to their relative capture of specific forms of mercury. The use of emissions control

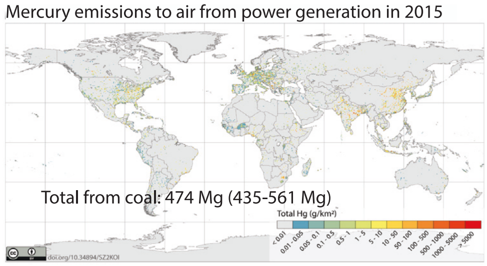
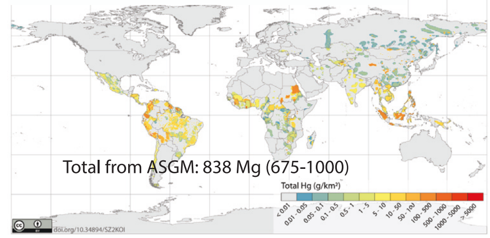
	Coal-burning	ASGM
Emissions	Mercury emissions to air from power generation in 2015 	Mercury emissions to air from ASGM in 2015 
Releases	Mercury captured by end-of-pipe controls can be released to land and water if not managed appropriately. By 2010, 55% of total mercury from coal was emitted to air, and the rest captured.	Largest quantified source of releases to land and water by Global Mercury Assessment (about 1220 Mg).
Key Regions	Largest present-day mercury emissions are in China and India, which are largest users of coal.	Occurs in >80 countries throughout the world, mostly developing countries.
Minamata Convention Provisions	Article 8 controls emissions from point sources including coal-fired power plants and industrial boilers. It requires the use of best available techniques (BATs) and best environmental practices (BEPs) for new sources no later than five years after the treaty enters into force, and for existing sources no later than ten years after the treaty enters into force.	Article 7 requires parties reduce and, where feasible, to eliminate mercury use in, and mercury emissions and releases to the environment from, ASGM. Relevant parties must develop action plans that outline national objectives, reduction targets, and actions to eliminate whole ore amalgamation and open burning or amalgam as well as burning of amalgam in residential areas.
Related SDGs		

Figure 2. Summary of mercury challenges and key sustainability connections for coal burning and ASGM
For coal burning, this involves SDG 7 (affordable and clean energy), SDG 8 (decent work and economic growth), SDG 12 (responsible consumption and production), SDG 13 (climate action), and SDG 14 (life below water). For ASGM, related SDGs includes SDG 1 (no poverty), SDG 2 (zero hunger), SDG 3 (good health and wellbeing), SDG 8 (decent work and economic growth), SDG 12 (responsible consumption and production), SDG 14 (life below water), and SDG 15 (life on land). Emissions data and emissions graphics are from Steenhuisen and Wilson.[60] Release data on coal burning are from Streets et al.[61] Releases from ASGM are from the 2018 Global Mercury Assessment.[4]

technologies in coal-fired power plants influences the environmental distribution and deposition of emitted mercury, as some forms of mercury tend to only travel regionally, while other forms can remain in the atmosphere for up to a year allowing for global-scale transport and distribution, as noted above.[50] Some technologies target mercury emissions specifically, while other technology-based efforts primarily focus on capturing other pollutants, including sulfur dioxide (SO_2), nitrogen oxides (NOx), and particulate matter, but also reduce some mercury emissions.[66]

Laws mandating mercury emissions controls from coal-fired power plants were absent in 1972. Controls of mercury emissions to air from point sources in the United States and the European Union date back to 1973 and 1989, respectively.[34] These controls were gradually expanded over time, including by setting stricter and more specific standards for mercury emissions from coal-fired power plants. Countries in other regions, including China, introduced domestic standards on mercury emission from coal-fired power plants in the 2000s and 2010s. Today, the Minamata Convention covers mercury emissions from five kinds of major point sources (listed in Annex D of the treaty): coal-fired power plants, coal-fired industrial boilers, smelting and roasting processes used in the production of non-ferrous metals, waste incineration facilities, and cement clinker production facilities. Under the Minamata Convention, as well as the UNEP voluntary mercury partnerships, much focus has been on reducing mercury emissions from coal burning rather than controlling coal burning per se.[34] In part as a result of the Minamata Convention, policies and regulations covering mercury emissions to air from coal-fired power plants are becoming more globally harmonized.

The expanded use of end-of-pipe pollution control technologies can further reduce mercury emissions to air from existing coal-fired power plants. One study estimated that retrofitting efforts in China between 2011 and 2015 prevented 23.5 Mg of mercury from entering the air, which was roughly equal to 20% of China's mercury emissions from coal-fired power plants in 2010.[67] The fraction of mercury emitted globally to the atmosphere during coal burning (relative to the amount of mercury in fly ash that is captured by end-of-pipe control technologies) dropped from 72% to 55% between 1972 and 2010, because of increasing use of emission controls.[61] The mercury captured by end-of-pipe technologies, however, is still mobilized from fossil-fuel sources, and can lead to additional mercury discharges if not managed appropriately. For example, re-use of fly ash from coal-fired power plants can result in mercury emissions during cement production if not properly controlled during the production process.[68]

The Minamata Convention specifies that parties must apply BAT, BEP, or emission limit values (ELVs) to all new point sources to control mercury emissions, and where feasible reduce them, no later than 5 years after joining the treaty. Parties must also control, and where feasible reduce, mercury emissions from existing point sources through BAT, BEP, or ELVs, or a multi-pollutant control strategy no later than 10 years after the Minamata Convention becomes legally binding for them. These control provisions are largely consistent with previous legislation in the United States and the European Union. Importantly, the Minamata Convention mainly leaves it up to each individual party to define BAT, BEP, and ELVs based on their own socio-economic and technical situation, but the Conference of the Parties to the Minamata Convention is tasked with developing technical guidance documents to assist parties formulate and apply technology-based controls. China has increased its standards over time, including as part of implementing the Minamata Convention.[31] China's standards are currently on par with Germany's, but less stringent than the US standards.[34] In contrast, India and other developing countries have been much slower to introduce domestic mercury emissions controls on coal-fired power plants.[30,69] This is partly because an absence of financial resources and modern abatement technologies, and many developing countries may also lack monitoring and enforcement resources.[30]

At the same time, new mandates for the application of stricter pollution prevention technologies to capture mercury emissions (and sometimes in conjunction with other pollutants) can have mixed results on the operational lifetime of coal-fired power plants. Empirical data suggest that the introduction of technology-based mandates for controlling mercury emissions from coal-fired power plants can both shorten and extend the lifetime of individual power plants. In the United States, some older coal-fired power plants in the 2010s were taken out of production earlier than previously planned when federal mercury emissions standards were introduced.[70,71] Rather than invest in the new, required emissions capture technologies, owners elected to close down power plants. In contrast, newer coal-fired power plants already equipped with relatively modern control technologies that meet more stringent emissions standards may avoid being shut down over air pollution concerns and will continue to emit carbon dioxide (CO_2), making it more difficult to meet the 2°C and 1.5°C goals for average global temperature rise in the 2015 Paris Agreement on climate change.[72]

The World Bank and regional development banks were major funders of energy projects, including coal-fired power plants, in developing countries in the decades following the Stockholm Conference. However, the World Bank stated in 2013 that it would largely stop funding new coal-fired power plants for climate change reasons, and leading regional development banks have increasingly followed suit.[73] In contrast, Chinese publicly sponsored development finance institutions, together with their Japanese and South Korean counterparts, starting in the 2000s emerged as major financers of coal-fired power plants in other countries. Support from Chinese development finance institutions helped bring online 56 GW of coal power between 2000 and 2018.[74] Japan and South Korea stated in 2020 that their development finance institutions would phase out support for new coal-fired power plants.[74] In 2021, China committed to do the same.[75] However, those and other coal-fired power plants that have been built in the 2000s and 2010s may be sources of mercury emissions for decades to come, depending on countries' emissions standards and future energy policy.

Efforts to reduce mercury emissions from coal burning increasingly interact with broader societal goals to reduce reliance on fossil-fuel-based energy sources, driven by growing climate change concerns. As such, emissions from coal burning are a sustainability issue with linkages to several SDGs, including the provision of affordable and clean energy and addressing climate change (see Figure 2). The Minamata Convention's focus on mercury emissions from coal burning creates linkages with the Paris Agreement and its associated system of parties formulating Nationally Determined Contributions, outlining their goals and policies for controlling greenhouse gas emissions.[76] In the near term, end-of-pipe controls will be the most important factor controlling the future of mercury emission from coal burning. This also connects the Minamata Convention to more traditional air quality concerns; a recent estimate attributed half of an estimated million fossil-fuel-related premature deaths from degraded air quality to coal burning.[77] In the longer term, meeting the temperature goals in the Paris Agreement will require the phase-out of coal burning, with benefits for both mercury emissions reduction and efforts to improve air quality.

Despite increasing policy attention to climate change, the phase-out of coal use remains politically contested. At the 26th meeting of the Conference of Parties to the United Nations Framework Convention on Climate Change in Glasgow in 2021, parties failed to agree on a common goal of phasing out coal use, with India and China in particular resisting a compromise at the last minute.[78] China, whose coal-related energy choices are particularly important to future emissions, has pledged domestic carbon neutrality by 2060, but, even if this goal is met, much mercury (and CO_2) will be emitted from Chinese coal-fired power plants over many years to come. There are an estimated 1.1 trillion tonnes of identified coal reserves worldwide, and this translates into 150 more years of coal use at current production rates.[79] Overall, it is clear that the degree to which the remaining coal is dug up and burned versus left in the ground by 2072 will have important consequences for future emissions of mercury, CO_2, and other air pollutants.

Mercury use in ASGM

Use of mercury in gold mining dates back centuries. The modern-day intensification of ASGM activity that is still ongoing began in the 1980s.[80,81] Much of this recent expansion in ASGM has been fueled by an increase in the price of gold.[82] Historically, mercury-based processes were extensively used to separate gold from ore. Large commercial gold mining operations, often carried out by multinational firms, have moved away from mercury-based extraction techniques, instead relying on a cyanide leaching technique.[83] However, mercury use remains integral in ASGM. Over the past 50 years, much industrial gold mining took place in a few countries, including Australia, Canada, China, Russia, South Africa, and the United States, with South Africa gradually producing less while China has increased its mining activities greatly.[84] During the same time period, gold production has increased in many other countries, as large mining companies have moved into areas where there has also been a growth in ASGM.[85] This has sometimes resulted in conflicts between mining companies and ASGM miners.

Definitions of ASGM vary across international forums and national legislation; the Minamata Convention in Article 2 defines ASGM as "gold mining conducted by individual miners or small enterprises with limited capital investment and production." A 1972 United Nations report on small-scale mining noted the importance of gold mining but also stressed that many small-scale miners of different minerals, especially in developing countries, lacked legal protections and worked under conditions that threatened their health.[86] Most efforts by the World Bank and other multilateral funding agencies working with developing countries in the decades after the Stockholm Conference, however, largely focused on promoting the development of large-scale mining, frequently by multinational companies headquartered in the global north, as a way to stimulate foreign direct investments in developing countries to facilitate economic growth.[87–90] National governments also often had close ties with large mining companies, protecting their interests over those of small-scale miners.

Many people in the developing world have entered the ASGM sector because of a desire to escape poverty, a lack of other employment opportunities, or because mining for gold offers an opportunity to make more money than other forms of manual labor, including in the agricultural sector.[91–94] ASGM continues to be relatively small-scale compared with mineral extraction by mining companies, but some more recent ASGM driven by entrepreneurs involves greater mechanization and professionalization.[95,96] It is estimated that over 20 million people currently work as ASGM miners in more than 80 mostly developing countries across the world; many more people including miners' relatives and others are indirectly dependent on money earned in the ASGM sector.[97] By the mid-2010s, ASGM was believed to produce 600 to 650 Mg of gold per year.[43] This would account for about a quarter of all gold mining globally. It is mainly since the late 1990s that multilateral organizations and national governments have engaged issues related to the ASGM sector, including mercury use, in a more consistent manner.[98]

The global use of mercury in the ASGM sector is uncertain, as different estimates range between 872 and 2,598 Mg of mercury in 2015.[43] The 2018 Global Mercury Assessment estimated that about two-thirds of mercury use in ASGM was released to land and water (1,220 Mg) while one-third was emitted to the atmosphere (838 Mg with an uncertainty range of 675–1,000 Mg).[4] The amount of mercury used in ASGM is in part shaped by whether gold is extracted from alluvial deposits, saprolites (weathered bedrock), and hard-rock deposits.[99] There is a major difference in mining techniques between panning for gold in river sediments and extracting gold from saprolites and hard rock, where the latter requires much more mercury. Levels of mercury use are also related to whether the gold-containing ore is mixed with mercury before or after it is broken down into a smaller mass. If all of the ore is mixed with liquid mercury, much higher quantities of mercury are needed than if the ore is first crushed. In general, the mercury-based amalgamation process is common because it is relatively cheap and easy, but alternative processes can be more effective in extracting larger amounts of gold from ore.[81]

Once the gold-containing ore has been mixed with mercury and the gold has affixed itself to the mercury, the amalgam is heated up so the mercury burns off while the gold remains. Sometimes this takes place outside in or near mining areas, or indoors in gold processing shops or larger processing centers, which can result in much exposure.[100] The use of retorts can help catch some of the mercury that would otherwise be burned off into air. The use of retorts has at least three benefits.[34] First, it reduces the amount of mercury that enters the environment. Second, it limits the amount of mercury vapor that is inhaled by those who are nearby, especially if the burning of the amalgam takes place indoors in gold processing shops and centers. Third, the captured mercury can be re-used, which reduces the need for miners to go out and buy more mercury. The introduction and use of retorts depend on both their availability and on miners being instructed on how to use them effectively and in ways to limit exposure to mercury vapor. This is especially true in cases of indoor burning.

According to Muntean et al., mercury emissions from ASGM increased dramatically in the four decades following the Stockholm Conference, as the share of mercury emissions from ASGM more than doubled from roughly 20% to just over 40% of total global mercury emissions.[46] For the year 2000, Muntean et al. estimate mercury emissions from ASGM at 499 Mg.[46] Streets et al. estimate 584 Mg for that same year.[39] Streets et al. estimate that ASGM-related mercury emissions increased by 2.2%–3.8% per year during the first decade of the 2000s, peaked at 786 Mg in 2012, and declined slightly to 775 Mg by 2015, driven by lower gold prices and demand.[38] Since 2015, gold demand has stayed roughly constant (with a dip during the outbreak of the COVID-19 pandemic in 2020), but gold prices have increased faster than inflation, from $1,162 per ounce at the beginning of 2014 to $1,900 per ounce at the end of 2021 (which is equivalent to about $1,660 in year 2014 dollars).[101] At an annual production of 600 Mg, gold from the ASGM sector currently has a market value of over US $36 billion.

The mercury used in ASGM poses local health risks as well as adding to the amount of mercury that cycles through the environment and interacts with other societal and environmental challenges. ASGM is a sustainability issue with linkages to SDGs, including those focusing on eliminating poverty and human development, decent work and economic growth, as well as responsible consumption and production, and life on land (see Figure 2). Droughts, which have increased in the last several decades as a result of climate change,[102] can affect livelihoods for farmers in regions such as West Africa, driving people into mining as a source of income.[103] Increasing globalization and population movements have also affected ASGM activities, where workers in extractive industries often move across borders such as between countries in Africa or in South America.[104] People may also move across continents, for example from China to Africa.[93,105] In addition, ASGM can cause serious environmental degradation, and mercury can accumulate in biota in areas in and near ASGM sites.[106,107] Much ASGM is taking place in biologically rich and sensitive areas, contributing to deforestation and biodiversity loss, including in the Amazonian region. Deforestation, in turn, is linked to the carbon cycle and climate change.

The Minamata Convention mandates that parties develop strategies to encourage mercury-free mining methods toward the longer-term goal of eliminating mercury use in ASGM. However, many more short-term efforts are focused on reducing mercury use and environmental discharges while improving human health protection. These kinds of sustainability efforts can involve the introduction of new technology, including retorts, as well as efforts aimed at changing human behavior (such as avoiding indoor burning of amalgam). Technology-focused and behaviorally focused interventions address both the mining and amalgamation steps of gold extraction. Combinations of technology-focused and behaviorally focused interventions are more likely to succeed than those that only rely on one of those approaches.[108–110] It is also important for their success that such combinations of interventions are supported over time. As mining and amalgamation processes can vary both within and across different mining sites and countries, it is necessary that interventions are tailored to local conditions. Miners may also not be aware of the dangers of mercury or how best to protect themselves.

In addition to its long-term goal of eliminating mercury use in ASGM, the Minamata Convention sets out to control the transnational flow of mercury into ASGM communities, including by restricting sources of mercury for use in ASGM. The Minamata Convention relies on a prior informed consent procedure to give the governments of importing countries the right to refuse the import of mercury. Many countries with ASGM have adopted import bans on mercury intended for ASGM alongside mercury export bans by the United States, the European Union, and other countries (see Box 1). However, much mercury is traded illegally.[43] Some mercury that may be legally imported into a country for other permitted uses (including in dentistry), can sometimes be sold on informal markets for use in ASGM once it has entered a country. Of course, actions that reduce mercury use in ASGM will be critical to help stem the overall illegal trade in mercury, as most of the mercury that is currently traded illegally is believed to enter the ASGM sector.

Minamata Convention negotiations and implementation processes have prompted a better understanding of the prevalence and global importance of mercury use in ASGM. Global mercury emissions inventories did not include ASGM before the mid-2000s.[111] Updated quantified estimates of mercury emissions for the 2013 global mercury assessment identified ASGM as the largest single sector, exceeding total mercury emissions from coal burning.[10] In the early 2000s, many developing countries had only scattered and incomplete information about the status of mercury use and pollution within their borders. Minamata Convention activities allowed such countries to enhance their understanding of domestic mercury issues, including with respect to ASGM. These efforts have also been supported by the global mercury partnerships, involving the United Nations Development Programme and UNEP as well as initiatives by the multi-stakeholder planetGOLD program launched in 2019.[8,112] In addition, non-state actors have designed gold certification schemes looking to reduce mercury use.[113–115]

The fact that there are major variations in legal, political, socioeconomic, cultural, and geological situations and contexts across local ASGM communities in Africa, Asia, and Latin America make it impossible to design a single globally applicable approach to interventions that effectively target all mercury-related problems in ASGM.[116] Addressing the demand for and use of mercury in ASGM, of which much of the mercury is smuggled across national borders and different mining areas, requires a multipronged approach. In doing so it is important to take bottom-up and participatory, multi-stakeholder community-based approaches when experts and government officials engage with miners in specific mining communities.[117–119] Such efforts are often made more complex by the fact that most ASGM miners operate in the informal sector where they lack formal mining licenses.[97] Carrying out bottom-up capacity-building approaches aimed at less mercury use requires access to financial and human resources. To this end, Prescott et al. call on governments, large mining companies, and consumers of gold to provide more funds.[97]

Some national governments have introduced bans on mercury use in ASGM. This has sometimes been combined with the use of force and punishment of miners who do not possess mining licenses. This approach, however, has often led to escalating tensions and outbreak of violence while doing little to reduce the demand for mercury in ASGM, also pushing miners further into the informal sector where they are vulnerable to exploitation.[34] In contrast, other measures, supported by intergovernmental organization and non-governmental organizations, have focused on formalization and legalization of ASGM and miners as a way to help reducing mercury use and improving health protection measures.[93,120–122] The Minamata Convention also mandates parties to include steps toward the formalization and regulation of the ASGM sector in their national action plans. However, many formalization processes to date have been very slow and largely failed to reduce mercury use and to prevent miners from engaging in polluting practices.[81,85,123–125]

Even if all mercury use in ASGM is effectively phased out by 2072 through the widespread introduction of alternative methods, many environmental and human health challenges associated with past mercury use in gold mining will remain. The long-term damage to the environment and human health from legacy mercury on a local and regional scale is likely to be substantial. In addition, a more long-term question is the degree to which the extraction of non-renewable resources, including mercury-free gold mining, can be considered a sustainable practice over multiple generations. Addressing associated longer-term sustainability challenges requires policy makers to work more effectively across sectors to address underlying interactions with issues such as poverty, Indigenous sovereignty, and alternative livelihoods.[96] Many initiatives targeting ASGM are also intertwined with environmental efforts to prevent deforestation and enhance species and biodiversity protection.

CHANGES IN MERCURY POLLUTION ON DECADAL TIMESCALES

One important role of science is to inform assessments of changes over time related to specific environmental issues, which often involves the use of indicators. Related to our third point, a global indicator of total anthropogenic discharges expressed in cumulative terms can provide useful information on the status of the mercury problem for global policy making, but

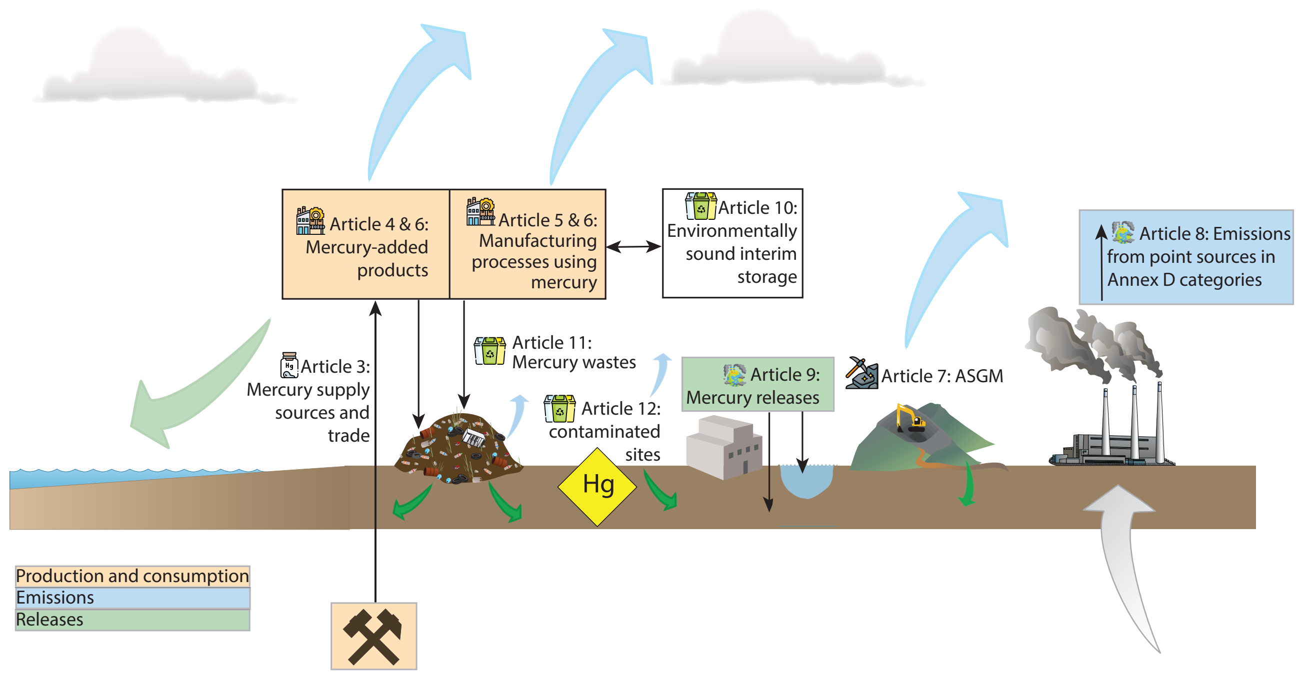


Figure 3. Minamata Convention control provisions related to the life cycle of mercury in the environment
Article 6 (time-limited exemptions from specific phase-out dates for individual categories of products and processes covered in Articles 4 and 5, which are available to parties on request) is not pictured. Black text and arrows represent Minamata Convention controls and icons for each article and follow Box 2; silver arrows represent environmental fluxes of mercury not directly controlled by the Minamata Convention. Select graphics from Integration and Application Network (ian.umces.edu/media-library).

global-scale indicators are not sufficient to effectively track relevant regional and local changes in mercury exposure and health risks in ways that are scientifically credible, policy salient, and politically legitimate to national and local decision makers. Figure 3 illustrates the different control provisions summarized in Box 2 graphically, with a focus on how they correspond to the biogeochemical cycling of mercury through air, land, and water. Figure 3 also highlights the stocks and flows associated with mercury production, consumption, emissions, and releases captured in Figure 1 and discussed above. Figure 3 illustrates graphically how the metrics of production and consumption, emissions, and releases shown in Figure 1 only provide a partial picture of the status of the global mercury problem.

An overall global indicator expressed in cumulative terms, for example an indicator of cumulative anthropogenic discharges, provides a more accurate picture of the evolving global status of the mercury problem than indicators focusing on annual trends.[126] The history of mercury pollution since 1972 illustrates that global trends in annual production, consumption, emissions, and releases (shown in Figure 1), which are commonly used as progress indicators, do not track changes in mercury pollution as a both present and long-term sustainable development challenge. Annual trends in mercury production, consumption, emissions, and releases provide inconsistent directional information, but changes in global cumulative discharges provide a better global picture of the mercury challenge; until primary human discharges of mercury reach zero, human activities will continue to add to the global biogeochemical cycling of mercury. That is, if from one year to another, mercury discharges have decreased by half, the mercury problem is not half as bad; in fact, the problem is still getting worse, just at a slower rate, because mercury cycles in the environment for a long time. In contrast, for short-lived pollutants such as atmospheric particulate matter, measuring progress using annual metrics is more helpful: a metric that showed a decrease in annual emissions of shorter-lived compounds would correspond more directly with environmental and air quality improvements than for mercury and other persistent pollutants.

The use of an overall global mercury-focused indicator that is expressed in cumulative rather than annual terms, focused on anthropogenic discharges, would be similar to the type of metrics that are useful for monitoring other long-term sustainability-relevant issues. For example, for climate change, global average temperature increases, which the Paris Agreement aims to limit to well below 2°C, is proportional to total cumulative greenhouse gas emissions.[127] Cumulative future greenhouse gas emissions between now and 2072 will influence additional temperature increases over the next 50 years, and the degree of further climate-related harms to people and societies in different parts of the world.[128] Temperatures will only stop rising when greenhouse gas emissions stop, as a focus on net-zero emissions has been recognized as an important policy goal.[129] Similarly, if all primary anthropogenic discharges of mercury have ceased by 2072, at that point all mercury emitted and released by human activities and cycling in the environment will be historical.

While cumulative indicators can reflect sustainability better than annual ones for some long-term pollution issues, no global-scale indicator can provide sufficient information to monitor local sustainability-relevant outcomes in a comprehensive way. Indicators that address outcomes involve gathering

Box 2. Main Minamata Convention control provisions

Supply and Trade (Article 3):

- New mercury mining is prohibited but existing extraction may continue for up to 15 more years after the treaty becomes legally binding for a party.
- Mined mercury may only be used in permitted products and manufacturing processes, and should be disposed of in ways that do not lead to continued re-use.
- Excess mercury from the decommissioning of chlor-alkali facilities cannot be re-used and parties should identify other major secondary sources and stockpiles of mercury.
- Mercury trades between parties can only take place after the importing party provides written prior informed consent.
- Parties can only export to non-parties that have measures in place to protect human health and the environment and follow treaty provisions on allowed uses, storage, and disposal.
- Parties shall only allow imports from non-parties providing guarantees that mercury comes from a source allowed under the treaty.

Products and Processes (Articles 4–6):

- Parties shall cease manufacturing, import, and export of nine mercury-added product categories by 2020, but can ask for 5 plus 5 years of exemptions.
- Mercury in dental amalgam is subject to restrictions, with a list of measures for reduced use that parties can elect to take.
- Parties shall phase out mercury use in chlor-alkali production and acetaldehyde production by 2018 and 2025 respectively, but can ask for 5 plus 5 years of exemptions.
- Parties shall reduce mercury use in vinyl chloride monomer (VCM) production, sodium or potassium methylate or ethylate production, and polyurethane production.
- Parties shall discourage the manufacture and commercial distribution of new mercury-added products and the development of new facilities that use mercury in manufacturing processes.

Artisanal and Small-Scale Gold Mining (Article 7):

- Parties shall take steps to reduce and, where feasible, eliminate mercury use in, and mercury emissions and releases to the environment from, ASGM.
- Parties with more than insignificant ASGM and processing shall develop a national action plan that outlines national objectives, reduction targets, and actions to eliminate whole-ore amalgamation and open burning or amalgam as well as burning of amalgam in residential areas.

Emissions and Releases (Articles 8–9):

- Parties shall require the use of BATs and BEPs to five categories of new point sources (in Annex D of the Minamata Convention) to control and, where feasible, reduce emissions no later than 5 years after the treaty enters into force.
- Parties shall control and, where feasible, reduce emissions from five categories (in Annex D) of existing point sources through emissions limit values, BAT, BEP, or other alternative measures including co-benefits strategies no later than 10 years after the treaty enters into force.
- Parties shall control and, where feasible, reduce mercury releases to land and water from point sources through BAT and BEP or alternative measures, including multi-pollutant strategies.

Storage, Waste Management, and Contaminated Sites (Articles 10–12):

- Parties must manage and dispose of discarded mercury and mercury-containing waste in an environmentally sound manner.
- Parties are required to endeavor to develop strategies for identifying and assessing mercury-contaminated sites.

environmental and human health data. In the case of the implementation of the Minamata Convention, relevant impacts involve changes in local levels of mercury concentrations in air, land, or water as well as methylmercury exposure of specific populations.[130] Providing credible and salient information on outcomes to inform policy making is a scientific challenge: the use of many outcome indicators relies on scientific methods and data that at present are not available for carrying out a detailed tracing of long-range transport of emissions from particular sources to faraway deposition and mercury concentrations in specific environmental compartments, or individual human exposure to methylmercury in all regions of the world. Improved analysis of mercury stable isotopes has the potential to help identifying specific sources of mercury in the future, but it is still uncertain whether such data can provide comparable results that can inform global policy making.[131] While both scientific methods and data can advance over time, analysis is also made difficult by the fact that mercury currently cycling in the environment is a combination of recently and historically discharged mercury from both human activities and natural processes.

The lack of a direct correspondence between global-scale trends in discharges and localized impacts also has important implications for the conceptualization and implementation of future assessments and management of hazardous substances. Researchers have suggested that a quantified planetary boundary for mercury and other chemicals (as novel entities) could provide a scientific underpinning that informs policy processes, but such a boundary has not yet been successfully quantified.[2] Determining such a boundary must also be informed by both science and policy to ensure its credibility, salience, and legitimacy.[132] Similar to the limitations of a global indicator of cumulative anthropogenic discharges, Selin and Selin caution that a planetary-scale boundary approach to assessment and policy making is not a good fit for adequately addressing mercury and many other toxic substances in the context of sustainability.[34] A global-scale boundary thus does not provide a suitable tool to address the decadal-scale challenge of an issue where local human societies will continue to be affected by mercury, in differential ways, and with varying impacts depending on multifaceted stressors and vulnerabilities.

Much credible information and data that are salient to Minamata Convention parties in the near term will be those that inform treaty effectiveness evaluations mandated under the treaty's Article 22, with the first one starting in 2023.[133] While cumulative indicators can inform this process, data uncertainties around global anthropogenic mercury emissions and releases past and present, as discussed earlier, limit the scientific ability to determine detailed estimates of discharges. Further, given that any global indicator can provide only partial information, and outcome indicators at multiple scales remain unavailable given current scientific knowledge and limitations, the first Minamata Convention effectiveness evaluation will rely heavily on process indicators, as parties consider them the most credible and salient. The use of process indicators focuses on collecting information on actions that parties have taken to prevent mercury from entering the environment. For the Minamata Convention that could, for example, involve quantifying how many parties have taken steps to control mercury emissions from stationary sources (e.g., treaty Article 8, illustrated in Figure 3) and identifying their standards. Other process indicators could focus on the other black arrows in Figure 3, which represent controls under the Minamata Convention.

Stocktaking and assessments of domestic measures to implement the Minamata Convention can help parties to identify areas for expanding cooperation and strengthen the scope and stringency of different controls and mandates. For this information to be viewed as legitimate by the parties, it is important that it comes from countries and regions all over the world. As scientists carry out analyses linking mercury discharges with their long-range environmental and human health impacts with greater certainty, it will be necessary to develop new outcome indicators at multiple scales, and to establish their credibility, salience, and legitimacy to Minamata Convention parties. Related, Wang et al. argued for the creation of a global science-policy body for chemicals and waste, and the United Nations Environment Assembly in March 2022 launched a process to establish such a body.[1] In the future, a global science-policy body could play a role in assessing environmental levels and cycling of mercury as well as mercury exposure in local communities in support of Minamata Convention implementation and effectiveness evaluations.

FUTURE INTERVENTIONS TO ADDRESS ONGOING MERCURY IMPACTS

Because of continuing mercury discharges and the fact that mercury cycles in the environment for decades to centuries, mercury will remain an important environmental and human health concern for generations to come.[34] The use of indicators that help monitor and evaluate the mercury issue and the implementation of the Minamata Convention, as discussed above, is also important for guiding effective interventions to address mercury pollution in the context of sustainability. Related to our fourth point, looking forward, many long-term interventions that are needed to address different aspects of the mercury issue are part of broader societal efforts to transition to greater sustainability. However, progress on meeting the SDGs is mixed at best.[134] Building on the discussion in the previous section and the specific issues of coal burning and ASGM, Figure 4 synthesizes the connection between sustainability transitions and mercury-specific interventions related to the SDGs. It highlights two areas of sustainability transitions: measures that promote sustainable livelihoods and food security, and those focused on clean energy and climate. These larger transitions involve multiple SDGs, as some mercury-specific interventions contribute to meeting these SDGs.

Interventions that center on sustainable livelihoods and food security can have important benefits for meeting mercury-related challenges. Efforts to address poverty can reduce the number of miners being driven into ASGM because they lack other options to support themselves and their families (SDG 1). Preventing hunger is linked closely to addressing fish and aquatic foods that contain methylmercury, as marine fisheries provide 60 million jobs worldwide and fish provide 4.3 billion people with at least 15% of their critical nutrients (SDG 2).[135] Broader efforts to ensure good health and well-being can mitigate vulnerabilities that enhance risks from mercury and other hazardous substances (SDG 3). Providing other options for

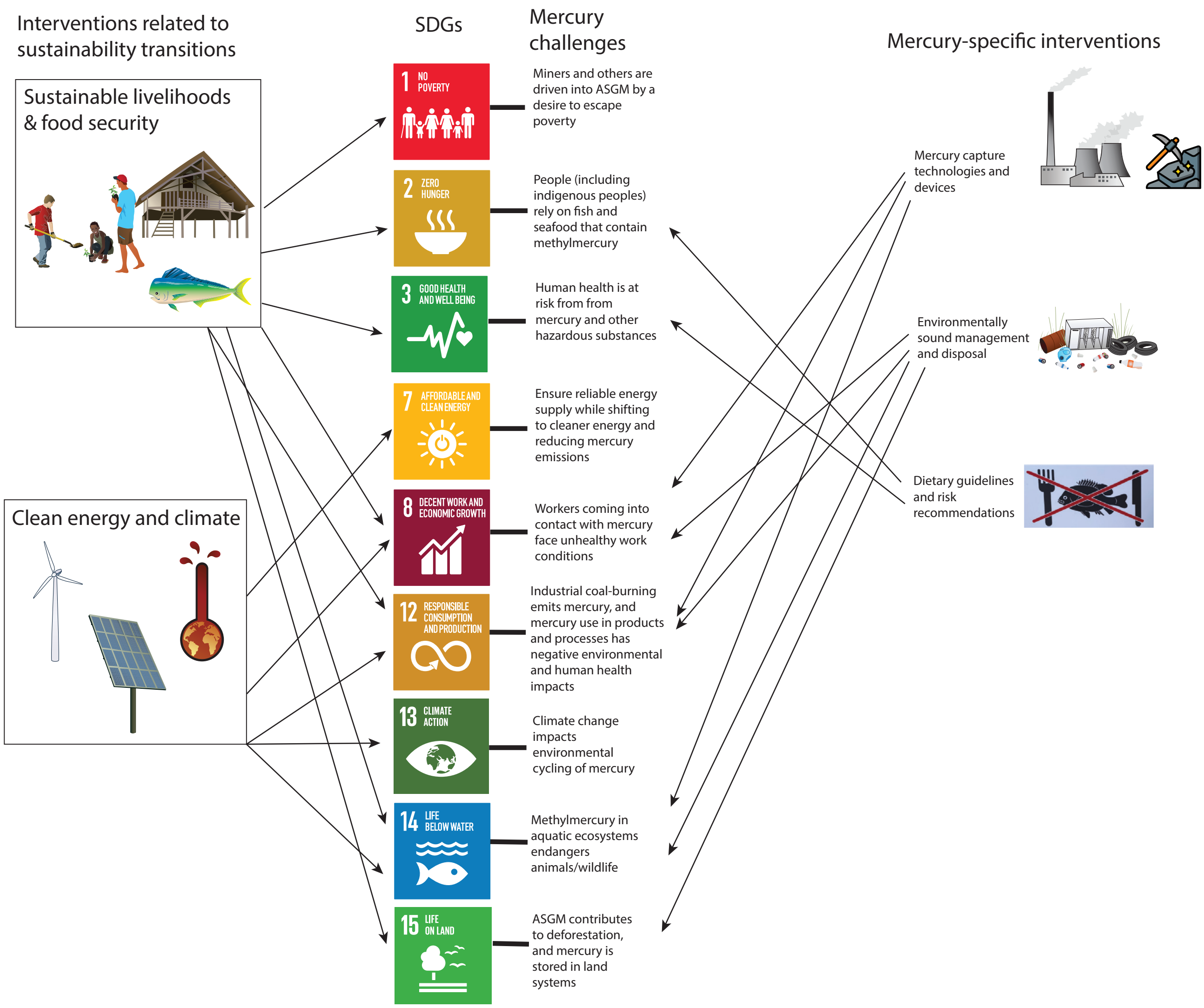


Figure 4. Interventions related to sustainability transitions, mercury-specific interventions, and their targets and connections

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decent work and economic growth can prevent ASGM miners and other workers from facing unsafe workplace conditions due to coming into contact with mercury (SDG 8). A focus on responsible consumption and production in part relates to the expansion of mercury-free gold production (SDG 12). Enhancing life below water helps preserve ecosystem services while at the same time protecting both animals and humans from dangerous exposure to methylmercury (SDG 14). Efforts to preserve life on land can help maintain forest ecosystems degraded by ASGM (SDG 15).

Larger-scale climate and energy transitions can address mercury challenges related to impacts of coal burning. A just transition away from coal burning is a multifaceted issue.[63,136] It is critical to expand year-round access to reliable electricity and energy to people who are currently lacking such access. Keeping electricity and energy affordable for low-income earners is also a central policy goal (SDG 7). Helping workers in the fossil-fuel industry to change careers and find alternative employment is another important dimension of a just transition away from carbon-based energy sources (SDG 8). A focus on responsible consumption and production highlights the impacts of industrial coal burning as well as the health and environmental consequences of mercury use in products and processes (SDG 12). Fulfilling the Paris Agreement's goal of keeping average global temperature increases well below 2°C requires the elimination of coal burning within the next 50 years (SDG 13).[128,137] The degree to which this is achieved will have substantial consequences for future mercury emissions.

With respect to mercury-specific interventions, the Minamata Convention sets out to prevent mercury reaching the environment through mercury capture technologies and devices related to both coal burning and ASGM. Research has shown that applying end-of-pipe emissions controls to coal-fired power plants provides more near-term mercury reduction than current trajectories of fossil-fuel phase-outs.[76] Technology-based controls are also more politically feasible in the near term.[34]

Mercury capture technologies and devices in ASGM prevent mercury from being released into aquatic ecosystems. A second set of mercury-specific interventions focus on enhancing environmentally sound management and disposal, including clean-up of previously contaminated sites. As mercury use in products and processes is reduced (including in ASGM), this benefits workers who experience reduced occupational exposure. At the same time, this creates a growing need to safely store and dispose of excess mercury. A third set of mercury-specific interventions look to develop dietary guidelines, which can be important in the near term to manage human health risks from fish and seafood consumption. The long-term impact of mercury creates a need for continuing mercury monitoring in aquatic environments as well as the diffusion of information about methylmercury concentrations in specific fish—both self-caught and commercially sold—to consumers.

Mercury-specific interventions provide immediate benefits to the environment and human health. However, a sole focus on mercury-specific interventions can also leave underlying sustainability issues unaddressed; for example, where efforts to reduce mercury from coal-fired power plants ignore the damages of CO_2 emissions or where actions to address mercury use in ASGM ignore linked issues of poverty and conflict. This highlights the simultaneous advantages and limitations of a substance-by-substance approach to policy making, which may facilitate more rapid action on individual substances in the near term but risks undermining longer-term sustainability goals by not paying enough attention to how a multitude of environmental and human health issues are linked. At the same time, environmental treaty making in the post-Stockholm Conference era shows the necessity of accommodating political realities. Future action on individual hazardous substances, such as a new treaty on plastics, will need to carefully balance these challenges.[138,139] Political change and global events will continue to affect efforts to promote sustainability over the next 50 years and beyond. There is, however, potential for policy innovation and designing new ways of approaching cross-institutional connections to reap the benefits of targeted action with due attention to sustainability.

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AUTHOR CONTRIBUTIONS

H.S. and N.E.S. jointly conceived the study and contributed equally to the writing of the article.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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