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Linking Science and Policy to Support the Implementation of the Minamata Convention

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Linking Science and Policy to Support the Implementation of the Minamata Convention on Mercury

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Abstract
The Minamata Convention on Mercury entered into force in 2017. Its objective is to "protect human health and the environment from anthropogenic emissions and releases of mercury and mercury compounds" (Article 1). As the Minamata Convention, which outlines a life-cycle approach to the production, use, emissions, releases and handling of mercury, moves into the implementation phase, scientific work and information are critically needed to support decision-making and management. This article identifies and examines areas in which the scientific community can mobilize knowledge in support of mercury abatement and the realization of the Minamata Convention's objective. It offers guidance for researchers who wish to connect with international, national, and local efforts in three focal areas: i) uses, emissions, and releases; ii) support, awareness raising, and education; and iii) impacts and effectiveness evaluation. The article ends with a discussion of the future of mercury science and policy.

Key Words
Environmental Treaty Implementation; Mercury; Minamata Convention; Science – Policy; Toxic Pollution

Introduction
The Minamata Convention on Mercury, which aims to "protect human health and the environment from anthropogenic emissions and releases of mercury and mercury compounds" (Article 1), was adopted in 2013. The world's countries, with the participation of many intergovernmental and nongovernmental organizations, negotiated the Convention to outline a set of shared principles, standards and rules (Andresen et al. 2013, Eriksen and Perrez 2014, Selin 2014a, You 2015). Countries voluntarily decide whether to become a party to an international legally binding agreement like the Convention, but once they commit to do so, its provisions bind all parties.[1] The Convention entered into force on August 16th, 2017, 90 days after it received its fiftieth

[1] The same is true for the European Union, which can join separately of its member states as a Regional Economic Integration Organization (Selin and VanDeveer 2015).

ratification. As of September 2017, the Convention had 74 parties and 128 signatories from all over the world (see Figure 1).[2]

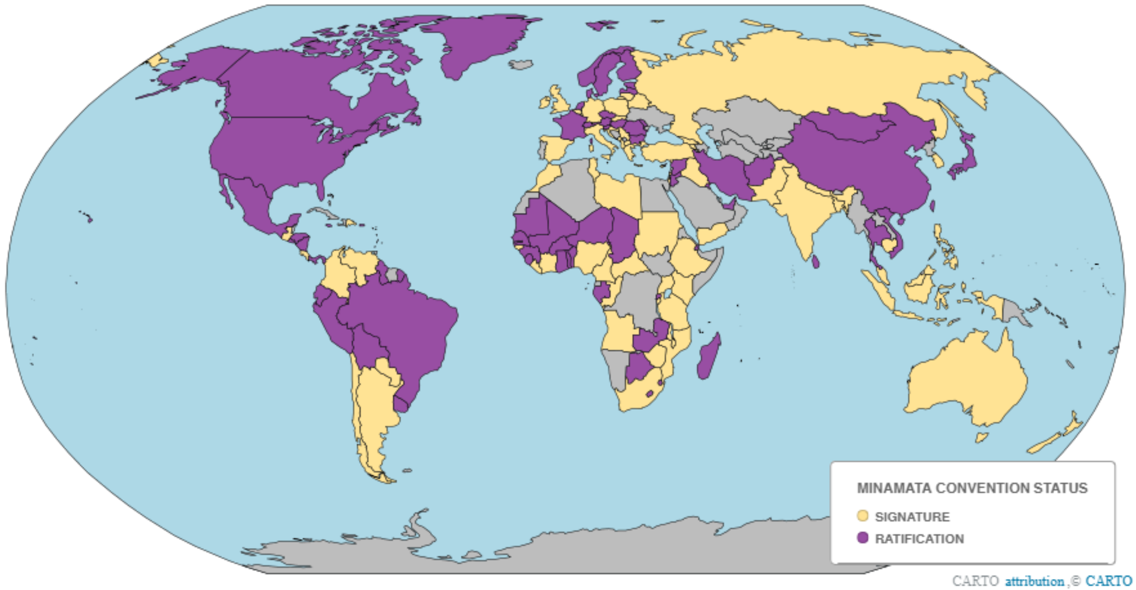

Figure 1: Map of Convention Parties and Signatories.

The Convention builds upon an extensive body of scientific knowledge on mercury and decades of policy efforts to manage its hazards. Science played a key role in establishing recognition for mercury as a global pollutant (United Nations Environment Programme 2002, 2008). Scientific knowledge helps to understand mercury's global distribution (Obrist et al. 2017), its changing cycling in response to local perturbations (Hsu-Kim et al. 2017), and its health and environmental impacts (Eagles-Smith et al. 2017). Voluntary efforts under the United Nations Environment Programme Global Mercury Partnership to reduce mercury use and emissions and to draw attention to environmental and human health risks from mercury date back to the early 2000s (Selin and Selin 2006, Sun 2017).[3] The Convention continues to draw on these efforts, as it requires a life-cycle approach to the production, use, emissions, releases, and management of mercury.

As the Convention moves into its implementation phase, different types of scientific work and information can support decision-making and management. The relationship between science and environmental treaty implementation is complex, as there is not a direct, causal link between more scientific data and "better" policy-making and outcomes (Shackley and Wynne 1995). Rather, the interplay between science and policy is multifaceted and often case-specific. Yet, studies show that treaty implementation can benefit from information and assessments that are scientifically credible, policy relevant, and politically salient (Farrell et al. 2001, Selin and Eckley

[2] For an updated list of parties, see the Minamata Convention website: http://www.mercuryconvention.org/

[3] For more on the Global Mercury Partnership and its different work areas, see: http://www.unep.org/chemicalsandwaste/global-mercury-partnership

2003, Mitchell et al. 2006). In addition, the field of sustainability science stress that researchers in their projects should actively engage stakeholder groups in support of societal transitions toward sustainability (Clark and Dickson 2003, Kates 2011).

This article identifies and discusses some major ways in which the scientific community, across a large number of disciplines and fields, can mobilize knowledge in support of the implementation of the Convention. It specifically examines three focal areas where research across the natural sciences, engineering, and social sciences can support mercury policy-making and management: i) uses, emissions, and releases; ii) support, awareness raising, and education; and iii) impacts and effectiveness. In each of these areas, the article synthesizes the status of scientific knowledge, identifies research needs, and offers guidance for researchers who wish to connect with international, national, and local efforts related to meeting the Convention objective to protect environmental and human health.

The next section provides a brief summary of the structure and content of the Convention. This is followed by an examination of how scientific work can support convention-related activities in the three focal areas. The article ends with a discussion of the future of mercury science and governance.

Minamata Convention Approaches to Mercury Management

Mercury is a chemical element that is intentionally mined, used in products and industrial processes, and emitted and released into the environment as a byproduct of human activities. Negotiators of the Convention were charged with designing an agreement with a comprehensive life-cycle approach covering all these areas. They also needed to accommodate different national interests and find ways to assist developing countries with domestic implementation. All parts of the Convention are legally binding for parties, but some provisions express required actions (using the word “shall”) while some are hortatory (using words such as “should” or “may”). The core of the Convention is its control provisions and enabling provisions, which are described below. Other Convention articles cover introductory material, definitions, and administrative matters.[4] Table 1 lists key Convention dates and deadlines.

Table 1: Main Convention Dates, Requirements, and Deadlines

UN Environment Governing Council agrees to begin negotiations on a legally binding agreement on mercury	2009
Minamata Convention adopted and opened for signature	2013
Entry into force of the Minamata Convention	2017
First Conference of Parties	2017
Prohibition of new mercury mining	Upon entry into force for a Party
Phase-out of mercury use in acetaldehyde production	2018 (extension up to 10 years possible in some cases)
Deadline to reduce mercury use in VCM production by 50% (2010 baseline)	2020
Phase-out of mercury use in mercury-added products	2020 (extension up to 10 years

[4] For more on the workings of public international law and legally binding treaty obligations, see Bodansky (2011).

listed in Annex A[4]	possible in some cases)
Deadline for submitting ASGM National Action Plans to the Secretariat	3 years after entry into force for Party (e.g. earliest 2020), or 3 years after notifying the Secretariat that ASGM activity is more than insignificant, whichever is later
Deadline for Parties to require use of BAT and BEP for new sources from emissions categories listed in Annex D	5 years after entry into force for a Party (e.g. earliest 2022)
Start date for the COP to begin first effectiveness evaluations	No later than 2023
Phase-out of mercury use in chlor-alkali production	2025 (extension up to 10 years possible in some cases)
Deadline for Parties to require use of ELV, BAT, BEP or alternative measures for existing sources from emissions categories listed in Annex D	10 years after entry into force for a Party (e.g. earliest 2027)
Phase-out of existing primary mercury mining	15 year after entry into force for a party (e.g. earliest 2032)

Control Provisions

The control provisions (Articles 3-12) identify actions that the parties must take to address mercury supply, trade, use, handling, emissions and releases to the environment. They apply to cases where mercury is intentionally extracted and used in a commercial product or industrial process, as well as where mercury is present in a raw material and emitted and released during processing or combustion. Provisions that restrict primary mercury mining and the use of excess mercury from decommissioned chlor-alkali facilities aim to reduce the supply of mercury. International trade in mercury for allowed uses is controlled through a system of prior informed consent (e.g. the national government of an importing country must approve the import of mercury before it can be exported from a supplier in another country).

Intentional mercury use is controlled through requirements to phase out its use in a large number of mercury-added industrial processes and products. The Convention establishes phase-out dates for specified processes and for the manufacture, import and export of listed products, but parties may apply for exemptions that allow national extensions of these deadlines for up to 10 years. Mercury use in artisanal and small-scale gold mining (ASGM) is addressed separately due to its widespread occurrence, frequently informal nature, importance for direct human exposure to inorganic mercury, and close connections with efforts to reduce rural poverty and promote human development. Parties with more than insignificant ASGM must develop National Action Plans as part of their efforts to address mercury use in this sector.

Control of pollution from the use and processing of materials that contain mercury impurities are considered separately for emissions to air and releases to land and water. Parties must apply technology-based pollution control technologies to new sources. A combination of other approaches can be used for existing sources, including a multi-pollutant control strategy that would deliver co-benefits in the control of mercury emissions while aiming to control other pollutants. Controls on releases to water and land are incorporated (implicitly or explicitly) into obligations for products, industrial processes, and sources of atmospheric emissions, but parties must also control releases from other relevant point sources. Parties must manage discarded mercury and mercury containing waste in an environmentally sound manner.

Enabling Provisions

The enabling provisions (Articles 13-24) are intended to help the parties implement and further develop the Convention, and to track progress and measure effectiveness of related management and policy measures. The Convention establishes an administrative Secretariat and the Conference of the Parties (COP), the main decision-making body on issues related to treaty implementation and development. The Convention also establishes a facilitative committee to promote implementation, review compliance, and explore ways to assist parties that have difficulty fulfilling their obligations. Critically, the Convention defines a new mechanism for the provision of adequate, predictable and timely financial resources to developing countries that include the Global Environment Facility Trust Fund and other sources.

Enabling provisions call on parties to promote strategies and programs for protecting public health and the environment from mercury pollution, share information with each other, and inform the public about mercury pollution and its impacts. The Convention encourages parties to cooperate to develop inventories of mercury use and release and technologies to reduce them, conduct modeling and monitoring of mercury in the environment, and identify impacts of mercury on human health and the environment. To help track progress, parties are required to report to the Secretariat on measures that they have taken toward implementation and their effectiveness and possible challenges in meeting Convention objectives. Enabling provisions also call on all the parties to cooperate to provide technical and capacity building assistance to developing countries.

The broader scientific community can contribute to treaty implementation for nearly all of these provisions. For simplicity, this article groups the Convention's provisions into three general areas: uses, emissions, and releases; support, awareness raising, and education; and impacts and effectiveness. Table 2 illustrates the relationship of these areas with the main relevant Convention articles. While the first area comprises control provisions, the latter two areas relate to the enabling provisions. The next three sections explore scientific needs for the three areas, first synthesizing the existing status of key scientific understandings and then identifying major knowledge gaps and future research needs.

Table 2: Three Key Convention Areas and Related Articles

Area	**Articles**
Uses, emissions, and releases	Article 3 – Supply and trade Article 4 – Products Article 5 – Processes Article 6 – Exemption to phase-out dates Article 7 – ASGM Article 8 – Emissions Article 9 – Releases Article 10 – Storage Article 11 – Waste

	Article 12 – Contaminated Sites
Support, awareness raising, and education	Article 13 – Financial mechanism Article 14 – Capacity building, technical assistance and technology transfer Article 16 – Health aspects Article 17 – Information exchange Article 18 – Information, awareness, education
Impacts and effectiveness	Article 15 – Implementation and compliance Article 19 – Research, development, monitoring Article 20 – Implementation plans Article 21 – Reporting Article 22 – Effectiveness evaluation

Uses, Emissions, and Releases

Several control provisions in the Convention address intentional uses of mercury and releases of byproduct mercury. Article 3 covers the phase-out of commercial mercury supply, including from existing and new primary mining, and trade restrictions for the export and import of mercury. Article 4 prohibits the manufacture, import or export of many mercury-added products, including certain types of batteries, switches, relays, lamps, pesticides, and cosmetics. The use of dental fillings containing mercury amalgam should be phased down, although no deadline is set. Article 5 obliges the parties to phase out mercury use in two manufacturing processes – chlor-alkali production and acetaldehyde production – and to restrict mercury use in three others – vinyl chloride monomer production (VCM), sodium or potassium methylate or ethylate production, and the production of polyurethane.[5] Article 6 allows parties to apply for time-limited extensions to set phase out dates. Article 7 obligates parties to take steps to reduce and where feasible eliminate mercury use in ASGM.

Articles 8 and 9 address mercury emissions and releases where parties are required to establish and maintain inventories, and apply control measures. For air emissions, sources include coal-fired power plants, coal-fired industrial boilers, non-ferrous metals processing, waste incineration, and cement clinker production. For releases to land and water, parties should identity any additional relevant point sources not addressed in other provisions no later than three years after the date of entry into force for it. Each party shall take measures to control and, where feasible, reduce mercury emissions and releases. The use of best available techniques (BATs) and best environmental practices (BEPs) is required for new sources. A party may apply the same measures to existing sources, or it may adopt different measures including emission limit values (ELVs). Articles 10 and 11 cover mercury storage requirements and environmentally sound waste management practices. Article 12 requires parties to endeavor to develop strategies for identifying and assessing mercury-contaminated sites, and also requires the COP to develop guidance for site management.

Existing Knowledge

Several studies quantify mercury emissions to air (Kim et al. 2010, Pacyna et al. 2010, Pirrone et al. 2010, United Nations Environment Programme 2013b, Zhang et al. 2015) A few studies quantify mercury releases to land and water (United Nations Environment

[5] Mercury use in acetaldehyde production is not known to be taking place currently.

Programme 2013b, Liu et al. 2016, Kocman et al. 2017). One study estimates that cumulative, all-time total mercury releases to land and water are 2.3 times emissions to air (Streets et al. 2017). Some case studies address integrated mercury flows in several countries (Chakraborty et al. 2013, Hui et al. 2016). Emission inventories are thought to be relatively accurate for some sources such as energy and industrial sectors, but with large uncertainties for other sources such as ASGM (Pacyna et al. 2016). Countries can use the United Nations Environment Programme Mercury Inventory Toolkit to help establish a national inventory of uses, emissions and releases.

Related to Article 3 on supply, primary mercury mining as the single largest source is estimated to account for 27 percent of all-time cumulative discharges to the environment (Streets et al. 2017). Despite long-standing collaborative international and national efforts to phase out existing mercury mining and prohibit the opening of new mines, there is evidence of a recent resurgence of informal domestic cinnabar mining in some countries such as Indonesia and Mexico even after the Convention was adopted (Camacho et al. 2016, Spiegel et al. 2018). Most of this increased supply of new mercury is used in the ASGM sector, either domestically or as exported to other countries. The intentional use of mercury in ASGM, commercial products and industrial processes, as well as its presence as a by-product of combustion and other processes, have dispersed mercury widely into the global environment (Horowitz et al. 2014).

Figure 2 synthesizes available information on global-scale sources and sinks of mercury, organized by Convention article. The left side of the figure identifies the main sectors of commercial activity that either use mercury directly or emit or release mercury as a by-product. Their relative importance is indicated by the size of the colored bar. The blue bars (largely in the middle of the figure) show which Convention articles cover each of these sources. The right side of the figure shows how much mercury from each sector goes to recycling, air, and land and water, respectively.

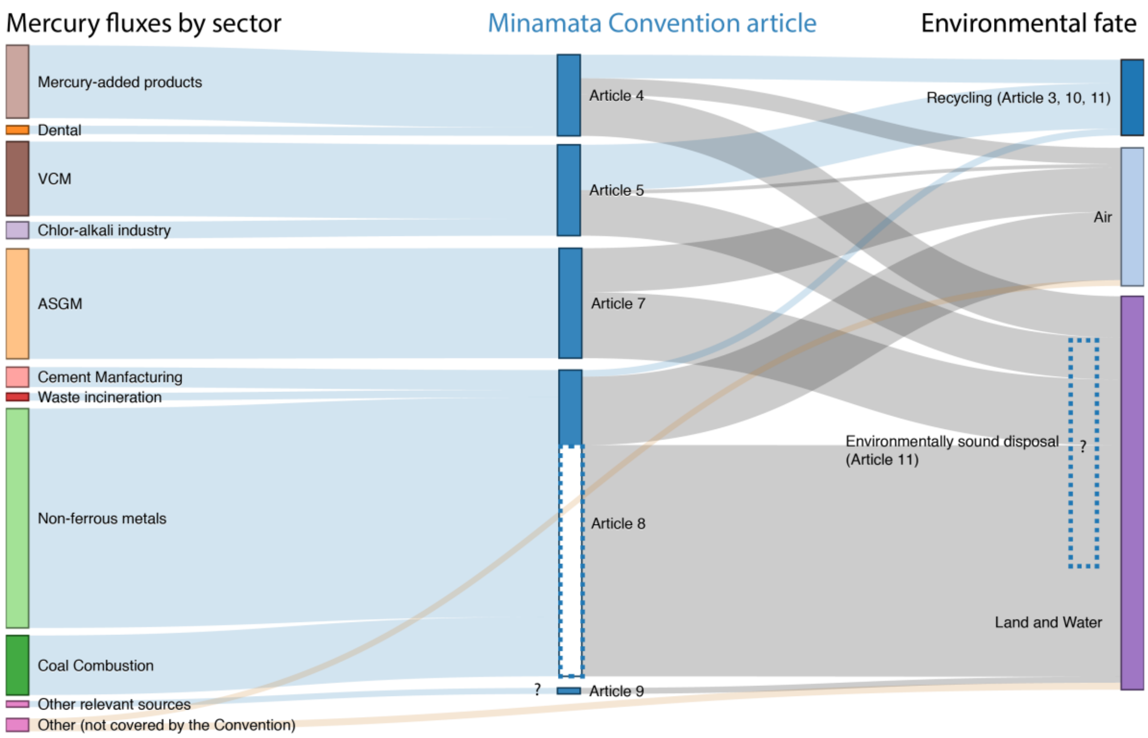

Figure 2. Global Mercury Sources and Sinks for Uses, Emissions, and Releases. Data from (Horowitz et al. 2014, Streets et al. 2017, United Nations Environment Programme 2017c). On the left side, annual fluxes of mercury are attributed to various sectors. The size of the flux is proportional to its magnitude. Fluxes in blue are addressed by articles under the Convention (indicated by blue bars). Unknown quantities (other relevant sources under article 9, environmentally sound disposal) are indicated by question marks. The dotted line in Article 8 represents releases to land and water from sources mentioned in Article 8, discussed in text.

Annual quantities of mercury use in products covered by Article 4 are estimated at 1200 Mg with an uncertainty range of 860-1540 Mg (United Nations Environment Programme 2017c). It is estimated that 20 percent is emitted to air, 51 percent released to land and water, and 29 percent recycled (Horowitz et al. 2014 and personal communication). For processes covered by Article 5, inputs are estimated from the VCM industry (1230 Mg, uncertainty range 1210-1240 Mg) and the chlor-alkali industry (280 Mg, uncertainty range 230-320 Mg) (United Nations Environment Programme 2017c). Emissions, releases, and recycling fractions from such uses are estimated as 4 percent, 46 percent, and 50 percent respectively (Horowitz et al. 2014 and personal communication). Yearly input from Article 7 ASGM is estimated at 730 Mg with an the uncertainty range of 410-1040 Mg (United Nations Environment Programme 2013b). 40 percent is emitted to air and the rest going to land and water. Estimated air emissions from sources not covered by the Convention (97 Mg) include coal from residential use and transportation, iron and steel, and oil combustion sources.

Article 8 covers air emissions from five sources. Streets et al. (2017) estimate that 23 percent of mercury from these sources is emitted to the atmosphere, but the amount of releases to land and water is uncertain. The same inventory estimates a large fraction of releases from non-ferrous metals production, representing the difference between the mercury content in the processed ore and the calculated emissions to air, but the environmental fate of this mercury is not well known. The un-shaded portion of the blue bar for Article 8 in Figure 2 denotes the uncertainty regarding how such releases may be addressed under the Convention, given that Article 8 only requires that BAT/BEP take into account the need to minimize cross-media effects. 3 percent of mercury from non-ferrous metal consumption is estimated to be recycled. For Article 9 releases, a question mark illustrates the unknown number and size of additional sources covered by this article, which applies to point sources not addressed in other provisions (i.e., sectors which result in releases to land and water other than those listed in Figure 2). Each party must identify such domestic sources and report on control measures.

With respect to Articles 10 and 11 on storage and waste data on the quantities of mercury are unavailable. In Figure 2, these articles are listed as relevant to recycling, along with Article 3 (supply and trade), as any mercury not reused will become waste. For Article 12 contaminated sites, global inventories of sources and sinks, including those used for figure 2, have historically omitted emissions and releases from mercury-contaminated sites. Such contamination is the result of different activities, including mercury mining and smelting, ASGM, large scale precious metal processing, non-ferrous metal production, and major industrial uses in the chlor-alkali industry and other sectors. One study estimates that over 3000 mercury-contaminated sites in different parts of the world release about 137-260 metric tons of mercury annually to the atmosphere and the hydrosphere (Kocman et al. 2013). Even if contaminated sites based on existing data only make up a small percentage of total atmospheric emissions, nonetheless they can be important sources, especially for local water pollution where many sites are located in coastal areas impacting rivers, estuaries, and oceans (Randall and Chattopadhyay 2013). Given that contaminated sites are created through releases to land, we have omitted them in Figure 2 to avoid double-counting.

Research and development have resulted in the introduction of non-mercury products and processes on national and international markets. Mercury-free alternatives are available for almost all commercial products that are covered by the Convention, which can be substituted for older ones that still contain mercury. The same is true for the main industrial processes that traditionally used mercury. Here, current focus is on accelerating ongoing substitution processes across different markets. On ASGM, one strand of research focuses on refining and disseminating better and cheaper technologies for using mercury to separate the gold from the ore that better protect the health of users and help to reduce emissions and releases into the environment ((Sippl and Selin 2012). A related area of research focuses on socio-economic factors and strategies for changing the attitudes and behavior of people who live and work in ASGM mining communities (Spiegel 2009, Saldarriaga-Isaza et al. 2015).

As countries phase out mercury uses, there will be a need to deal with excess mercury supply as well as discarded goods that contain mercury. Regional assessments for Asia, Europe, Central America, and Latin America and the Caribbean project that between 2010 and 2050, total excess mercury supply may exceed 28,000-46,000 tons (Maxson 2009, United Nations Environment Programme 2014, European Union 2015), creating major institutional and technical challenges for environmentally safe storage and disposal. The COP will also need to set threshold values for mercury content for the classification of mercury waste and provide guidance for the handling of such wastes. Here, the COP will build on mercury-related Technical Guidelines developed under the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal for environmentally sound management.

In addition, research and development have led to the availability of different kinds of mercury emission control technologies for major stationary sources, and several studies have reported on the degrees of effectiveness of these options (Krishnakumar et al. 2012, Sloss 2012, Trovant 2013, Ancora et al. 2016, Hu and Cheng 2016). Importantly, under the Convention parties may formulate their own national BAT and BEP standards (as well as ELV-equivalents) for mercury emissions from different stationary sources based on a combination of domestic technical and socio-economic factors (Lin et al. 2017). These emission standards may vary across different regions and countries, but there is a general expectation that they should be strengthened over time. Countries may also apply different metrics when formulating their emission standards. For example, the United States currently uses performance metrics (lb/Btu), while others such as China and the European Union apply concentration limits ($\mu g/m^3$).

Areas For Further Work

To address the large uncertainties in global scale mercury emissions releases, there is a need for further systematic and harmonized measurements and data collection, model refinement, and analysis. There is often a lack of knowledge about local situations, especially for developing countries due to data shortages and the high cost of sampling and analysis. To improve mercury inventories, as well as enhance the ability to evaluate control options, several lines of additional research and measurements are needed. Cost-effective sampling and analytical methods would enable more measurements, which are needed especially for newly employed air pollution control devices. Continuous measurements of mercury transformation and speciation under different operational conditions would enable better assessment of uncertainty and variability in inventories, as would more measurements of mercury emission from sources with large fluctuations (e.g., waste incinerators, crematories). New measurements could facilitate the development of locally-specific factors for air emissions, as existing inventories often apply these factors from other locations and regions, which may not reflect local conditions. Measurements of mercury releases to land and water from various sources and measurements of mercury from contaminated sites would also improve our ability to assess and regulate these sources.

Although the control measures for different sources under each Article are different, it is also important to recognize that measures to comply with one Article may lead to a decrease or increase of mercury emissions and releases that are addressed by another Article. For example, actions to curb mercury emissions from stationary sources can result in the capturing and storage of more mercury in the form of solid waste such as fly ash or gypsum from flue gas desulfurization. When these solid wastes are reused and heated to high temperatures, for example in cement production, mercury may be emitted to the air (Wang et al. 2014). As such, emissions estimates, and policy decisions to control emissions, should consider the life cycle of mercury (Lin et al. 2017).

In support, research is needed to measure mercury emissions and releases from major sources and establish national inventories, track mercury material flows, and monitor how emissions and releases change over time. Currently, most studies do not account for mercury demand using a supply chain perspective, which can provide more information on the drivers of uses, emissions and releases, and help identify activities that are interconnected through waste and byproduct flows (Hui et al. 2016, Wu et al. 2016). Developing a robust, detailed, bottom-up inventory that includes all relevant sources requires establishing a comprehensive national system for mercury material flows to track the mercury supply and trade in and across societies and movement in both air, water and soil. In many countries, this is challenging. However, further studies can help guide policy decisions to identify critical mercury use, emission and release sources and avoid secondary atmospheric mercury emissions.

To assist with further abatement of emissions and releases, scientists and engineers can contribute to the development and deployment of technologies to control mercury emissions from major sources; help determine ELVs that are based on BAT and BEP standards; and support the design of national emission reduction plans. Already, a group of technical experts brought together by the United Nations Environment Programme drafted guidance on BAT and BEP to assist parties in fulfilling their obligations (United Nations Environment Programme 2015). Parties are likely to call on experts to provide similar advice during BAT and BEP implementation at the national level. Where countries apply ELVs to domestic sources instead of BAT or BEP, these ELVs must reflect equivalent reduction levels that can be achieved with BAT/BEP. Therefore, policy-makers will need to rely on technical experts to regularly review ELVs to take account of progress of BATs and BEPs and ensure that ELVs are consistence with this progress.

When deciding what technologies constitute BAT, it is important to understand the cost-effectiveness of various mercury control measures, which is challenging due to the limited information on cost of mercury control measures, and difficulties in predicting cost trends and technical innovations. Costs of mercury control measures could decrease due to economies of scale, commercial maturity, or technical innovation. Also, because different air pollution control devices result in different speciation profiles for the emitted (and captured) mercury, the choice of specific devices influences not only the absolute amount of mercury emitted, but also its transport and spatial deposition, which in turn determines who will experience the benefits of policy actions (Giang et al. 2015). To help abate releases of mercury to water and land, engineers and scientists may help identify the most critical sources to control as well as develop the control measures and standards. Scientists can also play important roles in finding better ways to reduce emissions and releases from ASGM-related activities.

Researchers can also develop new mercury-free manufacturing processes and products, to support implementing phase-outs and restrictions on mercury uses in products and processes in different parts of the world. Countries and researchers can also draw on existing extensive technical knowledge on substitutes and alternate reduction measures, including from collaborative initiatives that were carried out under the Global Mercury Partnership (Sun 2017). Much focus is on phasing out the use of mercury catalysts in the VCM industry, which is the largest use of mercury in China. Some policy recommendations suggest enhanced reporting and establishment of closed-loop systems, but the ultimate solution is to completely eliminate the need for mercury in the VCM industry (Wang et al. 2016). Similarly, while some short-term efforts to address mercury use in ASGM focus on new technology development and deployment, researchers are also looking at longer-term approaches to phase mercury use also from this sector (Saldarriaga-Isaza et al. 2015).

Also important is expanding knowledge and means for environmentally safe handling of mercury wastes as well as further development and dissemination of guidelines and methods for easier and more cost-effective remediation practices for contaminated sites (Wang et al. 2012, Randall and Chattopadhyay 2013, Xu et al. 2015). While North America and Europe struggle to address old contaminated sites, the number and severity of mercury-contaminated sites continue to increase in Asia and other parts of the world (Li et al. 2009, Kocman et al. 2013). Engineers and scientists can play important roles to further develop and test different in-situ and ex-situ options (Wang et al. 2012, Randall and Chattopadhyay 2013, Xu et al. 2015). The choice of a specific remedial approach should be focused on site-specific parameters, as local conditions can vary tremendously across different sites (Randall and Chattopadhyay 2013, Xu et al. 2015).

Support, Awareness Raising, and Education

Several enabling provisions recognize the importance of increased support to countries, expanded awareness raising, and strengthened science-based education. The collective application of all of these mandates is important to achieve effective treaty implementation among all parties. They are, however, especially important in developing countries where the awareness of the environmental and human health impacts of mercury and the availability of human, economic, scientific and technical resources for comprehensive mercury management often are limited at the national level. To this end, Article 13 on financing and Article 14 of capacity building, technical assistances and technology transfer contain a set of provisions related to the importance of providing assistance to developing countries.

Article 16 calls on parties to promote the development and implementation of strategies to identify populations at risk from mercury exposure, to develop science-based public educational programs, and to adopt science-based health guidelines on mercury exposure and to strengthen health-care services. Article 17 stipulates that parties shall exchange scientific, technical, economic and legal information. This includes information on the reduction or elimination of the production, use, trade, emissions and releases of mercury; information about technically and economically viable alternatives for mercury use in products and processes; and epidemiological information concerning mercury-related health impacts. Article 18 states the parties shall promote and facilitate public information, awareness and education.

Existing Knowledge

Experience from other environmental treaties demonstrates that efforts to build capacity benefits from concerted efforts across global, regional, national and local governance scales (Selin 2010). In these cases, the Secretariat plays an important global role in collecting, publishing and disseminating data (Jinnah 2014). The Convention Secretariat works alongside major IGOs, including UN Environment, the World Health Organization, United Nations Development Programme and the United Nations Industrial Development Organization, in hosting and supporting regional capacity building programs and training sessions that promote information exchange, including helping to prepare country's treaty ratification and implementation. Stockholm Convention and Basel Convention regional centers, already working with countries on capacity building and technology transfer issues for those agreements, could also be engaged to address mercury (Selin 2012, United Nations Environment Programme 2016).

Studies and field experiences show that the design and implementation of effective awareness raising and science-based education programs require a comprehensive and long-term approach. Programs must be flexible enough so that they can be adjusted over time and be tailored to specific local legal, political, economic, social, cultural and environmental contexts (Chouinard and Veiga 2008, Sousa and Veiga 2009, United Nations Development Programme 2009, Arctic Monitoring and Assessment Programme 2015). Efforts to disseminate information and new methods and technology to change the behavior of targeted groups must include close and repeated interactions between authorities, experts and community members (García et al. 2015). Many of the more effective efforts also target key individuals whose actions will influence the decisions by others and outcomes of community-wide efforts to change attitudes and behaviors (Sippl and Selin 2012).

The use of scientific and technical knowledge is key to efforts to change attitudes and behavior among particularly vulnerable populations, and this is especially true in the ASGM sector. Studies show that programs aiming to reduce mercury use and exposure should comprise both the dissemination of science-based information on the environmental and health risks from mercury as well as engagement with miners to develop and apply new technologies for reducing mercury emissions and exposure (Zolnikov 2012). Also, inducing miners to shift to mercury-free techniques requires more than a demonstration of alternative technologies; it takes an understanding of local socio- economic and cultural factors and relationships among different actors along the gold supply chain (Spiegel et al. 2018). In addition, much ASGM takes place in the informal sector, creating a host of legal, political and management challenges and land use conflicts (Hilson and Gatsinzi 2014).

Dentistry is another major area of intentional mercury use where there are efforts to generate and communicate science-based information for behavioral change (Mackey et al. 2014). For example, a civil society initiated campaign to phase down the use of mercury amalgams in Asia and Africa faced initial resistance from policy makers and dentists who did not believe that mercury posed a risk. To overcome this skepticism, scientists from several countries in both regions used a portable device to measure mercury levels in air in dental offices (Ali and Khawja 2015). Such on-the-spot measurements demonstrating high mercury levels proved to be a strong method of risk communication with dentists across different cultural settings, and helped garner support for changing workplace practices to reduce exposure. The credibility of the education campaign was also enhanced by a WHO publication and other studies on options for mercury-free dentistry (World Health Organization 2010, Ferracane 2011).

Many public health education campaigns that focus on the presence of methylmercury in fish seek to raise awareness and communicate appropriate dietary guidelines, especially for vulnerable populations such as pregnant women and small children (Mergler et al. 2007, Mahaffey et al. 2011). In developing science-based dietary guidelines, it is critical that experts work closely with local communities, including indigenous communities where the harvesting and consumption of seafood are integral to long-standing cultural values and practices (Arctic Monitoring and Assessment Programme 2015). It is important that nutritional benefits of fish consumption are evaluated against risks of mercury exposure when designing consumption guidelines (Mahaffey et al. 2011). Some newer diet-related research focus on mercury in rice, which is sometimes grown in mercury-contaminated paddy fields (Li et al. 2009, Rothenberg et al. 2014). This research suggests that dietary guidelines around foods other than fish may need to be developed for vulnerable populations.

Areas For Further Work

The ability to meet many Convention goals depends on recognizing political, economic, social and cultural dimensions of collective and individual actions required to reduce mercury exposures and risks. Improving programs for capacity building and raising awareness to change human behavior requires research on the design of effective communication strategies and programs within different knowledge systems. It requires the expertise of specialists and educators to use different communication tools and craft effective messages tailored to local communities, policy makers and the general public (Arctic Monitoring and Assessment Programme 2015). Efforts to design better science-based communication strategies in turn are dependent on improved quality and quantity of data on mercury pollution, including biomonitoring data for different species and ecosystems as well as health effects of low-level exposure to different human populations (Arctic Monitoring and Assessment Programme 2015).

Many collaborative efforts on capacity building, raising awareness and implementing science-based education programs continue to focus on the ASGM sector, as past initiatives across South America, Africa and Asia have not been enough to address related problems of mercury use, emissions and releases negatively impacting the environment and human health. Researchers can work with national governments, stakeholder groups, and international organizations that are collaborating around the development of National Action Plans under the Convention. This includes further addressing the widespread situation where ASGM miners work outside of national laws without formal mining rights, often causing conflicts with both authorities and large mining corporations (Sippl and Selin 2012). Addressing these types of complex legal and political issues often requires the establishment of greater trust between authorities and miners and other community members (Spiegel et al. 2018).

To minimize environmental and health impacts to miners and their communities (including urban processing centers), it is necessary to refine existing technologies and/or develop new mining methods, and to work with individual miners to introduce them. Importantly, efforts to expand the introduction of mercury-free techniques in ASGM communities must consider the social and economic drivers of the use of mercury to see more widespread uptake of new methods and technologies. Related, it is necessary to further develop and apply performance indicators to evaluate education and technology diffusion programs (Sousa and Veiga 2009). To move toward mercury-free gold mining, researchers can also engage processes that are designed to explore opportunities for expanding alternative livelihoods for miners and to facilitate collaboration among mining communities, local and national governments, and international organizations in support of sustainable development.

Further communications research can support efforts to phase out the use of mercury and mercury-containing products, by considering both scientific information and local conditions and perceptions that underpin these uses. This includes working with dental professionals and patients to accept alternatives to mercury amalgam, as well as assuring medical practitioners about the efficacy of mercury-free alternatives to existing mercury thermometers and sphygmomanometers. Educational campaigns in Africa discovered that women still use mercury-containing skin lightening products despite the risks because women with fair skin are perceived to be more attractive by prevailing social standards (Agorku et al. 2016). Because these social pressures are not adequately addressed, legislation in several countries against these products has been difficult to implement. In addition, there are continuing needs for localized research to examine health risks from dietary intake of mercury-containing food, including fish and rice, and devise appropriate consumption guidelines for different communities (Meng et al. 2014, Arctic Monitoring and Assessment Programme 2015).

Impacts and Effectiveness

Several Convention articles relate to efforts to evaluate its effectiveness. Some of these articles focus on generating scientific data and making such data available through public reporting. Article 19 mandates that parties develop and improve methods for both modeling and monitoring of mercury in vulnerable human populations and in targeted environmental media. Article 20 stipulates that each party may develop and execute an implementation plan following an initial assessment while Article 21 mandates that parties report on national measures and their effectiveness to the Secretariat. Article 15 creates an implementation and compliance committee to review implementation progress and help parties that face challenges. Article 22 requires the COP to carry out periodic effectiveness evaluations based on scientific, environmental, technical, financial and economic factors. The first of these must begin no later than six years after the Convention enters into force (2023 at the latest).

Existing Knowledge

Identifying whether the Convention is protecting human health and the environment from mercury involves mobilizing scientific knowledge across a complex chain of causality and attribution. Changes in anthropogenic mercury emissions may result from implementation of Convention provisions, from other socio-economic or environmental policies, or from both influences concurrently. Changes in emissions in turn result in changes in mercury deposition to ecosystems, and subsequent conversion to methylmercury. Finally, changes in human and environmental exposure and adverse impacts result from different forms and levels of mercury exposure. Several areas of scientific research and data collection provide methods and information integral to connecting these elements into a causal chain for impact assessment. Yet, efforts to identify policy signals among these impacts must also account for factors other than the Convention that might affect outcomes.

Much scientific research to date has aimed to reduce uncertainties in factors that affect the first part of this causal chain, mercury emissions, cycling and environmental behavior. In addition to uncertainties due to incomplete scientific understanding, some of these factors are highly variable and source- and location-dependent. For example, the processes that drive rates of atmospheric depletion and deposition, such as mercury oxidation (Ariya et al. 2015) and meteorological factors, vary over spatial and temporal scales. Once mercury is deposited on land or in water, local conditions (such as temperature and the amounts of oxygen, organic matter, and sulfate) drive the transformation of elemental mercury into more toxic methylmercury (Faganeli et al. 2014, Wentz et al. 2014, Gascon Diez et al. 2016). Mercury exposure levels as well as health outcomes vary among populations due to differences in susceptibility to mercury impacts. These impacts can also change over time due to factors not related to mercury policy.

Measuring and monitoring mercury levels and trends in the environment is a key input to the policy-to-impacts causal chain analysis. Monitoring provides direct data on mercury in the environment, can identify significantly impacted ecosystems and human populations, and forms a basis for testing and calibrating models. For example, monitoring near specific emission sources can detect changes in mercury deposition over relatively short time scales (e.g. Lindberg et al. 2007). Such local- to regional-scale observations can be critical for demonstrating progress that can be reasonably attributed to local source reductions. In contrast, the response of global atmospheric mercury concentrations to Convention measures will be complex and influenced by a wide range of environmental and policy factors. In fact, global deposition may increase in the short-term even under some emissions reduction scenarios, as re-emission of legacy mercury exceeds sequestration in the environment (Sunderland and Selin 2013). Because of these complexities, interpretation of monitoring data can be challenging.

Existing atmospheric monitoring data show mixed trends. Both decreasing (Zhang et al. 2016) and increasing (Martin et al. 2017) trends are attributed to changes in emissions while other studies focus on the influence of the ocean (Chen et al. 2015, Chen et al. 2016). Trends in wet deposition are even more variable. Studies at sites in North America show a combination of increases and decreases that are sensitive to location and the time period of analysis (Weiss-Penzias et al. 2016). For fish concentrations, decreases in the Atlantic (Lee et al. 2016) and increases in the Pacific (Drevnick et al. 2015, Drevnick and Brooks 2017) are both linked to global-scale emissions changes. Further, mercury levels in open ocean fish will likely begin to decrease within years to decades as a result of reduction measures while mercury in fish from coastal areas contaminated by legacy mercury may take many decades, or even centuries, to decline, due to differences in mercury cycling in these different ecosystems (Chen et al. 2016). Environmental processes for mercury are also impacted by other global changes, including climatic changes (Krabbenhoft and Sunderland 2013).

To complete the causal chain analysis, some research uses information on mercury emissions, cycling, transport and deposition to simulate the health and economic impacts resulting from anticipated policy choices under the Convention. An economic evaluation of the health benefits of mercury emission controls consistent with Convention implementation in China found mercury-related health benefits >$400 billion by 2030 (Zhang et al. 2017). These kinds of analyses also makes it possible to quantify the relative importance of various sources of uncertainty and variability across the chain of policies-to-impacts when estimating human health and economic impacts of the Convention. Uncertainties in the mercury cycling and ecosystem dynamics that influence the timescale of changes in mercury concentrations have been found to strongly affect benefit estimates (mainly because of time discounting of future benefits) (Giang and Selin 2016).

Areas For Further Work

To determine whether the Convention is meeting its stated objective, the effectiveness evaluation ultimately needs to assess the link between policy measures and related changes in human exposures and impacts. However, the initial effectiveness evaluation is likely to be informed primarily by data and models representing early and intermediate steps in the causal chain from policies to impacts. Here, the COP may develop an approach similar to the framework for the effectiveness evaluation for the Stockholm Convention on Persistent Organic Pollutants. This includes developing a series of outcome indicators to reflect changes in impacts on human health and the environment (United Nations Environment Programme 2017a), complemented by a series of process indicators that indicate levels of compliance with control measures and other mandates (United Nations Environment Programme 2013a).

The use and interpretation of outcome indicators to measure effectiveness will pose an ongoing scientific challenge. Despite extensive efforts to understand the mercury cycle, scientific uncertainties and environmental variabilities limit the ability to link global changes in emissions to environmental concentrations and exposures, and obscure the ability to attribute changes due to Convention related implementation measures (Selin 2014b, Kwon and Selin 2016). To address these uncertainties, there is a need to collect better empirical data on mercury emissions and concentrations and on relevant environmental factors affecting atmospheric transport and biogeochemical cycling. In addition, the development of a reliable baseline is critical for evaluating the impacts and effectiveness of the Convention. While data are available in many cases for emissions and releases (e.g. from the Global Mercury Assessment), they may be lacking for other important variables. Further, political considerations may complicate which information the COP ultimately chooses as baseline.

Further, to address several analytical challenges in monitoring mercury, which is a fundamental way to measure Convention outcomes, scientists need to develop new sampling and analytical methods (including methods for quality control of measurements, particularly for oxidized and particulate mercury (Jaffe et al. 2014) as well as more cost-effective monitoring designs. Researchers will also need to dramatically improve models so that they can make better use of such data in more robust ways. It is especially critical to develop a better understanding of behavior of mercury in conditions common to tropical regions, where a large proportion of global mercury emissions now occur (United Nations Environment Programme 2013b). In addition, new methods are needed for integrating this scientific information with other social and economic information called for in Article 22, into a coherent framework against Convention effectiveness can be assessed.

Approaches used to collect and analyze monitoring data also need to be harmonized (Bank et al. 2014). Experts may recommend concentrating on more comparable, reliable and longer term monitoring in fewer locations, and place greater emphasis on strategic measurements in key human populations and ecosystems, rather than a greater number of measurements (Gustin et al. 2016). Many existing monitoring networks need expansion and enhancement to contribute to such important policy questions. One such effort concerns the Asia-Pacific Mercury Monitoring Network, which aims to create a coordinated Asia-wide network to monitor mercury transport and deposition. Scientists can guide such efforts, including how to appropriately interpret monitoring data given different spatial and temporal scales of mercury processes in the environment and the non-linear relationship of mercury deposition and biotic methylmercury concentrations.

The process indicators that are developed to complement outcome indicators will need to rely on reporting about the implementation of specific control measures, but can also be supplemented by targeted data collection on specific expected policy outcomes, such as the declining market availability of products to be phased out by 2020 (e.g., certain medical devices, skin-lightening creams). Additional research can build on existing proposals for a suite of such process indicators intended to reflect the effectiveness of five key control provisions (related to trade, products and processes, ASGM, and air emissions) in addition to recommending longer-term indicators based on biomonitoring of ecosystems and human populations (Evers et al. 2016). Specific process indicators can be proposed for the short term (less than 6 years), medium term (6-12 years) and long term (greater than 12 years), to match different target dates for the implementation of Convention provisions.

Using a broad definition of effectiveness, research can strengthen the evaluation by developing metrics related to changes in underlying social drivers that influence the uses and emissions of mercury. For example, indicators can be determined that reflect the increased capacity of scientists, governments and others to manage mercury according to Articles 14 and 17. Effectiveness of efforts under Article 18, to raise public awareness of mercury, can be evaluated by how well they have been able to modify cultural and social views among critical target populations whose behavior influences the rate of change of mercury use and emissions. Such changes are hard to quantify, much less directly observe and measure, and will require social scientists such as educators, communication specialists, and program evaluation specialists to develop appropriate indicators (Macdonald et al. 1996, Centers for Disease Control 1999, Abroms and Maibach 2008).

The Future of Mercury Science and Governance

The Convention is set to play a central role in environmental and human health protection from mercury-related exposures and risks. The most recent effectiveness evaluation of the Stockholm Convention notes that an environmental treaty can act as an important catalyst for expanded research, monitoring, and modeling and for bringing together findings from different parts of the world (United Nations Environment Programme 2017b). Future mercury research can support Convention implementation efforts in numerous ways and feed into policy-making and management at multiple times and entry points. This article’s discussion should not be seen as an exhaustive summary of all the areas and ways in which the larger research community can contribute, but rather as an effort to connect research with key Convention implementation needs. Here, there is a high demand for interdisciplinary expertise and perspectives.

As the parties move forward with implementation, building on work carried out under the Global Mercury Partnership and other international programs and agreements (Selin and VanDeveer 2004), there is a need to strengthen multilevel approaches to mercury management across global, regional, national, and local governance scales (Selin 2014a). Governance focused studies can continue to analyze how activities and decisions in different fora and governance levels by international organizations, countries, civil society organizations and scientists are linked, and explore ways in which such linkages can be used to create synergistic effects toward better mercury management. Such studies should be carried out alongside more research into the impacts of mercury on human health and the environment and how mercury cycles through different environmental media, because better mercury management is dependent on a combination of scientific information from different sources, fields, and disciplines.

To enable different forms of continued monitoring and applied mercury-related research in support of policy-making and treaty implementation, it is critical to build and support basic scientific and analytical capabilities, especially in developing regions of the world where the lack of such capabilities is a central issue. Developing and newly industrialized countries are likely to be the ones where the most wide-ranging policy measures are needed, as these countries now represent the majority of global mercury uses and emissions and releases. Such measures may include major cuts in atmospheric mercury emissions from coal-fired power plants and other major stationary sources, the phasing out mercury use in products and processes, and reducing and ultimately eliminating mercury use in ASGM. Building implementation capacities in these countries and supporting technology transfer will be critical to the success of the Convention.

As it is an essential governance challenge to simultaneously address mercury supply and demand in a coordinated way (Greer et al. 2006), this synthesis paper focuses mainly on scientific contributions to the implementation of existing treaty provisions that address current priority supply and demand elements of the mercury life-cycle. However, as the COP oversees the implementation of the Convention, including through the use of the facilitative compliance mechanism (Templeton and Kohler 2014), current mandates will be reviewed and new requirements can be added. For example, the COP may identify other sources of mercury emissions and releases, update BAT and BEP guidance, and/or introduce provisions to account for cross-media mercury management. In addition, the COP may expand focus to additional mercury-containing products and processes. On all such decisions, the COP will benefit from existing and developing scientific and technical information.

The implementation of the Convention also intersects with other environmental treaties. A greater attention to mercury wastes creates stronger linkages with the Basel Convention (Selin 2010), which is directly connected to Article 11. Climate change has implications on mercury pollution and its impacts (Arctic Monitoring and Assessment Programme 2015). For example, climate-induced changes in food web structures may enhance bioaccumulation and biomagnification of methylmercury in some marine species (Jonsson et al. 2017). In addition, mercury management takes place in a broader context of the sustainable development agenda, linked to Sustainable Development Goals on good health and well-being, clean water and sanitation, affordable and clean energy, responsible consumption and production, and sustainability of life below water.

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