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A Critical Time for Mercury Science to Inform Global Policy

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Abstract

Mercury is a global pollutant released into the biosphere from geologic stores by varied human activities including coal combustion, mining, artisanal gold mining, cement production, and chemical production. Once released to air, land and water, the addition of carbon atoms to mercury by bacteria results in the production of methylmercury, the toxic form that bioaccumulates in aquatic and terrestrial food chains resulting in elevated exposure to humans and wildlife. Global recognition of the mercury contamination problem has resulted in the Minamata Convention on Mercury, which came into force in 2017. The treaty aims to protect human health and the environment from human-generated releases of mercury curtailing its movement and transformations in the biosphere. Coincident with the treaty's coming into force, the 13th International Conference of Mercury as a Global Pollutant (ICMGP-13) was held in Providence, Rhode Island USA. At ICMGP-13, cutting edge research was summarized and presented to address questions relating to global and regional sources and cycling of mercury, how that mercury is methylated, the effects of mercury exposure on humans and wildlife, and the science needed for successful implementation of the Minamata Convention. Human activities have the potential to

enhance mercury methylation by remobilizing previously released mercury, and increasing methylation efficiency. This synthesis concluded that many of the most important factors influencing the fate and effects of mercury and its more toxic form, methylmercury, stem from environmental changes that are much broader in scope than mercury releases alone. Alterations of mercury cycling, methylmercury bioavailability and trophic transfer due to climate and land use changes remain critical uncertainties in effective implementation of the Minamata Convention. In the face of these uncertainties, important policy and management actions are needed over the short-term to support the control of mercury releases to land, water and air. These include adequate monitoring and communication on risk from exposure to various forms of inorganic mercury as well as methylmercury from fish and rice consumption. Successful management of global and local mercury pollution will require integration of mercury research and policy in a changing world.

Introduction

Mercury is a global pollutant released from geologic reservoirs in the Earth to air, land, and water by human activities. These include mineral extraction, coal combustion, chemical manufacturing, and other activities. Emissions and releases of mercury to the air, land, and water comprise: 1) emissions to the atmosphere from sources such as coal combustion and the evaporation of mercury in artisanal gold mining; and 2) discharges into water bodies, such as from mining, chemical facilities, historically contaminated (legacy) sites and runoff from land surfaces. Once deposited to land or water, the addition of carbon atoms to mercury by bacteria in reducing environments (wetlands, sediments) results in the production of methylmercury. Methylmercury is the form that bioaccumulates and biomagnifies in aquatic and terrestrial food chains. This process results in elevated exposure of humans and wildlife throughout the world.

For the past thirty years, scientists have met at a series of meetings of an international conference to share insights about problems posed by mercury. Most recently, in July 2017, more than one thousand scientists from 50 countries gathered in Providence, Rhode Island USA for the 13th International Conference on Mercury as a Global Pollutant (ICMGP-13) under the theme of *Integrating Mercury Research and Policy in a Changing World*. As part of the ICMGP-13, groups of scientists summarized cutting edge research in four synthesis papers¹⁻⁵. These syntheses came to a critical conclusion: broad-scale environmental changes are influencing the fate and effects of mercury, perturbations that are as important as mercury releases alone. These synthesis papers were timed to support the implementation of Minamata Convention on Mercury, the global treaty that aims to protect human health and the environment from anthropogenic emissions and releases of mercury. The Convention came into force on August 16, 2017.

Since the 1st ICMGP (1990) in Gävle, Sweden, understanding of the spatial extent and complexity of mercury pollution has advanced markedly, demonstrating the critical need for a global control effort. The ICMGP-13 synthesis papers reflect advances in our knowledge about mercury sources, transport, fate, and effects spanning local to global scales. The ICMGP-13 synthesis reflects the maturation of mercury science that informs and supports

policy efforts associated with the full life cycle of mercury. This spans its production, use, emissions to air and discharges to land and water, and environmentally sound management, all of which are covered by the Minamata Convention. These papers provide the mercury science and policy communities with insights and direction for addressing mercury pollution. Importantly, these syntheses show that human influenced environmental changes that are occurring locally and globally drive the long-term fate and effects of mercury. Successful measures to address mercury pollution will likely require consideration of these unfolding environmental changes. Addressing mercury pollution and implementing the Minamata Convention are closely linked to the United Nations' Sustainable Development Goals for 2015–2030 (including those on Good Health and Well-Being, Clean Water and Sanitation, Affordable and Clean Energy, Responsible Consumption and Production, and Life Below Water).

Mercury Science and Policy Developments

Advances in understanding mercury transport, methylation, bioaccumulation, and effects over the long term have been closely coupled with policy initiatives (Figure 1). The international scientific research community has been instrumental in demonstrating that historical and current human releases of mercury to air, water and land have created an environmental and human health problem of global proportion. Scientists have long been directly engaged in evaluating and informing a range of policies to address this important transboundary issue. In preparation for the 6th ICMGP (2006, Madison, Wisconsin, USA), five expert panels were convened to synthesize the state of mercury science in *The Madison Declaration on Mercury Pollution*⁶. The panels produced a group of synthesis articles that were widely used by both scientific and policy communities^{7–11} (Mergler et al. 2007; Swain et al. 2007; Munthe et al. 2007; Lindberg et al. 2007; Scheuhammer et al. 2007). The conference Declaration summarized consensus conclusions on policy-relevant questions concerning atmospheric mercury, exposure, human and wildlife impacts, mercury-contaminated fisheries, and socioeconomic consequences of mercury pollution.

A synthesis effort associated with the 10th ICMGP (2011, Halifax, Nova Scotia, Canada) updated the science behind mercury sources and human and wildlife effects^{12–15}. This resulted in a series of peer-reviewed papers as well as a report that focused on the sources and cycling of mercury in marine ecosystems and the resulting human exposure from seafood consumption^{12–14}. These materials were provided to delegates at the meeting of the 5th International Negotiating Committee for the mercury treaty in Geneva in 2013. Additionally, scientists have contributed to a series of four global-scale mercury assessments coordinated by the United Nations Environment Programme. Scientists' perspectives on mercury policy have appeared in numerous peer-reviewed journals. In addition to the publication of the recent ICMGP-13 synthesis papers, concise summaries (<http://web.unep.org/globalmercurypartnership/>) were provided to the first Conference of Parties (COP) of the Minamata Convention in September 2017 and translated into Chinese, Russian, Arabic, Spanish and French.

Advances in Mercury Science

The steady advancement of new knowledge in mercury science provides key opportunities for incorporation into international policy. Here, we highlight four areas where recent advances in science have improved the ability to trace and predict mercury pollution from sources to human and ecological receptors and to evaluate its potential impacts.

Understanding these links will be critical in formulating new policies and evaluating the effectiveness of the Minamata Convention.

Global Sources and Sinks of Mercury.

Our ability to quantify changes in mercury in air, land, and water and its transformations to methylmercury has improved, as has our understanding of the impacts of climatic and other environmental factors on mercury transport, transformation, and bioaccumulation¹ (Figure 2). Recent methodological advances such as using stable isotopes of mercury to identify mercury sources, pathways, and transformations have been instrumental in advancing understanding in the fate of mercury in the biosphere.

Atmospheric mercury concentrations have declined in the past two decades in North America and Europe in response to decreases in mercury use, changes in fuel sources, and emission controls. Decreases of mercury are measurable in the surface of the Atlantic Ocean, linked to decreases in mostly atmospheric and, to a lesser extent, riverine sources in North America and Europe. In contrast, mercury is increasing in the atmosphere in East Asia and the Southern Hemisphere, as well as in the Pacific Ocean.

Rather than a source to the atmosphere, most terrestrial ecosystems are a sink for atmospheric mercury mediated by plant uptake. However, during wildfires significant amounts of this mercury can be re-emitted to the atmosphere. Additionally, 50% of the global freshwater releases of mercury are estimated to drain into the West Pacific and North Indian Oceans. These global fluxes and trends are influenced by climatic changes. Coupled mercury and climate models are critical to understanding future transport and fate of mercury.

Landscape Management Opportunities to Reduce Mercury Impacts.

Watershed land-use activities (e.g. forestry, mining, reservoir creation, urbanization, agriculture) can have a dominant role in influencing mercury fate and effects in the local environment² (Figure 3). Different land-use perturbations can increase the mobility of contemporary mercury deposition and legacy mercury contamination in soils and sediments. In addition, landscape perturbations can enhance mercury methylation to its more bioavailable and toxic form, methylmercury, either through direct impacts on mercury availability or by creating conditions favorable for organisms that methylate mercury. This is the case with rice cultivation in mercury contaminated soils. As such, the management of water and other pollutants (particularly sulfate and factors that control organic carbon such as nutrients) ought to consider the potential impacts of methylating microorganisms and legacy mercury pools.

Most of the research on the effects of landscape perturbations and hydrologic impoundments on mercury fate and methylation have occurred in temperate regions. However, the majority of artisanal small-scale gold mining (ASGM) and reservoir construction for hydropower occurs in tropical and subtropical developing countries. As a result, there is a critical need for research in tropical regions. Best management practices for watersheds and careful remediation of contaminated industrial sites have been shown to reduce mercury mobilization and methylation. *In situ* methods including capping and amendments to reduce mercury availability are becoming more widely utilized due to lower ecosystem disruption and reduced costs compared to traditional removal efforts. These activities can greatly decrease the transport, methylation and bioavailability of mercury in local environments.

Environmental and Human Health Impacts.

Although the neurotoxic effects of mercury are well established, recent studies show that adverse health effects are complex and have included behavioral, developmental, nephrological, reproductive, endocrinological and immunological consequences³ (Figure 4). Additionally, increasing evidence points to the interaction of mercury exposures with other disease factors to further negatively affect health outcomes. These include infectious diseases (e.g., malaria), the microbiome and antibiotic resistance, and genetic and epigenetic factors. Other biomagnifying contaminants found in fish (e.g., PCBs) can also act synergistically with mercury. There is increasing evidence of the benefits of consuming fish, particularly for their omega-3 fatty acids. As a result, increased and improved efforts to communicate both risks and benefits of seafood consumption will help consumers and regulators make informed decisions. However, there remains much to learn about the combined effects of mercury with other chemical and biological stressors.

Science to Support Treaty Implementation.

The implementation of the Minamata Convention will benefit from recent scientific advances, but there remain many areas in which interdisciplinary scientific expertise, activities and advances are needed to understand and mitigate global mercury pollution⁴ (Table 1). More cost-effective and better sampling and analytical tools will be essential to improving local and regional capabilities to measure mercury releases, fate, and transport over time. The development and deployment of innovative technologies will be essential to control of mercury releases to air, water, and soil, particularly from ASGM. Financial and technical assistance will be essential to design and implement national reductions plans in developing countries.

Research is critically needed on wildlife and human health risks from mercury exposure, coupled with effective dissemination of science-based information on these risks. Science-based dietary guidelines should be established through close cooperation with communities where the consumption of fish and wildlife are integral to cultural values, particularly among indigenous peoples. Finally, science will play a fundamental role in establishing a framework for the effectiveness evaluation of the Minamata Convention scheduled to begin no later than 2023. The upcoming COPs and associated consultations will provide opportunities for timely communication of this new mercury science to decision makers.

Critical Uncertainties and Immediate Actions

Alterations of mercury cycling, mercury methylation, bioaccumulation and trophic transfer due to climate and land use changes remain critical uncertainties in the ability of the Minamata Convention to reduce mercury releases and exposure. Even though the Convention will likely curtail new anthropogenic sources of mercury, the legacy of previously emitted mercury will continue to affect global cycling for decades to centuries. Changes in mercury reemissions and cycling associated with changing climate will likely result in non-linear responses of mercury transport and methylmercury production in the biosphere. For example, climate-induced increases in drought and wildfires will likely increase the emissions of mercury from terrestrial compartments, while increases in plant production due to carbon dioxide fertilization effects could facilitate mercury deposition and sequestration to land. Resulting increases of organic carbon to aquatic systems could also increase anaerobic conditions and enhance methylation of mercury.

It is unclear how ongoing and projected increases in dissolved organic carbon or changes in primary productivity will affect the methylation and bioaccumulation of mercury in aquatic food webs. Additionally, enhanced air-sea exchange in the Arctic Ocean could reduce this reservoir of mercury through transfer from ocean to atmosphere, while the thawing terrestrial landscape could increase mercury transfer from land to ocean. Given these and other potential alterations of the mercury cycle, there is considerable uncertainty in how global change will influence the dynamics of mercury in air, land and water, and resulting human and wildlife exposure. As a result, comprehensive monitoring that incorporates these drivers will be key to inform the effectiveness of the Minamata Convention in a changing world.

In the face of these uncertainties at global, regional and local scales, policy and management actions will be needed over the short-term to support decreases of mercury releases. For example, obtaining measurements of mercury in understudied regions are critical to adequately establish a baseline and evaluate the effectiveness of the Minamata Convention. Increased accessibility to existing or new technologies also should help mitigate mercury emissions, releases and impacts of ASGM on local watersheds and exposed communities. Additional research is needed to understand the complex interactions of mercury with other contaminants and diseases. And given that mercury levels in fish will remain elevated in the short term, making available education and fish consumption advice will greatly benefit vulnerable populations.

As human induced environmental changes accelerate in the Anthropocene¹⁶, our understanding of mercury science becomes increasingly important. However, it must continue to encompass alterations to global cycling, local disturbances, and routes of exposure to living organisms. There is still much work to be done - and mercury scientists are ready and well positioned to take on the challenge by continuing to share their advances at the next ICMGP in Krakow, Poland in 2019.

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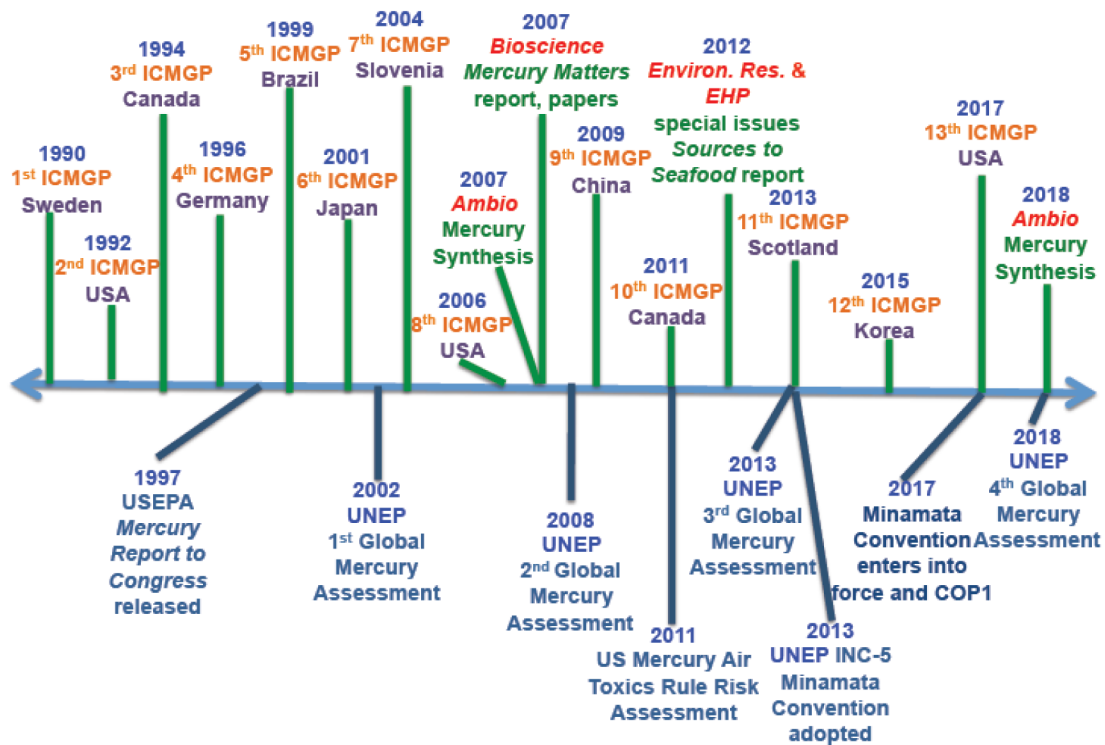


Figure 1. Timeline of mercury science and policy events. Mercury science events above horizontal line: year of event (blue), ICMGP meetings (orange) with hosting country (purple), mercury reports and papers (green), journals (red). USEPA (U.S. Environmental Protection Agency) and UNEP (United Nations Environment Programme) policy events below horizontal line.

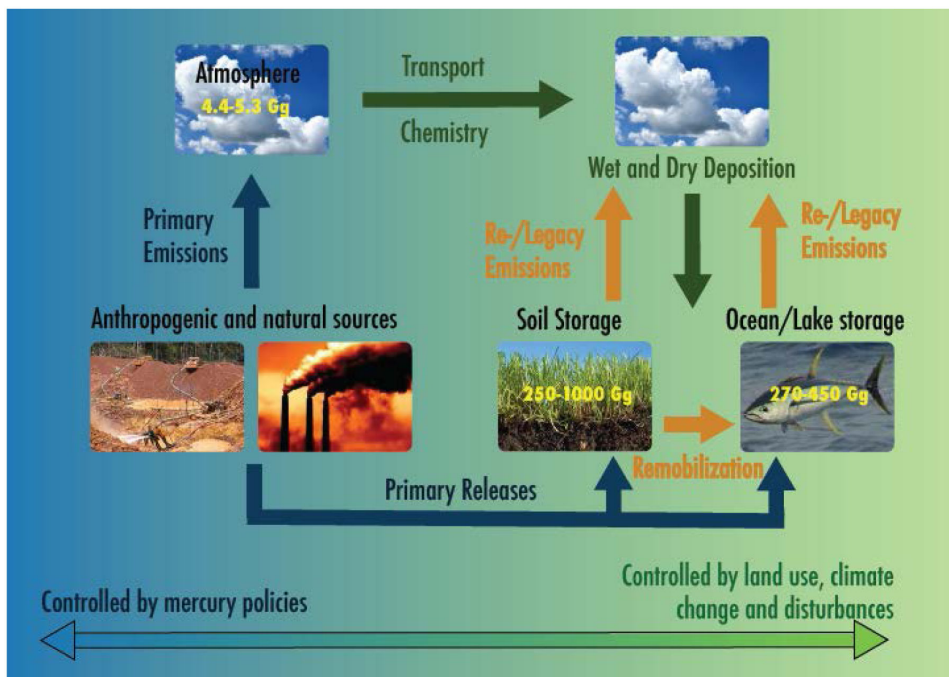


Figure 2. Atmospheric mercury influenced by new emissions, and recycling of legacy mercury in sources and sinks on land and in oceans (adapted from Obrist et al. 2018). Releases of mercury to the environment (blue), mercury transport (green), mercury recycling (orange), mercury quantity in each reservoir in gigagrams (yellow). Note that dry mercury deposition includes the deposition of mercury associated with vegetation uptake.

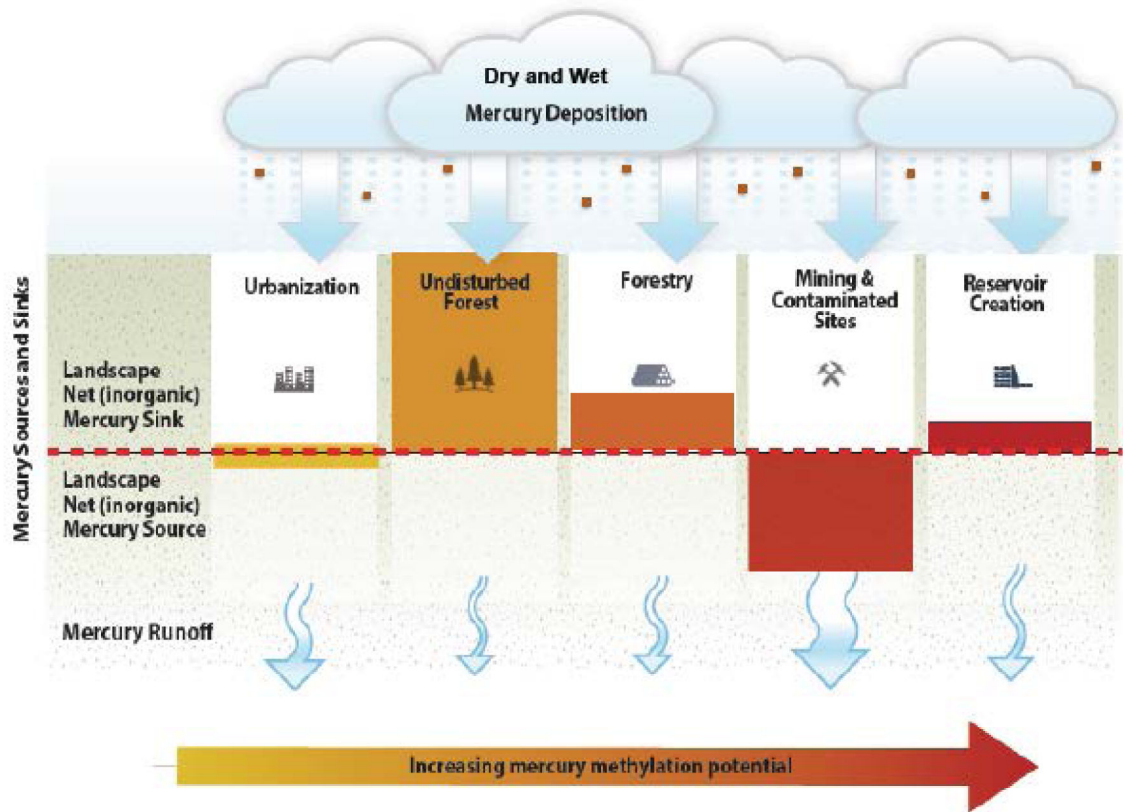


Figure 3. Impacts of landscape disturbances such as forestry, mining, and reservoir creation on mercury sources and sinks. Deposition includes various wet (blue) and dry (brown) deposition pathways (adapted from Hsu-Kim et al. 2018).

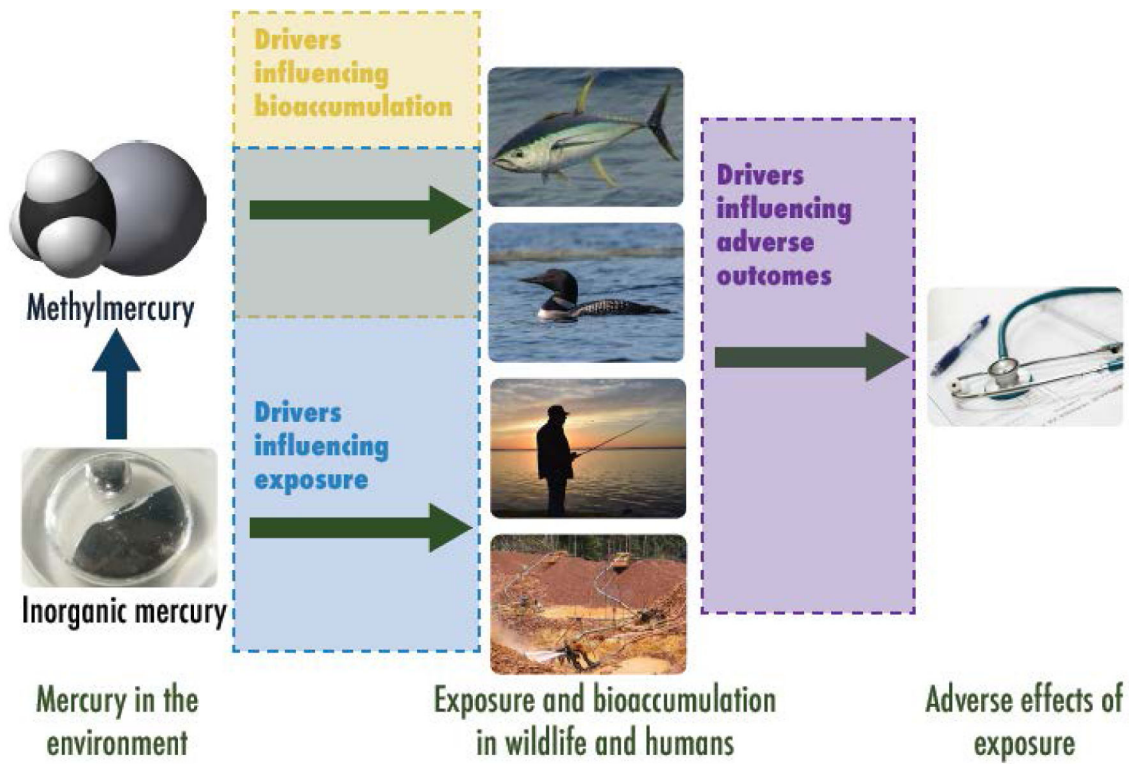


Figure 4. Biological, ecological, and socio-economic drivers that influence mercury accumulation, exposure, and adverse effects. (adapted from Eagle-Smith et al. 2018). Drivers influencing bioaccumulation and exposure overlap for fish and wildlife (gray box).

Table 1.

Scientific work and data needed to support decision-making and management outlined in three critical areas of the Minamata Convention. (adapted from Selin et al. 2018).

Area	Convention Articles	Illustrative Research Needs
Uses, emissions, and releasea	Article 3-Supply and need Article 4-Products Article 5-Processes Article 6-Exemption to phase-cut dates Article 7-ASGM Article 8-Emissions to air Article 9-Releases to Land and water Article 10-stroage Article-11-Waste Article 12-Contaminated sites	<ul style="list-style-type: none"> • Evaluate availability and efficacy of Hg-Free alternatives under a wide range of circumstances • Improve methods for creating more reliable inventories of sources and emissions/releases • Evaluate the effectiveness of control technologies • Assist in the definitions of BAT, BEP, and Ely's • Support development of guidance on indentification. Characterization risk assessment and management of contaminated sites <ul style="list-style-type: none"> • Quantify how mercy moves among land water and air to develop better controls
Support, awareness raising, and education	Article 13-Financial mechanism Article 14-Capacity –Biuilding technical assistance, and technology transfer Article 16-Health Article 17-Information exchange Article 18-Public information, awareness and education	<ul style="list-style-type: none"> • Design and evaluate communications programs for education • Asses risks and identify sources of exposure to vulnerable population • Engage in information exchange on technically and economically viable alternatives to Hg Use • Support technology transfer that addresses local social drivers of existing Hg use
Impacts and effectiveness	Article 15-Implentation and compliance Article 19-Research development and monitoring Article-20-Implentation plans Article 21-Reporting Article 22-Effectiveness evaluation	<ul style="list-style-type: none"> • Expand tools and networks for Hg monitoring. • Provide baseline data and ensure comparability og Hg measurements • Improve modeling methods to evaluate impacts from changes in emissions and releasea • Develop methods for collecting and compiling implementation compliance.and reporting data • Develop methods to integrate varied data into an effectiveness evalution framework