3 Global Human-Technical-Environmental Cycling: Chasing Quicksilver

Human activities have dispersed substances such as mercury, lead, and carbon in the atmosphere, ocean, and land, where they are now present in quantities much higher than before there was an anthropogenic influence. These substances spread across the Earth through winds and water currents. Many scientific studies of how people have altered the environment begin with the perspective of biogeochemical cycling, which accounts for how substances move and change form in the environment. However, biogeochemical cycling processes are not the only global-scale flows of materials relevant to sustainability. Substances in commerce also cross the globe through trade, as do products and wastes that contain them. A global human-technical-environmental cycling perspective provides an expanded view of the transport and transformation of substances relative to that of global biogeochemical cycling analysis by encompassing environmental and societal flows together.

While living in New Spain (now Mexico) in 1554, the Spanish merchant Bartolomé de Medina developed the patio process of silver amalgamation, which uses mercury in the silver mining process. The high value of silver in the 1500s and 1600s helped power international trade and commerce, connecting Europe, the Americas, and Asia (Flynn and Giráldez 1995). In the Americas, where mines contained large quantities of low-quality silver-containing ore, the patio process made extracting the valuable metal easier for the Spanish colonialists. It works by allowing an amalgamation of ore and mercury to mix in a shallow, open-air courtyard for several weeks. The large quantities of mercury required for this process originated mainly from mines in Almadén in Spain, Idrija in modern Slovenia, and Huancavelica in Peru. The “loss” of mercury to the environment in silver production could range from 0.85 to more than 4 times the amount of silver produced (Nriagu 1993). The total amount of mercury “lost” in South

America between 1570 and 1820 may have been as high as 126,000 tonnes (Nriagu 1994). That is more than 50 times the annual present-day anthropogenic emission of mercury to the atmosphere (UNEP 2019).

Centuries after the colonial South American mining boom, scientists are trying to determine where all of the mercury that was extracted and used ended up, and whether it remained locally or cycled globally through the environment. Scientists attempt to answer this key question by examining environmental archives such as lake sediments, bogs, and ice cores that record mercury deposition over time. Mercury pollution from colonial mining, for instance, can be found in sediments in South American lakes (Cooke et al. 2009). However, deposition recorded in other environmental archives, particularly in the Northern Hemisphere, was not elevated around the time that mercury was used during colonial mining in South America (Engstrom et al. 2014). Deep ocean sediments around Antarctica do not show elevated deposition from this silver mining activity either (Zaferani et al. 2018). Some modeling studies, in contrast, suggest that a substantial quantity of mercury from silver mining traveled globally via environmental processes, and that it continues to circulate in the environment worldwide (Amos et al. 2015). Other researchers who have attempted to synthesize measurement and model data argue that emissions from historic mining only had a moderate influence on current global mercury cycling (Outridge et al. 2018).

Identifying the time when human activities first distributed mercury globally in the environment, and thus the relative quantities of human-induced preindustrial and industrial mercury pollution, is not just of interest to scientists. It also provides policy analysts an environmental benchmark against which to compare the effectiveness of strategies to reduce mercury discharges and concentrations. Environmental records of pollutant deposition that predate the Industrial Revolution are often considered to be a proxy for natural levels absent human influence. Different environmental archives provide a remarkably consistent picture of a dramatic global-scale increase in mercury deposition since the beginning of the nineteenth century. The human influence is even larger if preindustrial mercury deposition was also elevated due to earlier anthropogenic activities, such as colonial mining in South America going back to the 1500s. This would also imply that present-day human influence on the environmental cycling of mercury could persist for many centuries in the future.

Studies of different environmental archives and models of biogeochemical cycling tell a mixed story of mercury mobilization, but they all focus on the environmental aspects of when mercury became a global pollutant. Mercury, however, also travels through societies. As we indicate in the chapter title, when examining the international distribution of mercury, it is also necessary to chase the quicksilver that travels across borders—as a commodity, in mercury-added products, and as a contaminant in food and biota. People carried mercury across the Atlantic Ocean in large quantities starting in the 1500s for use in South American silver and gold mining. The social and cultural consequences of the economic processes that this mercury fueled were also international in scope: the silver trade and its distribution of resources and capital was a driving factor in the growth of international economic systems of production and consumption starting in the sixteenth century (Moore 2003). The term “quicksilver,” a synonym for mercury in many languages as noted in chapter 1, is an adjective that means moving or changing rapidly and unpredictably—a fitting description of many of the dynamics of mercury’s travels in both the environment and society.

This chapter focuses on mercury as a global pollutant, and the role of the Minamata Convention in addressing activities that contribute to the global cycling of mercury. We use the perspective of global human-technical-environmental cycling to contrast with the narrower perspective typical of global biogeochemical cycling analyses. In the section on system components, we identify where mercury is present in the environment and society, and the institutions and knowledge that provide the context for its global-scale material cycling. We address processes that influence the distribution and fate of mercury in the section on interactions. In the section on interventions, we give an overview of the types of actions designed to address mercury at a global scale by discussing the structure and the main provisions of the Minamata Convention. In the final section on insights, we highlight the importance of accounting for a broad range of system dynamics in understanding the global cycling of mercury, how variations in timescales of societal and environmental cycling of mercury affect transitions toward sustainability, and factors that affect the implementation and effectiveness of the Minamata Convention.

System Components

The total quantity of mercury present on Earth is fixed, but human activities have moved large quantities of this mercury to different locations. Much mercury has dispersed throughout the environment, where it is present at varying concentrations. Additional mercury remains in places controlled by people as stockpiles, in products, or in landfills. A small amount of mercury is also present in wildlife and in human bodies. Figure 3.1 shows the human, technical, environmental, institutional, and knowledge components relevant to the global mercury cycling system.

Mercury is present in *geological reservoirs* in the Earth's "merciferous belts"—areas associated with volcanic activities and plate tectonic boundaries (Gustin et al. 2000). The highest concentration of mercury in these belts is typically in cinnabar (mercuric sulfide, or HgS), but mercury also exists in small amounts in other minerals and in fossil fuels such as coal. Mercury is emitted to the *atmosphere*, and circulates among *land* and *oceans*, as a result of natural processes (such as volcanic eruptions and the weathering of rocks) as well as human activities. Archeological data suggest that *miners* produced *extracted mercury* from cinnabar as early as 6300 BCE in the Sizma district in southwestern Turkey, which may have been the world's first underground mine (Brooks 2012). Early written mentions of cinnabar mines date back to the work of Theophrastus of Eresus in the fourth century BCE (Goldwater 1972). Much of the mercury mined over human history came from the historically large mines in Almadén, Idrija, and Huancavelica, as well as from mines in China (Wanshan), Italy (Monte Amiata), and the United States. The annual minerals commodity survey issued by the US Geological Survey (2017) reports that 600,000 tonnes of

Human components	Technical components	Environmental components
Miners Producers and consumers of goods Producers and consumers of energy	Extracted mercury Extracted geological materials containing mercury Mercury in commerce Mercury in stockpiles and landfills Mercury-added products Mercury in production processes	Geological reservoirs Atmosphere Land Oceans Terrestrial and aquatic ecosystems Living organisms

Institutional components	Knowledge components
Mercury markets Regional treaties Global Mercury Partnership Minamata Convention Trade controls	Forms of mercury Properties of mercury Long-range transport Mercury concentrations in the environment Quantities of mercury in stockpiles and trade

Figure 3.1

Components in the global mercury cycling system (referenced in the text in italic type).

mercury remain in the Earth's crust globally in places where extraction is currently or potentially feasible.

Elemental mercury is extracted from cinnabar through a relatively simple process of heating the crushed ore in a furnace. This process remained more or less the same for thousands of years. When heated, the mercuric sulfide reacts with oxygen from the air to form sulfur dioxide, and the mercury vaporizes. Mercury, which condenses at 357 degrees Celsius (675 degrees Fahrenheit), a lower temperature compared with the other gases, is then captured and cooled into liquid form before it is stored, traded, and used. Extracting mercury from cinnabar that often contains less than 1 percent of mercury has not only required vast amounts of ore, but also large quantities of biomass fuel from areas around the largest mercury mines. Data on mercury mining are uncertain; Lars Hylander and Markus Meili (2003) estimate that nearly 1 million tonnes of mercury have been extracted throughout history.

People have moved mercury from geological reservoirs both intentionally and unintentionally, and for many different reasons. Much of the early mercury extracted from cinnabar was used in other mining operations to produce gold and silver; mercury is still used in the artisanal and small-scale gold mining (ASGM) sector today (see chapter 7). *Producers and consumers of goods* relied on mined and recycled mercury for millennia: in ancient to modern medicines (see chapter 4); in a variety of products such as thermometers, paints, pesticides, and batteries; and in several mercury-based manufacturing techniques to help produce other goods such as mirrors, hats, and chemicals (see chapter 6). *Producers and consumers of energy* have unintentionally discharged mercury present in trace amounts in other *extracted geological materials containing mercury* into the environment. A substantial fraction of mercury emissions from such geological material has come from burning coal, but industrial processes such as metal smelting and cement production have also resulted in mercury emissions and releases (see chapter 5).

Mercury in commerce has been traded since at least Roman times. Elemental mercury has been measured and priced on *mercury markets* since 1927 using a common but unique unit—a 76-pound flask. The exact origin of this specific measurement unit is unclear, but mercury sellers and buyers likely first used this distinctive flask in the Almadén mine in Spain (Myers 1951). Mercury flasks come in different shapes, but they are typically made of welded steel, have a screw cap, and are roughly the size of a two-liter container. In metric units, a 76-pound flask equals 34.5 kilograms, and 29 of those flasks make up a tonne (Brooks 2012). The total quantity of mined and sold mercury that is under human control today is unknown. A report by the United Nations Environment Programme (UNEP) that quantified best estimates of the total amount of mercury supply, demand, and trade in 2015 did not include statistics for *mercury in stockpiles and landfills* or mercury accumulated in society (comprising the amount of mercury in *mercury-added products* and *mercury in production processes*) because reliable data were unavailable (UNEP 2017).

Knowledge of the different *forms of mercury* and their behavior is relevant to understanding mercury cycling in both the environment and in commerce. *Properties of mercury* have been discovered over time, and have important implications for how different forms can be used and for analyzing environmental flows and impacts on living organisms. Elemental mercury exists on its own, both in liquid form and as a gas. It is the only metal in the periodic table that is liquid at room temperature. This unique property gave mercury its moniker “quicksilver” as well as its chemical symbol Hg, which refers to hydrargyrum, or “water-silver” in Greek. Elemental liquid mercury is highly volatile. Left on its own in open air, it readily evaporates into the gas phase. Gaseous elemental mercury, the predominant form of mercury found in the atmosphere, is both colorless and odorless, and therefore difficult to detect without advanced measuring equipment. In aquatic systems, mercury can be present as dissolved gaseous mercury, which is predominantly composed of elemental mercury.

Mercury compounds involve atoms of mercury that are bound to atoms of other chemical elements that can only be separated by chemical reactions. Mercury compounds exist in two categories, inorganic (not containing carbon) and organic (carbon-containing). Elemental mercury is also inorganic, as it does not contain carbon. Some mercury compounds exist naturally in the environment, but scientists in laboratories have synthesized additional ones. Cinnabar, or mercuric sulfide, from which most commercially traded elemental mercury is extracted, is a solid and relatively stable inorganic mercury compound in the Earth’s crust. Mercurous chloride (Hg_2Cl_2), another naturally occurring solid inorganic mercury compound, is sometimes referred to as calomel. Various other inorganic mercury compounds can be found in freshwater, oceans, and soils. Organic mercury compounds include methylmercury ($[CH_3Hg]^+$) and dimethylmercury ($(CH_3)_2Hg$). These are present in aquatic systems and in biota. Other organic forms, such as ethylmercury ($C_2H_5Hg^+$) and phenylmercury (C_6H_5Hg), are largely commercially produced.

Levels of mercury in the environment, in animals, and in people increased rapidly following the onset of industrialization (AMAP 2011). Estimates of the total amount of mercury present in the global atmosphere, oceans, and soils today vary dramatically: a 2018 global mercury assessment conducted by UNEP estimated this number at just under 500,000 tonnes (UNEP 2019), but other estimates range as high as 1.5 million tonnes (Obrist et al. 2018). Much of this mercury originated from anthropogenic sources (Amos et al. 2013; N. E. Selin 2014). The amount of mercury in the atmosphere (4,400 to 5,300 tonnes) is reasonably well known; this amount is estimated to have increased, due to pre- and postindustrial human activities, by a factor of 5 or more (Amos et al. 2013; Outridge et al. 2018). Estimates of the total amount of mercury in the oceans range from 270,000 to 450,000 tonnes. This amount has increased by up to a factor of 2.8 due to human activities, and the amount in the surface ocean may have increased by up to a factor of 6 (Amos et al. 2013). Human activities may have increased the amount of mercury in terrestrial soils by 20 to 50 percent; current estimates of total mercury in soil range from 250,000 to 1 million tonnes (Obrist et al. 2018). Mercury is also present in *terrestrial and aquatic ecosystems* and in *living organisms* such as fish, birds, and marine mammals, as well as in people.

Estimates of mercury's global biogeochemical cycle attempt to quantify the amount of mercury that is present in and travels through the global environment, and the relative influence of human and natural activities. Biogeochemical cycle analyses evaluate how substances transport and transform through biological systems (living things, including plants and animals), geological processes (such as fossil fuel formation and plate tectonics), and chemical reactions (changing the chemical composition of specific substances). See figure 3.2 for an example of a global biogeochemical cycle diagram for mercury. Biogeochemical cycle estimates are constructed by combining measurement data and models, but many relevant environmental processes are uncertain, and data are lacking for some time periods and regions. As noted above, a major area of uncertainty is how much anthropogenically discharged mercury cycles globally versus mercury that remains locally. David G. Streets and colleagues (2017) calculated that 1.5

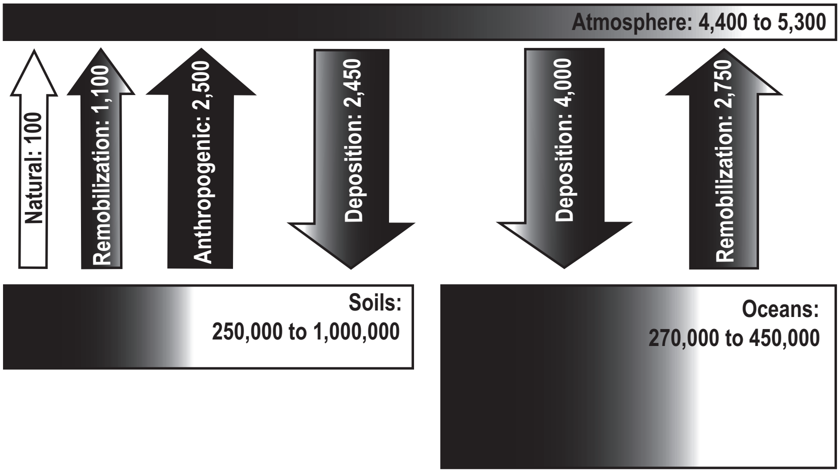


Figure 3.2
Global biogeochemical cycle for mercury. Quantities in boxes (tonnes) and fluxes in arrows (tonnes/year), drawing from Amos et al. (2013), Selin (2014), Obrist et al. (2018), and UNEP (2019). Shaded regions indicate approximate fractions of anthropogenic contribution.

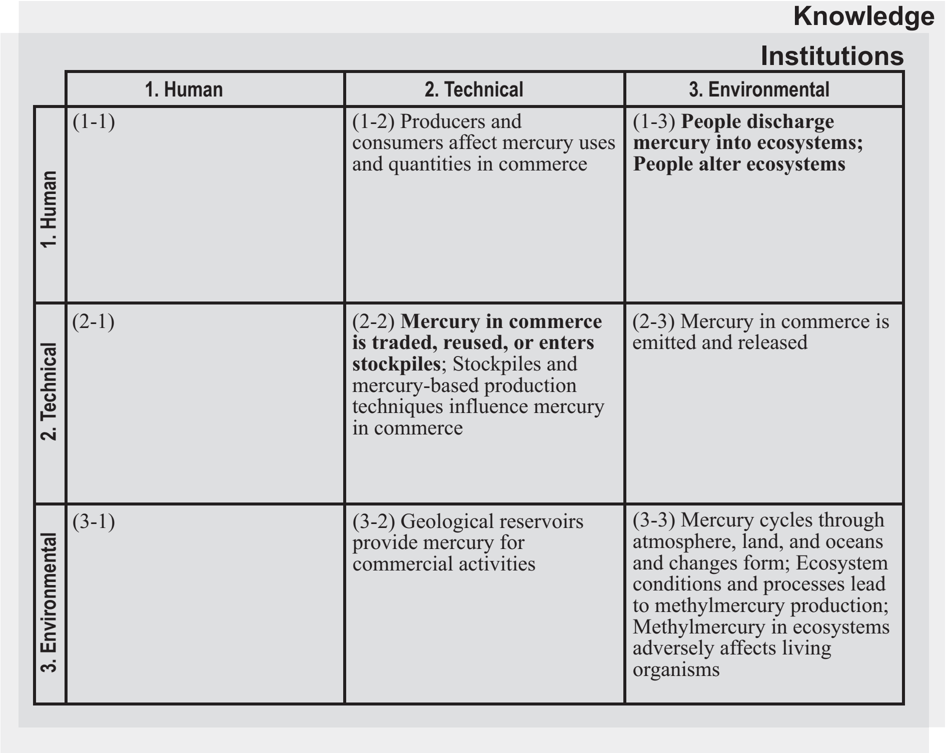
million tonnes of mercury have been discharged into the environment by anthropogenic activities over time, of which 30 percent was emitted to the atmosphere and 70 percent released to land and water. They estimated that 40 percent (390,000 tonnes) of those historical land and water releases are sequestered in sediments or at contaminated sites and do not cycle globally. Other estimates of total mercury entering the global biogeochemical cycle as a result of human activities are much lower: the 2018 global mercury assessment attributes only 79,000 tonnes in the global biogeochemical cycle to anthropogenic activities (Outridge et al. 2018; UNEP 2019).

Scientific knowledge that some forms of mercury undergo *long-range transport* in the environment emerged in the 1970s with the discovery of *mercury concentrations in the environment* in areas far from emission sources. Knowledge about environmental transport and levels of mercury at a global scale evolved somewhat separately from the development of information on the *quantities of mercury in stockpiles and trade*. A recently published study, however, combined information on product flows with environmental releases to quantify the mercury flows addressed by articles of the Minamata Convention (Selin et al. 2018). Other efforts have attempted to assess the quantities of mercury flowing through society, largely with the goal of better quantifying releases to the environment from different sources in selected countries through substance flow analyses (Sznopek and Goonan 2000; Cain et al. 2007). The societal circulation of mercury results from supply and demand dynamics on international and domestic mercury markets as well as trade in mercury-added products. Some work on tracing mercury flows in society has also been carried out at national and sub-national scales (Hui et al. 2016; Svidén and Jonsson 2001).

International institutions began to address mercury as a pollutant in the 1970s (Selin and Selin 2006). The Organisation for Economic Co-operation and Development (OECD) issued a recommendation to its member states in 1973 to reduce anthropogenic discharges of mercury to the lowest levels possible. Countries developed several *regional treaties* starting in the 1970s that addressed releases of mercury into bodies of water in Europe and North America. European and North American countries in 1998 adopted a heavy metals protocol that included mercury under the Convention on Long-Range Transboundary Air Pollution (CLRTAP). Global political efforts to address mercury problems gained momentum in the early 2000s, largely in the form of voluntary collaboration under UNEP's *Global Mercury Partnership* program (Sun 2017). This still-active program brings together national governments and other stakeholders to build and diffuse knowledge about the risks of mercury and the availability of mercury-free alternatives. The negotiations for the *Minamata Convention* began in 2010, and the treaty was adopted at the diplomatic conference in Kumamoto, Japan, in October 2013 (as mentioned in chapter 1). It entered into force in 2017, and by early 2020, 117 countries and the European Union (EU) had become parties. In addition, several countries have instituted *trade controls* on mercury in commerce, regulating exports as well as imports.

Interactions

Much of the mercury that people have extracted from geological storage continues to cycle through society and the environment. Figure 3.3 shows interactions in the system for global mercury cycling: we have selected three interactions in that matrix (the items in bold type in boxes 1-3 and 2-2) to focus on in this section; we then trace the pathways that influence them, which we summarize in figure 3.4 (where the bold boxes correspond



	1. Human	2. Technical	3. Environmental
1. Human	(1-1)	(1-2) Producers and consumers affect mercury uses and quantities in commerce	(1-3) **People discharge mercury into ecosystems; People alter ecosystems**
2. Technical	(2-1)	(2-2) **Mercury in commerce is traded, reused, or enters stockpiles**; Stockpiles and mercury-based production techniques influence mercury in commerce	(2-3) Mercury in commerce is emitted and released
3. Environmental	(3-1)	(3-2) Geological reservoirs provide mercury for commercial activities	(3-3) Mercury cycles through atmosphere, land, and oceans and changes form; Ecosystem conditions and processes lead to methylmercury production; Methylmercury in ecosystems adversely affects living organisms

Figure 3.3
Interaction matrix for the global mercury cycling system.

to the selected interactions). First, people discharge mercury into ecosystems (box 1-3), and the mercury then undergoes global biogeochemical cycling through the atmosphere, land, and oceans and changes form (box 3-3). Second, people alter ecosystems (box 1-3), leading to changes in mercury cycling and methylmercury production (box 3-3). Third, mercury in commerce is traded, reused, or enters stockpiles (box 2-2), as its supply is affected by geological availability and market interactions, and this mercury can subsequently be emitted and released to the environment (boxes 3-2, 2-2, and 2-3).

Mercury Discharges and Global Biogeochemical Cycling

People have discharged mercury into ecosystems (box 1-3), thus altering the global biogeochemical cycle of mercury. These mercury discharges

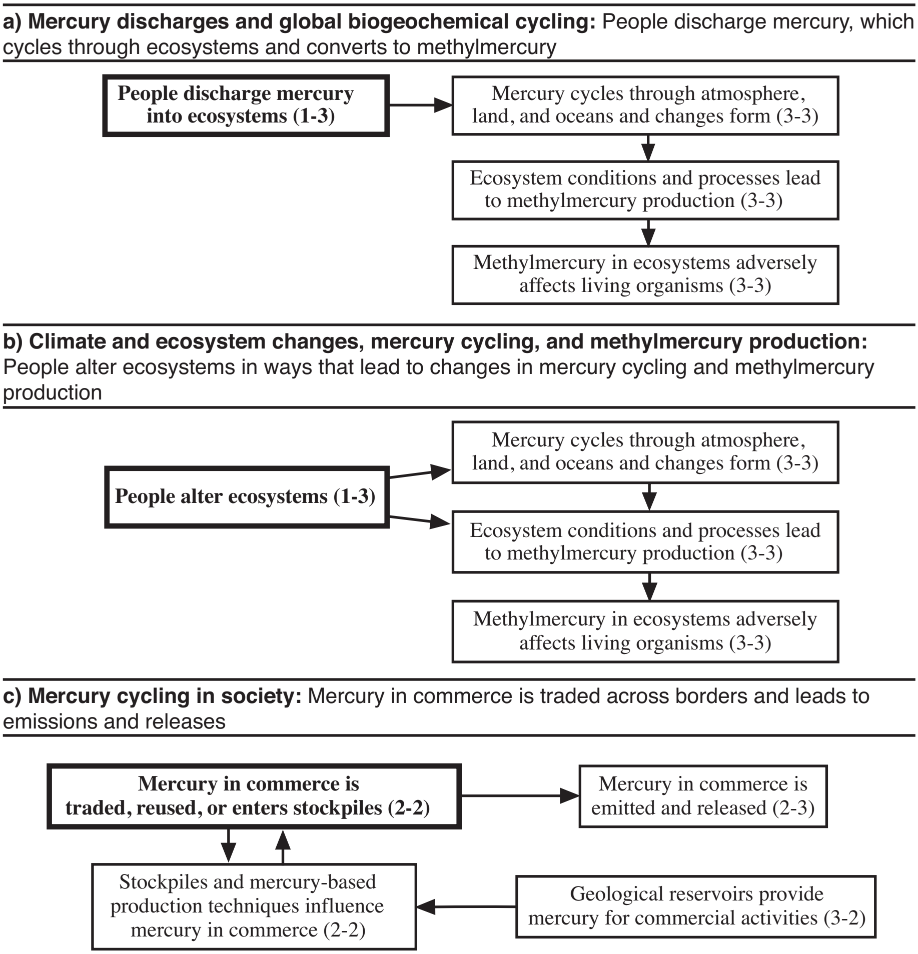


Figure 3.4

Pathways of interactions for the global mercury cycling system. Bold boxes indicate the selected interaction for the subsections below.

have occurred in several different ways, including through primary mercury mining, the use of mercury in gold and silver mining, the burning of coal, the loss of mercury from mercury-added products and industrial production processes, the failure to properly manage mercury in stockpiles and landfills, and the unsafe disposal of mercury and mercury-containing wastes. This anthropogenically discharged mercury, together with mercury that is emitted and released from natural sources, then cycles through the atmosphere, land, and oceans. Some of this mercury changes its form through chemical and biological processes during this cycling (box 3-3).

Scientists initially considered mercury a local pollution and exposure problem. In the 1970s, researchers made the first measurements of mercury in areas remote from anthropogenic point sources. Researchers who measured mercury in Greenland attributed increasing concentrations in glacial ice to human sources (Weiss et al. 1971), although another study conducted in Greenland a few years later found no evidence of anthropogenic increases (Weiss et al. 1975). Early mercury measurements were later found to have major contamination problems (Boutron et al. 1998). Nevertheless, in 1969, Göran Löfroth and Margaret E. Duffy (1969, 17) noted: "Mercury, like lead and the organochlorine pesticides, may turn out to be a global pollutant." This, however, was not a widely accepted conclusion at the time. A 1972 report of the Joint Food and Agriculture Organization/World Health Organization (FAO/WHO) Expert Committee on Food Additives stated: "The sources of direct pollution due to man's activities can have only local effects on the mercury levels found in fish, e.g., in estuaries and coastal areas. The largest reservoir of mercury is the open seas, and is not appreciably affected by pollution caused by man" (Joint FAO-WHO Expert Committee on Food Additives 1972, 12).

Scientists and policy-makers became increasingly aware by the late 1980s that mercury pollution could travel on a global scale before depositing into terrestrial and aquatic ecosystems. Studies of the human influence on mercury's biogeochemical cycle relied on growing evidence from environmental archives such as ice cores, peat bogs, and lake sediments. These studies were made possible by the development and increased use of ultraclean analytical procedures for trace metal analysis (Vandal et al. 1993; Fitzgerald et al. 1998). The first International Conference on Mercury as a Global Pollutant was held in 1990, in Gävle, Sweden, reflecting growing scientific agreement on mercury's global reach. Yet, some scientists in the late 1990s still debated whether the presence of mercury in remote areas was a result of human activities or of natural geological processes (Fitzgerald et al. 1998; Rasmussen 1998). A 2002 global mercury assessment synthesized the scientific literature and conclusively deemed mercury a matter of global-scale concern as a result of long-range transport and its potential hazardous impacts on the environment and human health (UNEP 2002).

The 2018 global mercury assessment estimated that human activities emitted roughly 2,500 tonnes of mercury to the air in 2015 (UNEP 2019). Global mercury emissions increased by 20 percent between 2010 and 2015 because of a growth in emissions in every region except Europe and North America. The 2,500 tonnes equaled about a third of total mercury emissions to air in 2015. Twice that amount, or about 5,000 tonnes, came from environmental processes that cycle previously released mercury from both anthropogenic and natural sources. These are sometimes referred to as legacy emissions. An additional (small) amount is from present-day natural sources, such as volcanoes and other geological processes. Emissions to air are generally considered to cycle globally.

Releases of mercury to water and land are less well quantified than emissions to air. Releases from ASGM to water and land together were estimated to total 1,220 tonnes in 2015 (UNEP 2019). Other mercury releases to water that researchers are able to quantify are from the mining sector, municipal sewage systems, leaks from mercury-added products, and wastewater from coal-fired power plants and coal washing; these sources totaled 580 tonnes in 2015. This inventory is incomplete, however, as data are lacking for additional sources. There are particularly high uncertainties regarding estimates for mercury releases to land beyond the combined estimate for ASGM to water and land. A very rough estimate put anthropogenic releases of mercury into soils at between 7,000 and 8,000 tonnes in 2015 (UNEP 2019). Large-scale mining and production of minerals such as gold and zinc, which shift large amounts of soil from one place to another, caused much of this release. Mercury-added products going into solid waste streams also add mercury to soils. It is unknown what fraction of present-day releases stays locally in soils compared to what enters waters and the air, and thereby adds to the global biogeochemical cycle.

Mercury in the atmosphere can travel longer or shorter distances, depending on its form. Much mercury is emitted as elemental mercury. Current research estimates that elemental mercury may stay in the atmosphere for an average of six months to a year before it returns to the surface (Horowitz et al. 2017). That is enough time for winds to carry it around the entire globe—a year is the average time that air takes to circulate between the Northern and Southern Hemispheres (Jacob et al. 1987). Elemental mercury lasts so long in the atmosphere mostly because it is relatively insoluble in water and does not get taken up into rainfall. But elemental mercury can settle out of the atmosphere through dry deposition (Jiskra et al. 2018). Some elemental mercury undergoes chemical reactions in the atmosphere that transform it into the more soluble form of gaseous oxidized mercury, which can then either more easily rain out or undergo dry deposition. The specific chemical composition of gaseous oxidized mercury, however, remains unknown (Jaffe et al. 2014). A fraction of the mercury emitted from anthropogenic sources is already in its soluble form, which can be attached to atmospheric particulate matter; these forms of mercury can deposit nearer to sources (tens to hundreds of kilometers).

Mercury continues to cycle among the atmosphere, oceans, and land long after it first enters the environment. Mercury falling out of the atmosphere through wet and dry deposition is taken up by land or water surfaces, where some of this mercury changes its form again in terrestrial and aquatic ecosystems. Because mercury is such a volatile substance, it can return from land and surface waters to the atmosphere as elemental mercury, and start the biogeochemical cycle all over again. In addition to its transport through the atmosphere, mercury moves from place to place with rivers and ocean currents, both across regions and between surface and deeper waters. Vertical transport of mercury to the intermediate and deep ocean occurs on timescales of decades to centuries. Returning to preindustrial levels of mercury in the atmosphere, oceans, and land would take centuries to millennia if anthropogenic emissions and releases stopped completely because the only way environmental processes can truly get rid of this legacy mercury is through burial in sediments, an extremely slow process (Selin 2009).

Specific ecosystem conditions and processes lead to the production of methylmercury (box 3-3). Only a small fraction of the elemental mercury that cycles through the environment is converted into methylmercury. This process largely occurs in aquatic environments lacking oxygen where bacteria transform inorganic mercury into methylmercury. The bacteria that do this share a common gene cluster, and include sulfate-reducing bacteria, iron-reducers, and methanogens (Hsu-Kim et al. 2018). Methylmercury, which is much more toxic than elemental mercury at low concentrations, bioaccumulates and biomagnifies in living organisms. (“Bioaccumulation” refers to the net accumulation of a substance over time in an individual organism from different sources. “Biomagnification” is the progressive buildup of a substance at successively higher levels of a food web.) Concentrations of methylmercury in ecosystems can consequently reach high levels that adversely affect living organisms (box 3-3). Methylmercury is taken up in multiple organs, including the brain, kidneys, and liver (Wolfe et al. 1998; Eagles-Smith et al. 2018). The highest risks are faced by top predators, which in many cases are humans and other large mammals, but can also be predatory birds and fishes (Scheuhammer et al. 2007).

Effects on wildlife are similar to—and maybe even greater than—those seen in humans (European Environment Agency 2018). (We discuss human health impacts in chapter 4.) Researchers base their knowledge of wildlife effects largely on laboratory studies, but have also observed some effects in the wild (Evers et al. 2008). At high exposure levels, fish can die, which happened in Minamata Bay. Non-lethal exposure levels can affect fish growth and their ability to reproduce (Depew et al. 2012). Swedish researchers trying to understand abnormal neurological signs in fish-eating birds in the late 1960s were among the first to identify wildlife impacts of methylmercury (Clarkson and Magos 2006). Exposure remains widespread; for example, 40 percent of the surface water bodies in Europe contain levels of mercury that exceed EU guidance intended to protect fish-eating birds and mammals from adverse effects (European Environment Agency 2018). Many Arctic species have methylmercury concentrations that may damage their health, including polar bears and whales (AMAP 2018). These impacts occur in the context of other stresses, including habitat loss, climate change, hunting, and infectious diseases.

Climate and Ecosystem Changes, Mercury Cycling, and Methylmercury Production

People alter ecosystems in multiple ways (box 1-3). These alterations influence the transport and distribution of mercury and the conditions for methylmercury production. That is, people's interactions with the environment can affect the environmental cycling of mercury even where those interactions do not directly involve mercury use or discharges. Human activities that alter ecosystems change how mercury cycles through the atmosphere, land, and oceans, and also affect the biological and chemical processes that convert mercury between its different forms (box 3-3). This means that even if people stopped discharging mercury into the environment, human activities would continue to influence the ways in which mercury cycles through it. Human impacts on the environment are increasing in the context of industrialization and a rapidly urbanizing population, and are changing landscapes, affecting biodiversity, and altering the global climate system. Human-driven change will remain a major influence on global mercury cycling in the future (Obrist et al. 2018).

Human-induced land use changes such as deforestation and infrastructure development have altered land surfaces and their characteristics, influencing the biogeochemical cycling of mercury (Hsu-Kim et al. 2018). Changing land use influences how, where, and when different forms of mercury, often after long-range atmospheric transport, enter ecosystems, both through wet and dry deposition. Wildfires, which people can set intentionally and unintentionally, move mercury from terrestrial ecosystems into the atmosphere. Changes in the frequency and scope of wildfires can alter not only the amount of mercury that is emitted, but also the movement of mercury within ecosystems that are affected by fire (Kumar et al. 2018). Any process that creates soil erosion, such as vegetation removal and road construction, can lead to runoff of mercury from land, increasing mercury concentrations in streams and rivers (Hsu-Kim et al. 2018). Studies have shown, for example, that converting forested land to agricultural use can cause mercury to be released from soils and enter waterways (Kocman et al. 2017).

People alter environmental processes in ways that make ecosystem conditions and processes more or less favorable to producing methylmercury (box 3-3). In turn, this methylmercury in ecosystems adversely affects living organisms (box 3-3). The building of hydroelectric dams, for instance, creates aquatic environments where biological production of methylmercury can increase (Friedl and Wüest 2002). Burning coal and other fossil fuels increases deposition of sulfates to aquatic ecosystems, fueling the activity of bacteria that convert other forms of mercury into methylmercury (Gilmour et al. 1992). Where human activities affect organisms such as plankton, this can lead to changes in mercury bioaccumulation that propagate through food webs (Krabbenhoft and Sunderland 2013). Changes in the input of terrestrial organic matter and nutrients to aquatic ecosystems, for example, can alter the processes by which methylmercury is taken up by plankton (Jonsson et al. 2017). Other actions such as harvesting of seafood can alter the structure of food webs and affect wildlife and human exposure to methylmercury (Eagles-Smith et al. 2018). One study calculated that because of changes in food webs related to overfishing, Atlantic cod ate a diet higher in methylmercury in the 2000s than they did in the 1970s, resulting in a 23 percent increase in their methylmercury concentrations (Schartup et al. 2019).

Human-induced climate change, a central driver of ecosystem change, leads to changes in mercury cycling and methylmercury production (Obrist et al. 2018). Climate change increases the frequency and intensity of wildfires, which as mentioned above can lead to increased emissions of historically deposited mercury from land. Many other processes that control the remobilization of historically discharged and naturally occurring mercury from land, oceans, and contaminated sites are temperature-sensitive, and are thus affected by rising global, regional, and local temperatures. Permafrost contains a large amount of mercury, some of which may be emitted to the atmosphere when it melts (Schuster et al. 2018). The loss of sea ice in polar regions may increase the amount of mercury that cycles between the oceans and the atmosphere, because ice prevents sea-air exchange of mercury (UNEP 2019). Climate-induced changes also affect ocean ecosystems. For example, changes in temperature and ocean dynamics influence mercury cycling, and changes in the productivity of ecosystems affect methylmercury production. In addition, climate change affects food web structures by changing the presence and health of species, altering patterns of methylmercury production and bioaccumulation.

Mercury Cycling in Society

A biogeochemical cycling perspective focuses on the ways in which mercury transports and transforms in the environment, but mercury in commerce also cycles as it is traded, reused, or enters stockpiles (box 2-2). UNEP estimated that total global demand for commercial mercury in 2015 was 4,720 tonnes. This mercury demand covered a range of uses in products (31 percent), industrial processes (32 percent), and ASGM (37 percent) (UNEP 2017). Some, but not all, of this mercury is included in global inventories of emissions and releases once it enters the environment. Global mercury trade still shifts large quantities of mercury across societies, though this trade has recently declined: exports of mercury reported in 2015 totaled just over 1,300 tonnes, a 2.5-fold decrease since 2010 (UNEP 2017). However, official trade data are incomplete, and some mercury is also traded illegally. The uncertainty in how much mercury is traded or remains in mercury stockpiles underscores the importance of better tracking commercial mercury as well as the difficulty in quantifying its magnitude and impact.

During much of human history, primary mining of cinnabar from geological reservoirs provided mercury for commercial activities (box 3-2). Starting in the 1800s, as mercury use increased with its growing application in products and industrial processes, more commercially available mercury came from reuse. Only about a third of mercury demand in 2015 was sourced from primary mining, with the rest coming from recovery and recycling, the production of mercury as a byproduct of other mining, and the drawdown of stockpiles (UNEP 2017). Roughly half of all of the demand of commercial mercury occurred in East and Southeast Asia. China was the world's largest producer of mined mercury in 2018 with an estimated 3,000 tonnes, representing 88 percent of globally mined mercury (US Geological Survey 2019). Most of the mercury mined in China was used domestically in industry. Primary mercury mining also occurred in the Kyrgyz Republic, largely intended for export to other countries. Previously closed mercury mines were recently illegally reopened in Mexico and Indonesia (UNEP 2017).

Historical changes in the demand and supply of mercury have resulted in large global price fluctuations and changes in the flows of elemental mercury in commerce. Mercury has been traded internationally for millennia, but mercury exports and imports increased sharply together with a growth in its industrial use. During the first half of the twentieth century, the international price of mercury spiked during both World War I and World War II (see figure 3.5). Some mercury uses during these wars were for purposes such as making explosives, but the 1943 US minerals yearbook noted that the principal use of mercury in wartime, like peacetime, was for manufacturing pharmaceuticals, and it reported sharp increases in mercury consumption for this purpose that year due to "the Army's large requirements for prophylactics and antiseptics" (Meyer and Mitchell 1945, 719). Coupled with disruptions in imports from major supply centers in Europe, the increased demand by the US military drove a sharp increase in the price of mercury (Meyer and Mitchell 1941). The modern price of mercury peaked in 1965. Commercial mercury use was at its highest in the 1970s (Horowitz et al. 2014). Reductions in mercury use and growing awareness of mercury as an environmental pollutant led to a strong decline in the global market price of mercury between 1970 and the early 2000s.

Increased demand and trade controls in the early 2000s changed the dynamics of the global mercury market. The price increase starting in 2003 was in large part driven by a growth in ASGM. Anticipation and implementation of bans the EU and the United States placed on elemental mercury exports, which were adopted in 2008 and came into effect in 2011 and

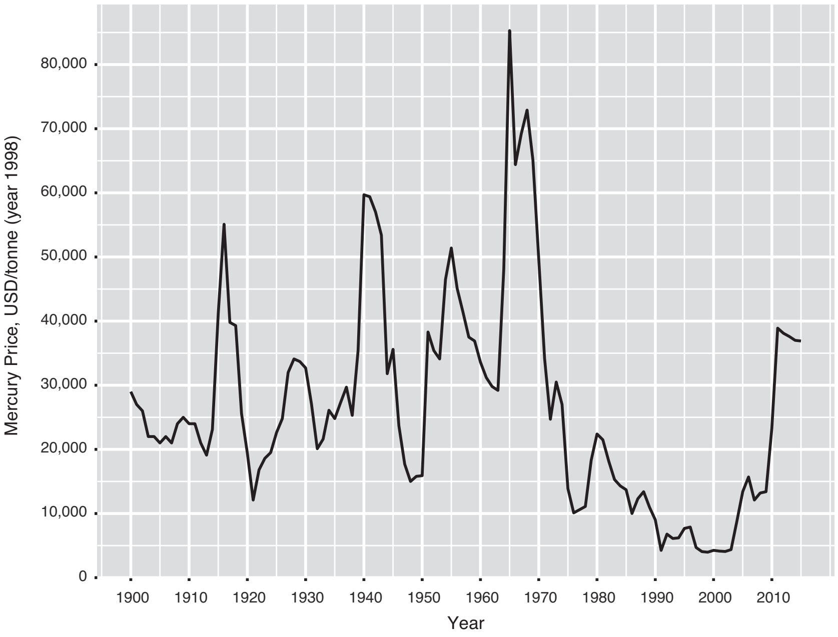


Figure 3.5
Global mercury price, given in USD per tonne in 1998 dollars. *Data source*: US Geological Survey (2014).

2013, respectively, also affected mercury prices (Wilburn 2013). Because of these export bans as well as other trade restrictions instituted by a growing number of countries, there is no longer a globally uniform price for mercury, but rather several different markets. The current price of mercury is relatively low and stable in the EU and the United States, because in both of these closed markets demand is lower than supply. In contrast, mercury prices are higher in other places as a result of restricted supply and continuing demand mainly in the ASGM sector. After the EU and the United States export bans, other places emerged as major mercury trading hubs, including Hong Kong and Singapore (UNEP 2017).

Changes in the dynamics of mercury markets influence the supply and global distribution of mercury. This includes the presence of mercury stockpiles as well as the use of mercury-based production techniques, which influence the amounts of mercury in commerce (box 2-2). Much of the short-term increase in exports from the EU and the United States in the late 2000s and early 2010s—before their export bans on elemental mercury took effect—came from the decommissioning of old chlor-alkali plants that had used large quantities of mercury (see more about the process of chlor-alkali production in chapter 6). Some of this excess mercury made its way, both legally and illegally, to developing countries for use in the ASGM sector, as did the excess mercury from other countries experiencing a simultaneous decline in industrial mercury demand. Many countries also have mercury import bans, or restrict imports to specifically approved uses. The amount of mercury trade that occurs outside legal channels is difficult to document, but has likely increased concurrently with the decrease in legal mercury trade since 2010 (UNEP 2017). Illegal primary mining of mercury, particularly in Indonesia and Mexico, has also increased as a result of the growing demand for mercury in ASGM coupled with tighter restrictions on supply and export in the 2010s.

Much mercury in commerce is emitted and released to the environment (box 2-3). One estimate is that 540,000 tonnes of commercial mercury has entered the environment since 1850 (Horowitz et al. 2014). Some of this mercury was likely in forms that neither cycle further in the global environment nor form methylmercury, but this is still a much larger amount than some estimates of the anthropogenic contribution to the global biogeochemical cycle (underscoring the high degree of uncertainty in much mercury data). Discharges can occur shortly after its initial use, as in the case of ASGM, or after a time lag, for example after a mercury-added product such as a thermometer is discarded at the end of its useful life. Just over half of all global mercury demand in 2015 (2,490 tonnes of the total demand of 4,720 tonnes) was estimated to be discharged into the environment directly after its initial use (UNEP 2017). Nearly 70 percent of this discharged mercury came from ASGM. Of the remainder, 600 tonnes were from mercury used in industrial processes, and 150 tonnes originated from commercial products.

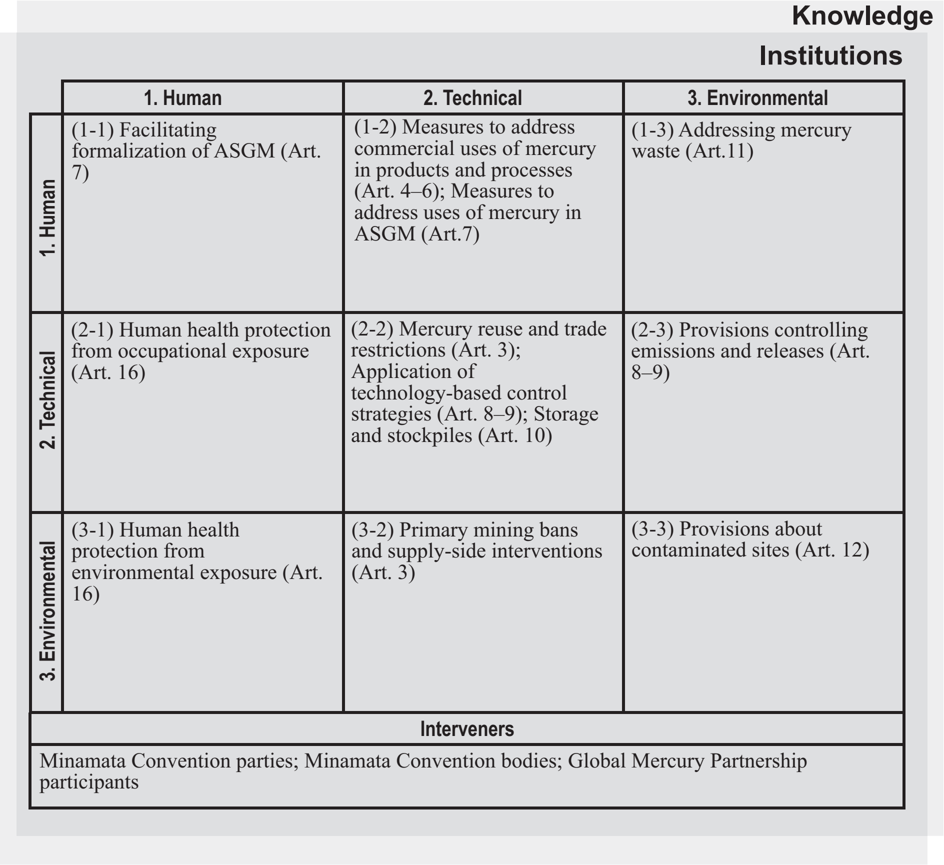
Interventions

The Minamata Convention, the primary global-scale intervention addressing mercury, is the outcome of scientific and political processes that date back to a UNEP Governing Council decision in 2001 to launch the global scientific assessment of mercury completed in 2002. The resulting assessment report published a year later concluded that there “was sufficient evidence of significant global adverse impacts to warrant international action to reduce the risks to human health and/or the environment” (UNEP 2002, paragraph 139). This led Norway, Switzerland, and the EU to call for an international legally binding agreement on mercury (Selin and Selin 2006; Eriksen and Perrez 2014). Other industrialized and major developing countries including the United States, Canada, Japan, Russia, China, India, and Australia opposed treaty negotiations at that time. Several of these countries were reluctant to negotiate yet another global treaty on hazardous substances, having recently adopted the 1998 Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade and the 2001 Stockholm Convention on Persistent Organic Pollutants (POPs). In addition, some countries opposed international mercury controls impacting mining, industrial manufacturing, and the energy sector (H. Selin 2014).

As a compromise between countries that supported and opposed treaty negotiations, the UNEP Governing Council in 2003 launched an international voluntary program to reduce mercury pollution, and in 2005 created the Global Mercury Partnership program. Countries agreed at the UNEP Governing Council meeting in 2007 to establish a working group to assess options for enhanced voluntary measures and to explore the possible role of existing and new legal instruments. There was enough political support by 2009 to launch treaty negotiations on mercury; in particular, the new Obama administration's support for a new multilateral agreement was a major political trigger, causing first Canada and Australia and later India and China to remove their objections (H. Selin 2014). Treaty negotiations began in Stockholm in June 2010 and concluded in Geneva in January 2013 where, as we mentioned in chapter 1, organizers played Queen's "We Are the Champions" to celebrate the historic moment. Current parties to the Minamata Convention include the EU, larger political powers such as the United States, China, India, Canada, Brazil, Nigeria, Indonesia, and Japan, and many medium-sized and smaller countries in Africa, Asia, Europe, and Latin America.

The Preamble of the Minamata Convention, consistent with the first global mercury assessment as well as with more recent assessment reports, recognizes mercury as a chemical of global concern. As stated in Article I, the overall objective of the Minamata Convention is to "protect the human health and the environment from anthropogenic emissions and releases of mercury and mercury compounds." The treaty specifies a set of legal mandates that cover the entire lifecycle of production, trade, use, emissions, releases, handling, stockpiles, and disposal of mercury. When it comes to implementing its provisions, the individual parties that have joined the treaty hold ultimate responsibility: as with all international treaties under public international law, joining the Minamata Convention is voluntary, but implementation is obligatory for all parties. All parts of the Minamata Convention are legally binding for the parties, but some treaty provisions mandate action (using the directive "shall") whereas other provisions adopt a more persuasive tone (using words such as "should" or "may"). The Minamata Convention includes control provisions that address specific aspects of the mercury issue in Articles 3–12 and enabling provisions in support of treaty implementation in Articles 13–24 (Selin et al. 2018).

Figure 3.6 identifies interventions in the global mercury cycling system, focusing on Articles 3–12 and Article 16 of the Minamata Convention.



	1. Human	2. Technical	3. Environmental
1. Human	(1-1) Facilitating formalization of ASGM (Art. 7)	(1-2) Measures to address commercial uses of mercury in products and processes (Art. 4–6); Measures to address uses of mercury in ASGM (Art.7)	(1-3) Addressing mercury waste (Art.11)
2. Technical	(2-1) Human health protection from occupational exposure (Art. 16)	(2-2) Mercury reuse and trade restrictions (Art. 3); Application of technology-based control strategies (Art. 8–9); Storage and stockpiles (Art. 10)	(2-3) Provisions controlling emissions and releases (Art. 8–9)
3. Environmental	(3-1) Human health protection from environmental exposure (Art. 16)	(3-2) Primary mining bans and supply-side interventions (Art. 3)	(3-3) Provisions about contaminated sites (Art. 12)

Interveners

Minamata Convention parties; Minamata Convention bodies; Global Mercury Partnership participants

Figure 3.6
Intervention matrix for the mercury global cycling system.

The figure's bottom row identifies interveners: Minamata Convention parties, Minamata Convention bodies, and Global Mercury Partnership participants. The control provisions in Articles 3–12, together with Article 16, address nearly all aspects of the interaction pathways described in figure 3.4. In the following section, we refer back to figure 3.6, first as we summarize how each of the main treaty provisions applies to the aspects of the mercury issue that we examine in this and the next four chapters, and then as we discuss the provisions in the Minamata Convention on knowledge and institutions. We omit the additional enabling provisions found in Articles 13–15 and 17–24 from the intervention matrix in figure 3.6 because they address knowledge and institutional components that affect the entire mercury global cycling system.

Provisions Addressing Mercury in Human-Technical-Environmental Systems

The Minamata Convention sets up several supply-oriented controls in Article 3 by addressing primary mining of, reuse of, and trade in mercury (boxes 3-2 and 2-2). The treaty prohibits the opening of new mercury mines, although parties with operating mercury mines may continue mining for up to 15 years after becoming a party. Historically large mercury mines in Idrija and Almadén had been closed in 1995 and 2002, respectively. China, by far the country with the most continuing primary mercury mining, announced in 2017 that it would prohibit primary mercury mining in existing mines in 2032. The only major legal exporting mine still operating when treaty negotiations began was the Khaidarkan mine in the Kyrgyz Republic, which generated roughly 250 tonnes of mercury in 2009 (Brooks 2011). The government of the Kyrgyz Republic in the late 2000s announced its intention to close the mercury mine in return for outside financial and technical assistance (Earth Negotiations Bulletin 2010). The mine, however, still produced an estimated 20 tonnes of mercury in 2018 (US Geological Survey 2019), and the Kyrgyz Republic had not yet become a party to the Minamata Convention by early 2020.

Article 3 mandates that parties identify individual mercury stocks exceeding 50 tonnes, and mercury supply sources generating over 10 tonnes per year. It prohibits the reuse of excess mercury from chlor-alkali facilities, the largest secondary source of mercury. The Minamata Convention bans the export of elemental mercury from one party to another unless it is intended for a use that is allowed under the treaty or for environmentally sound interim storage. The permitted trade in elemental mercury is governed by a prior informed consent (PIC) scheme. Under this PIC scheme, the government of a firm seeking to sell mercury to a buyer in another country must receive written approval from the government of the importing country before the trade can proceed. Parties are only allowed to export elemental mercury to non-parties that have measures in place to protect human health and the environment, and that follow treaty provisions on allowed uses, storage, and disposal. Parties can only import elemental mercury from a non-party if that country provides guarantees that the mercury comes from a source allowed under the treaty.

Minamata Convention parties that have enacted policies going beyond the treaty's trade provisions have further influenced societal flows of mercury. Sweden took on a leading role when it banned elemental mercury exports in 1997. As noted above, the EU and the United States both adopted elemental mercury export bans in 2008. The EU ban entered into force in 2011 and the US ban took effect in 2013. The United States in 2016 and the EU in 2017 expanded their bans to include mercury compounds (not addressed by the Minamata Convention PIC scheme). The United States banned the export of several mercury compounds as of 2020, and the EU's ban was implemented stepwise in 2018 and 2020. Many other parties also strengthened their export provisions in the 2010s as part of implementing the Minamata Convention, but some stopped short of total bans. For example, Switzerland announced in 2017 that it would allow export of elemental mercury for dental amalgam for another decade (Carey 2017). In addition, a growing number of countries have elected to ban all imports of mercury, or restrict it to a few uses such as in dentistry.

The Minamata Convention has a clear focus on human health protection in its overall objective, as well as under Article 16 on health, which deals with both environmental exposure (box 3-1) and occupational exposure (box 2-1). Implementing the treaty provisions would contribute to the protection of human health in varying ways. The preamble notes that mercury poses health concerns for vulnerable populations—especially women, children, and also future generations—particularly in developing countries. Under Article 16, parties are encouraged to promote the development and implementation of strategies to identify populations at risk from mercury exposure based on different exposure routes across different groups of people, countries, and regions. Parties are urged to promote the availability of health care services for the prevention, treatment, and care of populations who are affected by mercury exposure. Parties should establish and strengthen the institutional and professional capacities for the prevention, diagnosis, treatment, and monitoring of health risks from mercury. In chapter 4, we discuss human health aspects of the use of, and exposure to, elemental mercury and mercury compounds and related efforts to mitigate human health risks.

A major part of the Minamata Convention addresses mercury emissions to air and mercury releases to land and water. Articles 8 and 9 of the treaty introduce a set of mandates for parties to control mercury emissions and releases (box 2-3). These rely on technology-based control strategies (box 2-2) and are focused on large industrial point sources. Parties have some flexibility in defining and applying their own specific strategies to control emissions, but they are required to take action to address mercury emissions from both new and existing stationary sources for the purpose of controlling and, where feasible, reducing such emissions. Parties shall also identify and control releases from other relevant point sources that are not covered by the obligations for products, processes, and sources of air emissions. In chapter 5, we discuss mercury emissions to air from coal combustion and other industrial point sources, and examine efforts to address mercury emissions from such sources.

The Minamata Convention focuses on different areas of intentional mercury use that result in direct human exposure and environmental emissions and releases, including in commercial products and production processes, in Articles 4, 5, and 6 (box 1-2). Article 4 prohibits the manufacture, import, and export of nine mercury-added product categories, and states that parties should take steps to phase down the use of mercury in dental amalgam. Article 5 mandates the phase out of mercury use in two industrial processes and imposes mercury use restrictions in three others; 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. Parties can also apply for exemptions to phaseout dates for both products and processes under Article 6. Article 10 mandates that parties store and manage stockpiles of mercury in an environmentally sound manner (box 2-2). Article 11 addresses the disposal of mercury wastes (box 1-3). Article 12 requires that parties endeavor to develop strategies for identifying and assessing mercury-contaminated sites (box 3-3). We discuss the use of mercury in products and processes, its consequences (including for stockpiles and contaminated sites), and efforts to reduce and phase out such mercury use in chapter 6.

ASGM, an area of growing mercury use that leads to substantial environmental discharges and human health problems, is included in a separate article in the Minamata Convention. Under Article 7, parties with ASGM within their territory shall take steps to reduce (and where feasible eliminate) mercury use (box 1-2). They shall also take steps to reduce the emissions and releases of mercury in such activities. To this end, parties with "more than insignificant" ASGM are required to develop a national action plan. Among other things, such a plan must outline national objectives and reduction targets, actions to eliminate mercury-based amalgamation practices that are particularly damaging to the environment and human health, and strategies for promoting the reduction of emissions, releases, and human exposure to mercury. It must also include steps to facilitate the formalization of the ASGM sector (box 1-1). The parties that develop national action plans must submit them to the Secretariat, and every three years they also need to provide the Secretariat with progress reviews toward meeting their obligations under Article 7. In chapter 7, we discuss the ASGM and mercury issue, including different strategies for reducing mercury use, discharges, and exposure.

Provisions Addressing Institutions and Knowledge

The Minamata Convention identifies the Conference of the Parties (COP) as the treaty's supreme decision-making body (Article 23) and stipulates that the Secretariat, hosted by UNEP Chemicals in Geneva, provide administrative services to all treaty bodies and parties (Article 24). The treaty also establishes a committee to promote the implementation of, and review compliance with, articles and provisions (Article 15). The COP can create additional bodies, and has set up a governing board for the treaty-specific funding mechanism—the Specific International Programme—that provides financial support together with the Global Environment Facility (GEF). The Minamata Convention explicitly identifies the importance of the World Health Organization (WHO) and the International Labour Organization (ILO) in treaty implementation. Other international organizations that support implementation include UNEP, the United Nations Development Programme (UNDP), and the United Nations Institute for Training and Research (UNITAR). Continuing work under the Global Mercury Partnership also involves national governments and many different non-state organizations.

The Minamata Convention contains language on support geared to helping developing countries meet their treaty-based obligations in Articles 13 and 14. Article 13 defines the treaty-based mechanism for providing financial resources to developing countries. Pursuant to Article 14, parties shall cooperate to provide capacity-building, technical assistance, and technology transfer to developing countries. These treaty-based mandates are practically and politically important to developing-country parties, which may struggle with a lack of domestic resources or see the fulfillment of these obligations by wealthier countries as an important indication of their commitment to effective and equal treaty implementation. In addition, during negotiations, developing countries considered the inclusion of strong treaty language on financial support, capacity building, and technical assistance as necessary for agreeing to the establishment of the implementation and compliance committee (H. Selin 2014).

Several Minamata Convention articles relate to knowledge provision. Parties are required to facilitate the exchange of scientific, technical, economic, and legal information on a number of topics (Article 17). These topics include the reduction or elimination of the production, use, trade, emissions, and releases of mercury; on technically and economically viable alternatives for mercury use in products and processes as well as control measures; and on mercury-related health impacts. Parties are also required to promote and facilitate public information, awareness, and education about mercury (Article 18). They must endeavor to cooperate to develop and improve: inventories of use, consumption, emissions, and releases of mercury; scientific information on the environmental behavior and human impacts of mercury; information on commerce and trade in mercury and mercury-added products; and research on control techniques (Article 19). Parties may develop an implementation plan for the entire Minamata Convention if they deem that helpful for domestic purposes, but they must report on national measures and their effectiveness (Articles 20–21). The COP is tasked with carrying out periodic evaluations of the effectiveness of the Minamata Convention, with the first one beginning no later than six years after the treaty entered into force—which is 2023 at the latest (Article 22).

The provisions of the Minamata Convention affect broader efforts to promote sustainability, including those under the Sustainable Development Goals (SDGs) (UNDP 2016). Goal 3 (Good Health and Well-Being) focuses on protecting human health, where mercury is an important element of a suite of pollution problems. Goal 14 (Life below Water) targets marine pollution, as methylmercury threatens the well-being of both marine animals and humans who consume seafood or who are exposed in utero. Food consumption also connects to Goal 2 (Zero Hunger), as many less affluent people rely on fish for much of their food and nutrition intake. Goal 8 (Decent Work and Economic Growth) draws attention to safety in the workplace, where workers who come in contact with mercury are at risk. Goal 1 (No Poverty) is relevant to ASGM miners and others who are driven into mercury-using sectors by poverty. Goal 12 (Responsible Consumption and Production) puts a focus on reducing the negative environmental and human health impacts of the use of hazardous substances, including mercury. Goal 7 (Affordable and Clean Energy) highlights the challenge of coal burning, which leads to mercury emissions, as a source of energy and driver of climate change.

Insights

The South American colonial mining story that began this chapter illustrates how a systems view of global mercury cycling comprises not only the quantities and fluxes incorporated in assessments of mercury's biogeochemical cycle, but also societal flows, institutions, and knowledge. In this section, we examine insights from our analysis of the global mercury cycling system and illustrate some of the difficulties in chasing quicksilver in the environment and society. First, understanding important system dynamics requires considering a broad range of material and non-material connections. Second, it is difficult to define criteria for sustainability with respect to the global human-technical-environmental cycling of mercury, but incremental change is occurring. Third, the implementation and effectiveness of the Minamata Convention are shaped by the global human-technical-environmental cycling of mercury in the context of other efforts to govern sustainability.

Systems Analysis for Sustainability

A systems-level accounting for global-scale mercury cycling needs to consider mercury in the environment and society simultaneously. Focusing only on the biogeochemical cycle of mercury in the environment misses important societal and technical processes. Accounting for mercury's cycling in society alone, in contrast, omits the extensive cycling of mercury through the atmosphere, land, and oceans. Some studies suggest that the global environmental cycling of mercury from human activities goes back at least five centuries, but most mercury from anthropogenic sources has been discharged during the industrial era. The trade of mercury across societies accelerated with the start of the Spanish colonial mining in Latin America in the 1500s, and industrialization further increased its societal flows. Commercial mercury may be reused multiple times, and excess mercury can be stored before it is traded, used, and discharged into the environment. Discharged mercury connects near and distant ecosystems as well as human health harms through its environmental cycling, but data on the quantities and locations of mercury in society and in the environment are incomplete. The ability to better analyze global mercury cycling would be aided by further and more comparable data on mercury in technical and environmental components.

The global mercury cycling system changed dramatically over time as a result of human activities. Concentrations of mercury in the atmosphere, land, and oceans are now greatly elevated, human-mobilized mercury has reached ecosystems in all regions of the Earth, and some of this mercury has been converted into methylmercury. This increase is consistent with trends in other human-induced environmental pressures, including global population and carbon dioxide emissions, as well as economic indicators such as world gross domestic product (Steffen et al. 2007). Mercury will continue to cycle in the environment over long timescales, but mercury methylation and bioaccumulation processes can change more rapidly along with ecosystem changes. Interventions targeting societal flows of mercury can also have relatively rapid impacts. Yet, people and wildlife are unable to adapt biologically to make methylmercury concentrations less damaging to their bodies. Human forces affecting the supply and demand for mercury have historically shaped its trade patterns as well as its price. The Minamata Convention sets out to further reduce the supply, trade, and use of mercury over the next few decades. It is too soon to say if this will happen, but the rapid decline in mercury use in some regions over the past 30 years shows that change is possible.

Evolving knowledge about the extent to which elemental mercury and mercury compounds cycle in the environment has changed perceptions of the scale of the mercury problem over time. Mercury was thought of as mainly a local, national, and regional pollution problem until the late 1900s based on the common understanding at the time of how mercury was dispersed in the environment. Global concern about mercury emerged with the realization that mercury can travel long distances in the atmosphere. Mercury remains both a local and a global pollution challenge, and its local and global dynamics are linked. Mercury that deposits locally may re-volatilize and begin to cycle in the environment later, posing future risks in other places. Local land use changes and global climate change may alter the form and availability of mercury compounds that cycle in the environment, further complicating systems-focused efforts to analyze the scale and scope of the mercury problem. Changing knowledge about the extent to which mercury travels globally in the environment has also influenced views of the appropriate scale of institutions to address mercury use and pollution. A comprehensive view of the mercury problem should account for its local and long-range aspects simultaneously.

Sustainability Definitions and Transitions

Defining whether the global mercury cycling system is becoming more sustainable is complicated because of the long timescales of mercury cycling in the atmosphere, land, and oceans. Definitions of sustainability focusing on hazardous substances often stress the importance of eliminating uses and discharges, but much mercury from anthropogenic (as well as natural) sources already exists in the environment. Societal measures to reduce discharges from human activities will lower the overall amount of mercury that will cycle in the environment in the future. Other human activities, however, increase the global environmental cycling of mercury. Human-induced trends of land-use changes and climate change contribute to the remobilization from environmental storage of mercury previously discharged from both human and natural activities. This means that merely lowering the levels of mercury uses and discharges will not solve the problem of mercury damaging the environment and human health. Assessing whether the global-scale human-technical-environmental system for mercury is moving toward sustainability will thus require attention to societal as well as environmental trends.

Societal efforts addressing the supply of mercury have gradually become more stringent over time with the closure of large primary mercury mines and tighter controls on the reuse of mercury, especially from industrial sources. Supply of new mined elemental mercury was seen as critical to meeting societal demand well into the second half of the twentieth century. Commercial mercury use only began to decline in the early 1970s, partially as a result of environmental and human health concerns. The adoption of elemental mercury export bans by the United States and the EU in the 2000s further affected the international supply and price of elemental mercury. The Minamata Convention provisions that phase out primary mercury mining, ban the reuse of excess mercury from chlor-alkali production, and permit exports of elemental mercury only for those few uses that are still allowed under the treaty are important global-scale interventions in an ongoing incremental transition process. The closing of mercury mines and expanded introduction of other supply restrictions, including the recent actions by the US and the EU to ban the export of mercury compounds, will reduce the environmental distribution and cycling of mercury and also have positive effects on human exposure and well-being.

Global-scale transitions involving mercury will occur over various timescales moving forward. Environmental concentrations of mercury will not return to preindustrial levels for centuries and perhaps millennia, but changes involving use and discharges will advance over the coming decades. The Minamata Convention's control provisions on mercury use, emissions, and releases vary with respect to their deadlines and stringency. The bans and phase-downs of mercury use in many mercury-added products were relatively rapid, with an initial target date of 2020. Bans on uses of mercury in some industrial production processes are in effect as of 2018 and 2025, but mercury use can continue in other processes. Parties to the convention also have the ability to request extensions from the target dates for products and processes, and the controls on emissions and releases from point sources do not rely on universal numerical reduction targets. Parties must apply technology-based standards, but they are given much freedom in setting their own standards. This will, at least in the short-term, result in much national variation in regulatory stringency and mercury discharges. As a result, trends in environmental discharges may differ across countries and regions. Some environmental compartments will also respond more rapidly than others to varying changes in discharges.

Sustainability Governance

The global scope of the Minamata Convention, together with its lifecycle approach, is designed to fit both the socio-economic and environmental dimensions of the mercury issue. The treaty was adopted based on the scientific and political recognition that mercury transports globally, both in the environment and society. The trade of mercury across continents has been documented for centuries, but only after the release of the first global mercury assessment in 2002 did a global political forum officially recognize that mercury also travels worldwide in the atmosphere. The stated goal of the Minamata Convention to protect human health and the environment from anthropogenic emissions and releases of mercury and mercury compounds puts a clear focus on human well-being in the context of sustainability. To this end, the Minamata Convention sets out a global legal framework explicitly designed to address all aspects of the lifecycle of the mercury issue, including production, trade, use, emissions, releases, handling, stockpiles, and disposal.

Effectiveness evaluation is an important part of implementing the Minamata Convention, as mandated in Article 22, and the ability to conduct such evaluations is shaped by the fact that material components in the global human-technical-environmental system for mercury change over vastly different timescales. The long timescales of global environmental cycling of mercury, and the growing importance of remobilizing legacy emissions from environmental compartments, make it difficult to causally link changes in environmental concentrations with measures taken under the Minamata Convention. An increase in legacy emissions may result in additional mercury entering into global environmental cycling, offsetting some of the anthropogenic mercury emissions and releases that are reduced by measures related to the implementation of the Minamata Convention. A full analysis of the effectiveness of the Minamata Convention should also consider political and technological factors, such as the degree to which parties phase out mercury supply and use, mandate the application of pollution control technology on point sources, and fulfill provisions on financing, capacity building, and technology transfer.

The ability to protect the environment and human health from mercury is increasingly affected by the governance of other sustainability issues. Policies that address coal and other fossil fuel uses in the context of other forms of air pollution and climate change affect levels of mercury emissions from these sources. Material connections with other sustainability issues also influence the global environmental cycling of mercury. Human alterations to the carbon cycle through the burning of fossil fuel and deforestation change the ways in which mercury travels in the atmosphere, land, and oceans as well as the processes it undergoes in the environment. These include processes of methylation and bioaccumulation in aquatic environments, which have important implications for animals and seafood consumers worldwide. The Minamata Convention's links to several SDGs show that mercury abatement is connected with human-centered efforts on addressing poverty, hunger, food safety, good health, work, consumption and production, and energy. In this respect, implementing the Minamata Convention is an important aspect of broader global governance efforts that aim to move societies toward greater sustainability.

The global cycling of mercury makes it necessary to chase quicksilver through both the environment and society. Mercury is discharged into the environment from natural events as well as by human activities. People have dramatically altered the global biogeochemical cycling of mercury in the environment over millennia, but especially during the last few hundred years. The international trade in mercury and mercury-containing goods increased during that same time period, resulting in large amounts of mercury cycling through society. Much of this mercury eventually ended up in the environment. Human-induced land-use and climate changes increasingly contribute to the re-release of historical emissions from both natural and anthropogenic sources, making it more analytically difficult, and less useful for informing sustainability transitions, to separate between natural and anthropogenic sources of mercury cycling in the environment. The Minamata Convention takes a lifecycle approach to mercury, addressing both societal cycling and environmental discharges. The legacy of past mercury discharges, and the impacts of today's discharges, will affect ecosystems and people for generations, as it can take centuries, if not millennia, for discharged mercury to return to geological storage.

Mercury Stories

Understanding Sustainability through a Volatile Element

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