Edward B. Swain, Paul M. Jakus, Glenn Rice, Frank Lupi, Peter A. Maxson, Jozef M. Pacyna, Alan Penn, Samuel J. Spiegel and Marcello M. Veiga

Socioeconomic Consequences of Mercury Use and Pollution

In the past, human activities often resulted in mercury releases to the biosphere with little consideration of undesirable consequences for the health of humans and wildlife. This paper outlines the pathways through which humans and wildlife are exposed to mercury. Fish consumption is the major route of exposure to methylmercury. Humans can also receive toxic doses of mercury through inhalation of elevated concentrations of gaseous elemental mercury. We propose that any effective strategy for reducing mercury exposures requires an examination of the complete life cycle of mercury. This paper examines the life cycle of mercury from a global perspective and then identifies several approaches to measuring the benefits of reducing mercury exposure, policy options for reducing Hg emissions, possible exposure reduction mechanisms, and issues associated with mercury risk assessment and communication for different populations.

INTRODUCTION

Mercury (Hg) has historically been used in a wide variety of activities, both in compounds and as a liquid metal, resulting in widespread dispersion and the creation of some heavily contaminated sites. Geologic materials that contain high concentrations of Hg are usually found only in areas known as mercuriferous belts, such as along the west coast of the Americas. Even though most natural materials (including coal, oil, and minerals) contain very low levels of Hg, the use of large quantities of these materials releases significant amounts of Hg into the biosphere each year. Because Hg can vaporize at ambient temperatures, the Earth's atmosphere plays a major role in the dispersion of Hg. Human activities, including Hg mining, use, and waste disposal, combined with releases from the refining of other metals and the combustion of fossil fuels, have significantly increased Hg emissions to the atmosphere. Compared with preindustrial times, atmospheric deposition has increased uniformly in remote regions by a factor of about 3 (1). Deposition increases above threefold have been documented near emission sources; depositions depend on stack height, the quantity and chemistry of the emitted Hg, and local atmospheric chemistry (1). Bacteria in aquatic systems convert a small proportion of the deposited Hg to methylmercury (MeHg), which bioaccumulates in fish (inorganic Hg does not bioaccumulate). Aquatic systems vary in the efficiency with which atmospherically deposited Hg is bioaccumulated in fish. For example, the Hg concentration of fish in neighboring lakes can vary by as much as 10-fold, even when atmospheric Hg is similar (2). Nevertheless, in a given aquatic system, the production of MeHg is believed to be approximately proportional to atmospheric Hg deposition, so it is likely that historical increases in Hg emissions have increased MeHg concentrations in fish (3).

Hg use and releases are of concern because of two exposure pathways: consumption of MeHg-contaminated fish and inhalation of elevated concentrations of Hg vapor. The most common route of MeHg exposure for humans and wildlife is the consumption of fish from marine and freshwater sources. While low levels of Hg vapor are normally measured in the atmosphere, elevated concentrations can result from a variety of intentional Hg uses and accidents involving Hg, especially indoors where dilution is constrained.

In industrialized societies, although Hg was once a component in many products, it is now viewed as a material for which the risks of use generally outweigh the benefits. Hg-free substitutes are now viable for nearly all uses (energy-efficient lighting remains a notable exception), although their adoption varies greatly across jurisdictions and industrial sectors. The link between Hg emissions to the atmosphere and fish contamination has influenced policy development in industrialized countries since the mid-1990s, variously resulting in mandatory control of Hg emissions from waste incineration and other sources; restrictions on the labeling, sale, and disposal of Hg-containing products; and control of Hg emissions from coal-fired power plants as recently mandated by federal and state regulations in the United States (4, 5) and Canada (6).

Hg is also a commodity, with net flow from industrialized countries to developing countries, where its uses are less constrained. Annual global Hg consumption peaked at about 10 000 tonnes (t) in the 1960s; at that time large amounts were used in electrolytic and chemical processes, pesticides, paints, and batteries. Use gradually decreased to an estimated 3500 t in 2005 (Fig. 1a) (7–9). In 2000, however, global trade statistics reveal that at least 9000 t of metallic Hg were bought and sold across national borders, confirming that Hg is an actively traded commodity (Fig. 1b). However, the Hg market is opaque, with considerable uncertainties associated with many of the estimates presented here.

Significant and growing coal combustion, particularly in developing countries, and industrial-scale refining and smelting of metals also are responsible, in part, for the continued elevation of atmospheric Hg levels (10). Although global Hg pollution of the biosphere is likely a major contributor to the widespread MeHg contamination of fish, effective international agreements that address Hg pollution have yet to be developed.

This paper describes how certain human activities mobilize Hg from geologic stores into the biosphere and outlines the resulting social and economic consequences. We present possible policies to reduce exposure to Hg and MeHg, and explore issues associated with risk assessment and communication for different populations. We utilize substance flow analysis, which reveals not only the source and fate of a material, but also potential control points. We discuss policy options for addressing control points in the flows of Hg that could ultimately reduce fish contamination while simultaneously reducing the potential of harmful exposure to Hg vapor.

Concern about MeHg in Fish

Exposure to MeHg through consumption of contaminated fish by humans has the potential to interfere with normal neurological development and function and may increase the risk of myocardial infarction (heart attack) (11). Negative

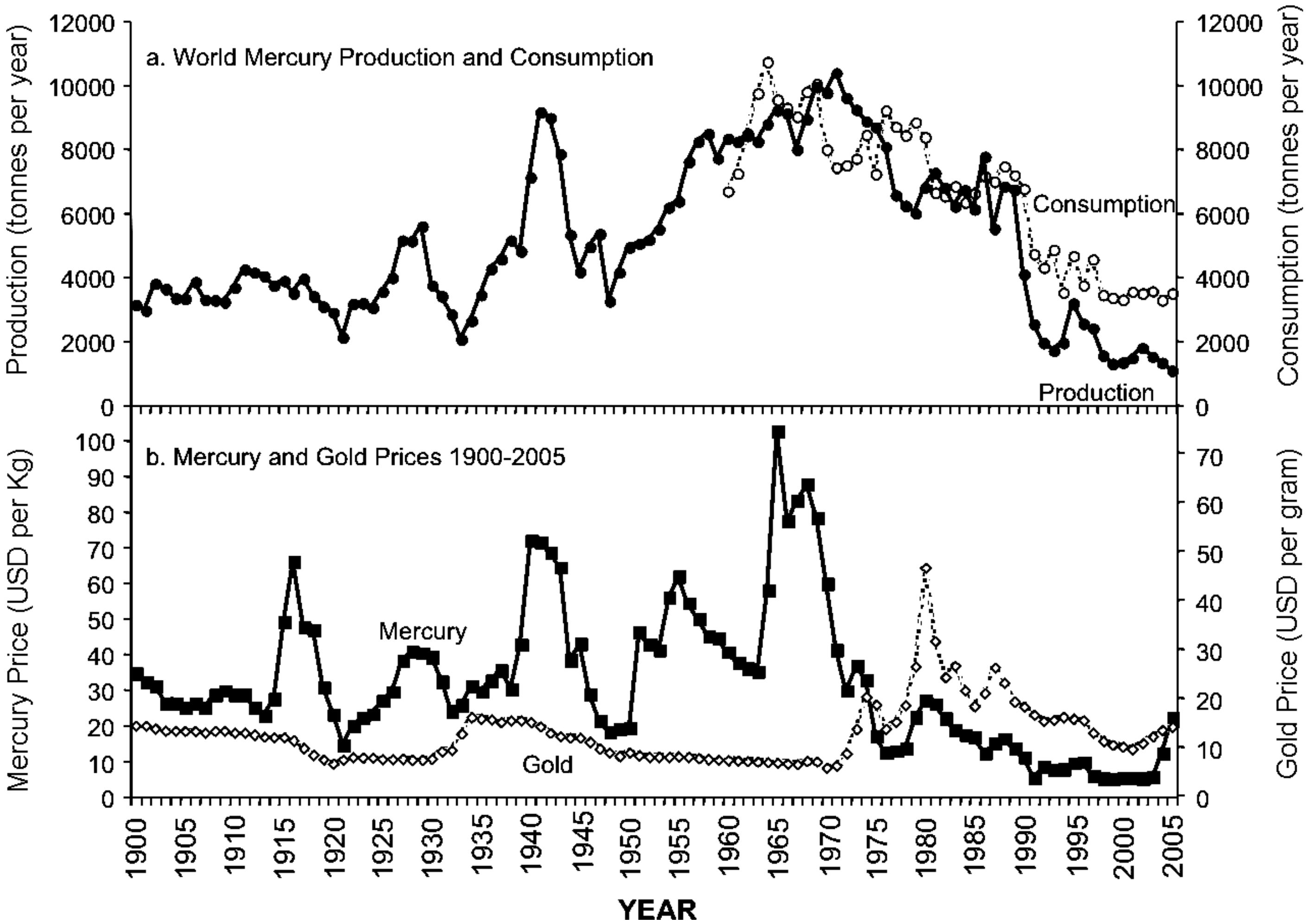

Figure 1. (a) Historical mercury production and consumption. Consumption has exceeded production since about 1990, with demand met by large supplies from government stockpiles and closed chlor-alkali plants, plus contributions from recycling (7). (b) Mercury and gold prices in the United States from 1900 to 2005, adjusted to constant 2005 US dollars (USD). The correlation between gold and mercury prices begins after 1971 with the breakdown of a fixed exchange rate system (7–9).

neurological and reproductive effects of MeHg on fish-eating wildlife—birds (e.g., loons), mammals (e.g., river otter and mink), and fish that eat other fish—are also a concern (12).

Concern about Inhalation of Hg Vapor

Absorption of liquid Hg through the skin or digestive system is quite limited, but the body retains 80% of inhaled Hg vapor (13). An indoor spill of metallic Hg, even in quantities as small as a gram, can give rise to Hg concentrations in ambient air that approach WHO recommended limits for occupational exposure. Heating metallic Hg and Hg compounds, such as cinnabar and scrap dental amalgam, has generated fatal inhalation doses (14). Although heating Hg is a rare activity in most societies, an estimated 10 to 15 million people earn their living in small-scale gold-mining operations by amalgamating gold with Hg, and then concentrating the gold by heating the amalgam, thereby releasing the Hg in vapor form. This process directly exposes the miners and can expose their families and neighbors (estimated to total about 50 million people), to elevated Hg levels (15). In 2005, small-scale or artisanal gold mining was estimated to contribute more than 10% of annual global anthropogenic Hg loading to the atmosphere (about 300 out of a total 2400 t, Fig. 2).

Concern about Hg vapor extends beyond small-scale mining to include Hg in products. One such application, dental amalgam, is the most common way that people are exposed to elevated Hg vapor, although the levels are not as high as those frequently encountered in artisanal gold mining. Even though Hg levels in autopsy brain samples correlate positively with the number of amalgam fillings, vapor concentrations from amalgam are usually well below those associated with even subtle neurobehavioral effects (13). Otherwise, Hg is usually encapsulated in consumer and commercial products, such as fluorescent lamps and thermometers. However, these devices can break during use or disposal, releasing Hg into indoor air and the environment. Historical uses of Hg left a legacy of many small bottles of liquid Hg. In the United States, Hg spills have caused expensive and disruptive clean-up efforts (16). Although adverse health effects have rarely been documented from Hg spills, we do not consider this as evidence of a low potential for harm. For example, three children were hospitalized in Michigan (United States) as a result of Hg poisoning, including one child who was no longer able to walk. Investigation revealed that exposure occurred after a small vial of Hg was spilled in the children's bedroom approximately two to three months prior to detection of the gross symptoms (17).

GLOBAL COMMERCIAL AND ENVIRONMENTAL PATHWAYS

Although somewhat simplistic, conceptually, it is useful to divide the Earth's Hg between two repositories: Hg in the biosphere and Hg stored in geological formations. The biosphere encompasses

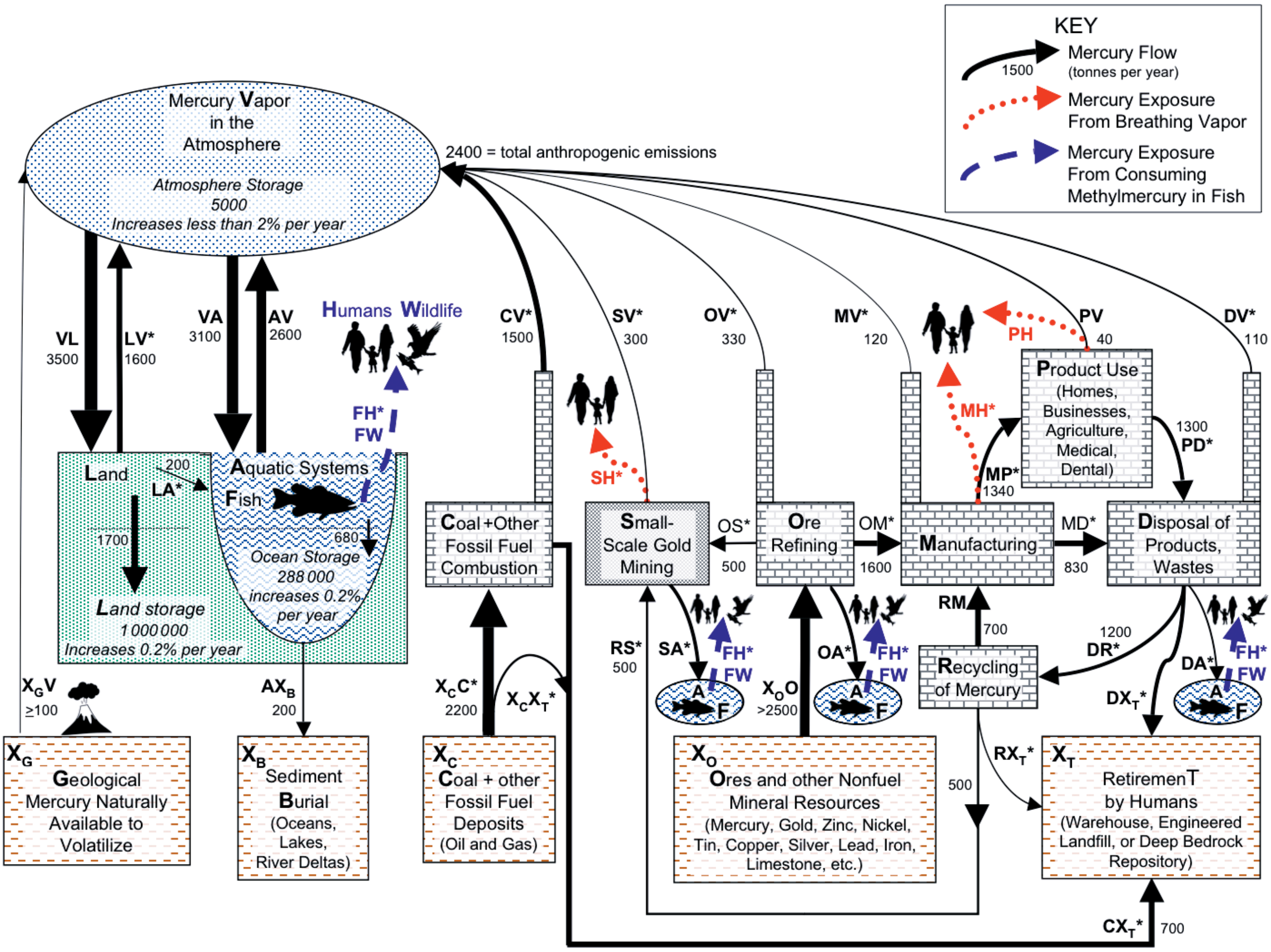

Figure 2. Important global pathways of mercury in commerce and the environment. Width of pathway line is proportional to the flow per year. See Table 1 for explanation of abbreviations and the text for discussion of the compartments and Table 2 for discussion of the pathways.

the portion of Earth and its atmosphere that supports life; geologic formations include deep sediment deposits, buried minerals, and fossil fuels. The most significant human impact on Hg is its mobilization from long-term geologic storage into the biosphere, where Hg cycles between air, soil, and water.

Assuming only two repositories is simplistic because mobilized Hg can enter subcompartments that appear to be stable, such as Hg encapsulated in a device such as a thermometer, Hg that has settled into deep ocean waters, and Hg sequestered in deep soils, such as the vast peatlands of Canada and Siberia (18, 19) or the ancient soil of the Amazon Basin (20). However, use of only two repositories is useful from a policy perspective because human activity can mobilize the Hg from apparently stable compartments of the biosphere. Thermometers inevitably break, and the Hg in soils can be mobilized through fire (19), forestry practices (21, 22), agriculture (20), climate change (18, 19, 23), and the creation of reservoirs (24). Additional research is needed to understand the fate of Hg that enters both coastal and deep-water marine systems (1).

The movement of Hg into and out of the biosphere is shown in Figure 2, based on the global model of Mason and Sheu (25), a model that is representative of the current scientific understanding of global Hg cycling [see review of four models by Seigneur et al. (26)]. Although there is a considerable range of estimates in the models for specific components of the global Hg cycle and there is uncertainty regarding the scale of natural emissions and reemission of deposited Hg (1), the four models converge on a relatively tight range for total global emissions (natural and anthropogenic); that is, from 6060 to 6600 t y^{-1}, and for current anthropogenic emissions alone, from 2000 to 2400 t y^{-1}. Reemission of previously deposited anthropogenic emissions roughly equals current anthropogenic emissions (1). In general, the global models can be considered uncertain, but useful, frameworks.

Although current anthropogenic emissions in Figure 2 are constrained to 2400 t y^{-1} to conform to the Mason and Sheu model, it would be reasonable to assign an uncertainty of ±30% to total anthropogenic emissions (1), with some sectors embodying less uncertainty than average and some sectors more. It has been suggested that Hg emitted from global coal combustion has a ±25% uncertainty; nonferrous metal production ±30%; waste disposal and incineration has uncertainty up to 500%; and Hg use in artisanal and small-scale gold production is too poorly understood to allow a quantitative uncertainty factor to be assigned (1). A protocol, or "toolkit," has been developed to assist countries that wish to identify and quantify sources of Hg emissions (27). The toolkit, including extensive text and a spreadsheet template, explains how to develop detailed quantification of Hg pathways that are only broadly defined in Figure 2.

Given the uncertainties in the current understanding of global Hg pathways, Figure 2 can reasonably be used as background information for discussions of policy options that

Table 1. Important global compartments of mercury in commerce and the environment, as diagrammed in Figure 2.

Code	Mnemonic	Definition
A	Aquatic system	Hg in wetlands, lakes, rivers, and oceans. Hg introduced to aquatic systems may become MeHg, which may be bioaccumulated by fish.
C	Coal and other fossil fuel combustion	Hg mobilized by the processing and combustion of the fossil fuels coal, oil, and natural gas (X_C).
D	Disposal	Hg in discarded products or process wastes from chlor-alkali or VCM plants.
F	Fish	Hg in fish, virtually all of which is in the form of MeHg, which is produced by naturally occurring bacteria in aquatic systems.
H	Humans	Hg absorbed by humans following exposure, generally through fish consumption or inhalation of vapor.
L	Land	Hg in soil, mostly derived from atmospheric deposition of vapor, but can be elevated from mine waste, Hg waste disposal, or geologically rare mineral deposits containing Hg.
M	Manufacturing	Hg used in the manufacture of Hg-containing products, or in processes that use Hg to make Hg-free products (e.g., chlor-alkali and vinyl chloride monomer processes).
O	Ore refining	Hg mobilized by the processing and refining of nonfuel mineral resources X_O.
P	Products	Hg contained in products, including thermometers, switches, fluorescent lamps, batteries, fungicides, preservatives, seed-coatings, pharmaceuticals, etc.
R	Recycling	Hg that is extracted from discarded products or wastes, purified, and put into commerce or retired.
S	Small-scale gold mining	Hg utilized by independent, artisanal, miners to concentrate geological gold through amalgamation.
V	Vapor	Hg vapor in indoor and outdoor air.
W	Wildlife	Hg absorbed by fish-eating wildlife, such as seal, whale, otter, mink, osprey, eagle, kingfisher, and loon.
X	Out of the biosphere	Hg in the "X" compartments are not part of the Hg cycling in the biosphere and therefore do not harm humans or wildlife. "X" Hg may be mobilized at some point in the future, but for practical purposes is permanently stored unless humans intervene.
X_B	Buried	Hg, formerly in the biosphere, that has been buried in the sediments of oceans, lakes, and river deltas.
X_C	Coal and other fossil fuel deposits	Hg in buried fossil fuel deposits such as coal, oil, and gas, that may be extracted and burned.
X_G	Geological	Hg in geological materials that release Hg vapor to the atmosphere through natural processes.
X_O	Ores	Hg in nonfuel geological resources that are subject to mining and refining, including minerals containing Hg, gold, zinc, nickel, tin, copper, silver, lead, and iron. All geological materials contain some Hg, even limestone that is heated to make lime.
X_T	Retirement	Hg permanently stored, or "retired" by humans in warehouses, engineered landfills, or deep bedrock repositories.

might be adopted to reduce Hg emissions and, ultimately, exposure from fish consumption and small-scale gold mining.

Each letter in Figure 2 codes for a compartment in which Hg is stored or from which it is released (see Tables 1 and 2). A two-letter code indicates a path from one compartment, indicated by the first letter, to another compartment represented by the second letter. For instance, VL denotes the pathway of atmospheric Hg to the Earth's surface whereas LV is the path of Hg volatilization from land to the atmosphere, with the annual flux in tonnes next to each arrow. Note that Hg is relatively mobile in the biosphere; in this model, over 80% of the Hg deposited to the oceans is reemitted to the atmosphere. In contrast, only about half of the Hg deposited to land is reemitted within a few years because Hg can associate strongly with soil.

Pathways with an asterisk (*) are amenable to manipulation to minimize Hg release or exposure at the time this manuscript was written. Therefore, we refer to these pathways as control points. For example, FH* denotes that the exposure of humans (H) to MeHg from contaminated fish (F) may be reduced through selection of fish to consume; it should be noted, however, that in some societies or regions there may be little choice of fish species to consume. The lack of an asterisk indicates that it is unlikely that present social or economic policies can affect that pathway. MP* indicates that the creation of products by manufacturers does not have to include Hg. PV indicates that once Hg is a product component, it is inevitable that some of that Hg will be released to the atmosphere as a result of breakage, no matter what policies, such as recycling, are adopted.

FOSSIL FUEL COMBUSTION: COMPARTMENT C

Fossil fuels (coal, oil, and natural gas) contain a wide range of Hg concentrations in their natural state. Some natural gas supplies are high in Hg vapor, but the Hg is routinely removed during refinement before distribution to avoid degradation of aluminum heat exchange surfaces via amalgamation in gas-processing plants (28). Few analyses have been performed on the Hg content of petroleum or oil sands, or on the fate of Hg throughout the oil exploitation and refinery process. While there is a lack of general data on Hg concentrations in oil and oil sands in their natural state, once refined, the Hg emissions from the combustion of these fuels appear to be much lower than from coal (28).

Coal combustion is responsible for about 60% of anthropogenic Hg emissions (pathway CV*, 1500 t y^{-1}; Fig. 2; 29). A continuous decrease in Hg emissions in Europe and North America since 1980 has resulted from the installation of emission-control equipment, particularly electrostatic precipitators (ESPs), fabric filters, and flue gas desulfurization (FGD) technologies. These existing technologies incidentally capture Hg largely to the extent that coal combustion produces divalent Hg. Metallic Hg vapor (Hg^0) is usually poorly controlled by equipment designed to capture particulates or sulfur. The emitted form of Hg (and its removal) is highly dependent on the coal type and the installed emission control equipment (30).

There are two major types of FGD systems: wet and dry. In general, removal efficiency for Hg in FGD systems ranges from 30% to 85% depending on the proportion of divalent Hg, which is related to the halogen content of the coal. The greatest removal efficiencies with existing technology can be expected when a wet FGD system is installed downstream of a fabric filter (30).

Most utility power plants in developed countries are equipped with either ESPs or fabric filters for particulate control. Removal of Hg by these devices is highly dependent on halogen content and unburned carbon in the flue gases. Generally speaking, fabric filters remove approximately twice as much Hg as ESPs under similar flue gas conditions (4, 30). As part of efforts to control Hg emissions from coal-fired power generation, significant new information is emerging on flue gas chemistry (Hg, chlorine, sulfur, and the effect of nitrous oxide, or NOx, control) that will help to improve Hg control. A wide variety of technologies are being developed (4, 31, 32) and applied (33) to reduce Hg emissions. As with other emission control technologies (e.g., SO_2, NOx, etc.), it is possible that innovations will yield commercially available options that are significantly less costly than initially estimated (34).

ORE REFINING: COMPARTMENT O

Ores of metals, especially nonferrous metals such as gold, silver, copper, lead, zinc, and nickel, often contain Hg because the geological processes that concentrate these metals typically also concentrate Hg. In particular, sulfide ores often contain significant concentrations of Hg because of a high chemical affinity between Hg and sulfur. Cinnabar—mercuric sulfide—has been the main source of Hg as a commodity for thousands of years. Despite recent mine closures in Spain and Algeria, cinnabar mining of 1300–1400 t annually remains the largest source of elemental Hg (Fig. 2; 9) and is increasing in China to meet internal demand. The processing of cinnabar is associated with elevated atmospheric Hg emissions. As global Hg demand declines, however, less expensive sources of Hg—recycling, Hg from closed chlor-alkali plants, and as a by-product from large-scale gold, zinc, and copper mining—may be expected to supply a greater proportion of Hg demand. The availability of Hg as a by-product may increase significantly if new regulations restrict Hg emissions from ore refining.

Hg IN MANUFACTURING AND PRODUCTS: COMPARTMENTS M AND P

Sources of Hg to industries include new Hg from current mining (pathway OM) as well as recycled Hg (pathway RM). Hg has been intentionally used in many products and processes, although consumption decreased by ~50% from 1990 to 1998 (Fig. 1; 35). Annual use of Hg in products in 2004 (Fig. 3) comprised mostly dental amalgams (270 t), electrical switches and relays (150 t), measuring and control equipment (160 t), energy-efficient lighting (110 t), and disposable batteries (estimated at 600 t). Smaller quantities also continue to be used in an array of other products. For example, some Hg is

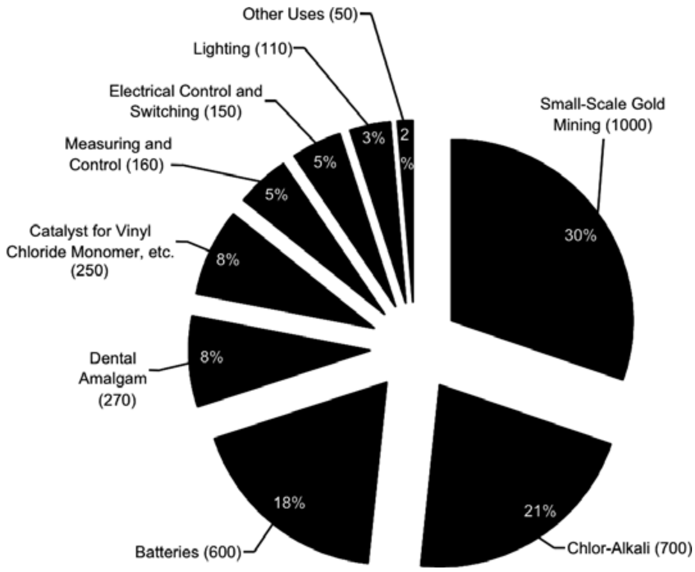

Figure 3. Estimates of global mercury consumption for 2004 (9, 36).

used in cosmetics; in the United States, up to 65 ppm is allowed. Hg continues to be used in chlor-alkali (chlorine and caustic soda) production (possibly 700 t in 2004, but is declining every year) and as a catalyst for the production of vinyl chloride monomer. The latter remains a significant use in China, India, and Russia [estimated at 250 t y^{-1} in this paper, although recent information from China puts this number as high as 600 t (36)].

Before 1990, large quantities of Hg were used in ways that dispersed Hg widely in the biosphere; these uses included fungicides used in seed coatings, the paper industry, and latex paints (37). Today, most Hg added to products is not released during normal use, with the exception of Hg-containing skin-lightening soaps and creams; vaccines containing thimerosal (a Hg-containing preservative that is injected into the body during vaccination); dental amalgams; and volatilization from Hg-catalyzed polyurethane products. The largest remaining dissipative use of Hg is in dental amalgams, which can result in direct human exposure during inhalation, occupational exposure in the dental office, releases to wastewater both from dental offices and homes, emissions during incineration of dental wastes, and flue-gas emissions during cremation (pathways PH, PV, PD*, DA*, and DV*).

Electrical switches and relays, measuring and control equipment, energy-efficient lighting, and batteries do not release Hg until disposal, except as a result of misuse or accidents (pathways PH and PV). It is possible to manufacture these products in such a way as to limit air or water emissions of Hg (pathways MV* and MH*). Therefore, the extent of Hg emissions from Hg-added products is likely a function of the method of disposal (pathways MD* and PD*). Chlor-alkali factories reportedly have greatly decreased their Hg releases in many nations (38, 39). However, considerable uncertainty remains regarding the environmental fate of hundreds of tons of Hg unaccounted for annually by the global chlor-alkali industry, much of it released within developing countries.

Polyvinyl chloride (PVC) is typically manufactured from petrochemical feedstocks. There is, however, a Hg-catalyzed method to make a PVC feedstock, vinyl chloride monomer (VCM), from coal; this method typically results in large Hg consumption. Such PVC production is a substantial contributor to Hg releases (pathways MV*, MH*, but mostly MD*), conservatively estimated at 150 t y^{-1} (9, 40), but possibly twice that amount (36). However, there remains considerable

Table 2. Important global pathways of mercury in commerce and the environment (diagrammed in Figure 2). An asterisk (*) on the pathway code indicates that the path is amenable to manipulation by society's policies. The estimates of annual anthropogenic flow are constrained by setting total anthropogenic emissions at 2400 t y^{-1} (25).

Code	From	To	Comments	Annual flow (t)	Information source
AF	Aquatic system	Fish	Only a portion of Hg entering an aquatic system bioaccumulates in fish, partly because only a portion is converted to MeHg.		
AV	Aquatic systems	Vapor	The oceans are estimated to re-emit over 80% of atmospheric deposition; there is little binding capacity in ocean water, and photochemistry produces Hg^0, which has low solubility in water.	2600	25
AX_B	Aquatic system	Sediment burial	Some of the Hg entering an aquatic system associates with particles that settle to the bottom and is buried permanently by new sediment. Mason and Sheu (25) conclude that Hg is building up in deep ocean water and only a small proportion is buried.	200	25
CV*	Fossil fuel combustion	Vapor	Emitted Hg vapor may be elemental or divalent, which greatly affects distance traveled before deposition to earth.	1500	29
CX_T*	Fossil fuel combustion	Retirement	Hg vaporized during combustion may associate with ash or can be caught separately. Coal ash is often used in construction, which may not retire the associated Hg as permanently as putting it in a landfill.	700	Estimate
DA*	Disposal	Aquatic system	Some Hg is discharged directly into surface water, or indirectly through treatment plants. In treatment plants, most Hg associates with solids, which if not discharged are incinerated or land-applied.		
DR*	Disposal	Recycling	This category includes Hg from closed chlor-alkali plants, which is saleable as is. The Hg in product waste can be purified at relatively high cost per kilogram of Hg (100 USD to 1000 USD kg^{-1}), which is then sold for less than 20 USD kg^{-1}. Retirement of recycled Hg may be a better economic choice for societies.	1200	Estimate
DV*	Disposal	Vapor	Disposal to the solid waste stream may include incineration, which vaporizes all Hg, of which some may be caught by pollution control equipment and place in a landfill.	110	29
DX_T*	Disposal	Retirement	Manufacturing waste Hg may be retired in landfills as sludge. Hg-products might be put in landfills after breakage and spilling of Hg.		
FH*	Fish	Humans	Humans absorb most of the methylmercury (MeHg) consumed in a fish meal. The MeHg is in the protein, not the fat, of fish.	25 (as MeHg)	Estimate, assuming 0.2 ppm
FW	Fish	Wildlife	Fish-eating wildlife are particularly vulnerable to elevated Hg in fish.		
LA*	Land	Aquatic system	Of the Hg deposited from the atmosphere to land, a variable proportion (approximately 5% to 20%) is delivered to lakes and rivers draining the land. Human alteration of the landscape (e.g., agriculture and urban development) can affect the transport to aquatic systems.	200	25
LV*	Land	Vapor	The land reemits about half of the Hg deposited from the atmosphere. Human alteration of the landscape (e.g., climate change, fire, agriculture) can change the rate of reemission to the atmosphere.	1600	25
MD*	Manufacturing	Disposal	Any manufacturing process that employs Hg will have Hg waste.	830	Estimate
MH*	Manufacturing	Human vapor exposure	Any manufacturing process that employs Hg will produce Hg vapor that potentially exposes the workers.		
MP*	Manufacturing	Products	Products containing Hg are still manufactured even though cost-effective Hg-free substitutes exist for almost all uses, probably because of economic and technological inertia.	1070	Estimate
MV*	Manufacturing	Vapor	Manufacturing both makes Hg-containing products and uses Hg in processes that emit Hg (chlor-alkali and VCM).	120	Estimate
OA*	Ore refining	Aquatic systems	The processing of Hg-containing ores sometimes produce wastes or tailings that enrich aquatic systems with Hg.		
OM*	Ore refining	Manufacturing	Almost all Hg mines in the world are now closed, because the world's Hg demand is now met by by-product Hg from non-Hg ores, recycling, and the closure of chlor-alkali plants.	1600	Estimate
OS*	Ore refining	Small-scale gold mining	By-product Hg is one source for gold mining.	500	Estimate
OV*	Ore refining	Vapor	Heating ores will vaporize any Hg present, either emitting it to the atmosphere or incidentally catching it with air pollution control devices, unless special Hg control efforts are made.	330	29
PD*	Products	Disposal	Hg-containing products will eventually reach the end of their useful life and will either break or be disposed of.	1020	Estimate
PH	Products	Human vapor exposure	When Hg-containing products break and spill, they create the risk of human exposure and time-consuming clean ups.		
PV	Products	Vapor	Hg spills from broken products contribute to the atmospheric burden of Hg.	40	Estimate
RM	Recycling	Manufacturing	Recycled Hg can be used by many manufacturers.	700	Estimate

Table 2. Continued.

Code	From	To	Comments	Annual flow (t)	Information source
RS*	Recycling	Small-scale gold mining	Hg used in mining does not have to be of a high purity, so recycled Hg, especially from chlor-alkali plants, can be used.	500	Estimate
RX_T	Recycling	Retirement	Hg need not be purified to be retired, although there may be some advantages in handling and containment. 4400 t retired in 2006 (62)		
SA*	Small-scale gold mining	Aquatic systems	Hg may be used directly in flowing water to concentrate gold, contaminating water and its sediments.	700	Estimate
SH*	Small-scale gold mining	Human vapor exposure	The gold–Hg amalgam is heated to concentrate the gold, exposing miners and their families to Hg vapor.		
SV*	Small-scale gold mining	Vapor	Hg vaporized during heating of Hg–gold amalgam adds significantly to the global atmospheric burden of Hg.	300	45
VA*	Vapor	Aquatic Systems	All atmospheric Hg eventually deposits to earth, with oceans receiving almost half.	3100	25
VL*	Vapor	Land	Hg deposition rates to the continents has increased by about a factor of 3 over preindustrial rates.	3500	25
X_CC*	Fossil fuel deposits	Combustion	Although the Hg concentration in fossil fuel is usually low, much is burned, and all Hg vaporizes during burning, but some binds to particles and is captured. Pretreatment of fuel has the potential to remove Hg prior to combustion.	3000	Estimate
X_CX_T*	Fossil fuel deposits	Retirement	Some of the Hg in fossil fuel is separated from fuel prior to combustion through coal cleaning or natural gas treatment. Oil refineries are poorly understood where the fate of Hg is concerned.	700	Estimate
X_GV	Geology	Vapor	Hg is naturally released from geological deposits, naturally enriched soils, and volcanoes. Lindberg et al. (1) point out that this path is poorly known and may be greater than 1500 t y^{-1}.	100	25
X_OO	Ore resources	Ore refining	Hg is in relatively high concentrations in sulfide ores of gold, silver, copper, lead, and zinc, and in lower concentrations in nonsulfide ores. Heat and other processes release the Hg, which enters the biosphere unless efforts are made to capture it.	>2500	Estimate

uncertainty as to what part of those releases go into the atmosphere in contrast to other waste streams.

The substantial reduction of global Hg use (Fig. 1a) is due to two factors: *i)* substitution of non-Hg products (e.g., paints, batteries, thermometers, and pesticides) and production processes (mainly chlor-alkali) and *ii)* more efficient use of Hg in production, except, typically, in cases where production has been shifted to developing countries.

SMALL-SCALE GOLD MINING: COMPARTMENT S

A combination of high gold prices and persistent poverty contributes to a proliferation of small-scale gold mining that uses Hg amalgamation to concentrate gold (41, 42). While the scale of gold production by artisanal miners is not well defined, it may constitute 20% to 30% of global gold production, ranging from 500 to 800 t of gold each year (43, 44) and occurs in over 50 developing countries (15). Because gold is easy to sell and transport, and its value remains relatively stable in countries with unstable currencies, it constitutes one of the more important extraction economies (41).

Hg is widely used in small-scale gold mining, despite laws prohibiting its use. Hg is combined with gold-containing silt or crushed ore to form a gold–Hg amalgam, simplifying recovery of the gold. Generally the amalgam is then heated with a blowtorch or over an open fire, vaporizing the Hg and leaving the gold behind (pathways SV*, SH*). Miners are estimated to lose, on average, 1 to 2 g of Hg per gram of gold produced; thus, this process annually releases approximately 1000 t of Hg to the biosphere, of which an estimated 300 t is emitted directly to the atmosphere (Figs. 2 and 3; 45). Virtually all of the Hg consumed by this activity is released somehow to the environment. The leading consumer of Hg through this activity is thought to be China (200 to 250 t y^{-1}), followed by Indonesia (100 to 150 t y^{-1}), while Brazil, Colombia, Peru, the Philippines, Venezuela, and Zimbabwe each consume an estimated 10 to 30 t y^{-1} (46–48). The unregulated trading of Hg in developing countries makes it readily available at the mine sites (pathways OS*, RS*).

Hg use in small-scale mining has left a legacy of thousands of polluted sites with impacts extending far beyond localized ecological degradation, often presenting long-term health risks to persons living in mining regions (49). Inhalation of Hg vapor is the primary exposure pathway for miners, gold shop workers, and people living near areas where the gold–mercury amalgam is produced and processed. Miners and community members often breathe air with Hg concentrations above 50 μg m^{-3}—50 times the World Health Organization maximum public exposure guideline. Consequently, many miners and others—particularly amalgam burners, who are often women—demonstrate tremors and other symptoms of Hg poisoning (50). Two mining practices may be increasing local Hg exposure because of inadequate information: Improper use of retorts to recover Hg may increase exposure to vapor (51) and cyanide leaching after Hg amalgamation may increase Hg bioavailability and fish contamination (14).

UNIDO efforts to reduce Hg releases have yielded new retorting techniques using readily available pipes and kitchen bowls, which allow miners to contain Hg emissions and recycle as much as 95% of the Hg from the vaporization process (52, 53). Such approaches are garnering increased attention, in particular because Hg prices increased fourfold and more between 2002 and 2005 (Fig. 1b). While the international price for 1 kg of Hg increased from less than 5 USD to more than 20 USD (all prices in constant 2005 USD), the price for 1 kg reached more than 100 USD in the small-scale gold mining sites in Mozambique, Zimbabwe, and Indonesia.

Hg-free alternatives to dissolve gold (cyanide) or to concentrate gold (e.g., gravity separation, magnetic sluices, and coal-oil gold agglomeration methods) are relatively costly and currently inaccessible to most miners in developing countries (54). Other promising Hg-free techniques to extract gold from concentrates include electro-oxidation and alternative methods of leaching, such as the iGoli Process (15, 55). Widespread adoption of Hg-free gold-mining methods would require substantial time and investment in both technology and social-development (55).

RECYCLING AND RETIREMENT: COMPARTMENTS R, D, AND X_T

All products eventually enter the waste stream. Hg contained in waste products may be recycled (DR*), incinerated (DV*), left in place, disposed on land, disposed into wastewater (DA*), released through breakage during use or disposal (PV), or "retired" through placement in a warehouse, engineered landfill, or deep bedrock repository (DX_T). Every time Hg moves from one compartment to another, there is some loss to the atmosphere and potential for human exposure via inhalation and eventually via deposition, aquatic methylation, and fish consumption (56–58). In some societies, regulations may protect workers from exposure, incinerators may have Hg-control devices, and diversion of Hg-containing products from the waste stream may be mandated. But in much of the world, Hg exposure and disposal are unconstrained (43). The incentive for firms in industrialized countries to recycle is regulatory in nature rather than economic because the market value of recovered Hg is usually much lower than the cost of recycling. On the other hand, recycled Hg may be considered a "cheap" Hg source because it is a product of the waste disposal process that has already been paid for.

Recycling

From a sustainability perspective, recycling of materials is generally preferred over landfill disposal because recycling obviates the need for (and costs associated with) landfills as well as the environmental costs associated with extraction of virgin material. However, unless it is integrated into a larger strategy of stable or decreasing Hg supply and demand, recycling Hg may not decrease global Hg pollution levels if the recycled Hg is merely returned to the marketplace. In the latter case, Hg recycling could have the effect of increasing the Hg supply and decreasing the price.

Under current regulations in most developed countries, it is cheaper to recycle waste containing a significant percentage of Hg and to sell the recovered Hg on the open market, than it is to dispose of Hg-bearing waste at a hazardous waste landfill (59). The generation of Hg from recycling and the recovery of Hg from decommissioned chlor-alkali plants have become increasingly significant contributors (10%–20% in recent years) to global supplies because recycling has increased and the production of mined Hg has declined. However, in the interest of eliminating surplus Hg supplies from the global market, the European Union (EU) has a draft regulation for a Hg export ban, which is presently under discussion in accordance with Actions 5 and 9 of the EU Hg strategy. This ban targets all Hg from decommissioned EU chlor-alkali plants for retirement as of 2011 (60). The supporting analysis suggests that recycled and by-product Hg (along with reduced Hg mine production, as necessary) will be more than adequate to meet global Hg demand (35).

Retirement

The alternative to marketing surplus Hg is the intentional retirement of Hg, that is, permanent storage that removes Hg from commerce and the biosphere. Hg need not be recycled, or purified, before it is retired. Unprocessed wastes or pure Hg could be stored indefinitely in warehouses or engineered land disposal sites, such as lined and capped landfills. There have been few efforts to compare the benefits of recycling and retirement, although Sweden has decided to retire Hg wastes (61).

The US government, through the Defense National Stockpile Center (DNSC), owns one of the world's larger stocks of Hg, and in the early 1990s began selling it on the international market after declaring it unneeded for future defense needs. A moratorium on sales was declared in 1994 as a result of concerns that marketing Hg may contribute to global environmental contamination. The relative merit of selling *versus* retiring the Hg was studied (62), and in February 2006 the US government announced that the stockpile of some 4400 t of Hg would be stored indefinitely in a warehouse.

Hg IN FISHERIES AND HUMAN COMMUNITIES: COMPARTMENTS F & H

The consumption of fish is the primary route of exposure to Hg in the form of MeHg (pathway FH*). Patterns of human exposure to MeHg are largely determined by the global distribution of fisheries, the trade in fish, and fish consumption.

Concentrations of MeHg in fish tissues vary by over a factor of 10 (63) because of variation in the environmental biogeochemical pathways of Hg and in aquatic food webs. Efforts to quantify the benefits of reducing anthropogenic Hg pollution are dependent on biogeochemical and food web models relating Hg releases to fish concentration. Much of the research on the biogeochemical pathways of MeHg has focused on freshwater ecosystems; in contrast, marine fish make up 92% of the global fish harvest (64). The quantification of reduction benefits would be enhanced if research efforts more closely matched the source of fish that people eat.

The global fish harvest has increased in recent decades and appears to have stabilized at around 130×10^6 t, a figure that includes aquaculture (30×10^6 t) and fish reduced and processed for use in meal employed in both agriculture and aquaculture (20×10^6 t) (64, 65). Based on these estimates, per capita consumption is 24 and 14 kg live weight per year in developed and developing countries, respectively. In some countries (notably in the western Pacific region), annual fish consumption is appreciably greater, ranging up to 75 kg per person-year. Freshwater fish account for about 5% of the total fish harvest in developed countries and 15% in developing countries.

Over one third of the global marine harvest of approximately 85×10^6 t enters international trade. Half of the production from developing nations, including tuna and other high-value piscivores, is exported to industrialized nations. The ability to assess patterns of exposure to MeHg is limited by data needed to link Hg concentrations to trade statistics. The quantity of fish produced via aquaculture is an increasing proportion of the global fish production (some 25%), but little is known about MeHg concentrations in these fish.

Fisheries are not easily classified. Commercial, recreational, and subsistence fisheries are often closely interrelated. Subsistence fishers often sell part of their catch commercially—a practice that yields cash for goods that must be purchased, such as boats, motors, gasoline, and market foods. Small-scale production of fish appears to involve some 35 million producers and their families, of whom fewer than 5% are from developed nations (65). Subsistence fishing—fishing primarily for local

Table 3. Summary of economic analyses that have been performed on the costs or benefits of reducing mercury emissions or just reducing exposure through fish consumption advisories (e.g., 92). All of the studies concern the United States.

Study	Scenario	Health endpoints or other endpoints	Benefits measurement tools	Costs or benefits in 2004 USD (entire US unless noted)
EPRI (77)	Utility sector cap of 15 tons by 2018 or MACT by 2008 (about 24 tons emitted).	IQ change in fraction of population above MeHg RfD.	Benefits not monetized	Cost of cap: 6×10^9 Cost of MACT: 19.3×10^9
Gayer and Hahn (78)	Utility sector cap of 15 tons by 2020 or MACT by 2008.	IQ	Parental willingness to pay for IQ increases through chelation therapy.	Cost of cap: $3.4–5.5 \times 10^9$ Benefits of cap: $60–150 \times 10^6$ Cost of MACT: $15.4–20.7 \times 10^9$ Benefit of MACT: $82–142 \times 10^6$
Hagen et al. (69)	50% reduction from all sources in Minnesota (US).	Unspecified health effects, recreational fishing, effects on wildlife	CVM	Benefits to Minnesota residents: 255×10^6 y^{-1} (1996 Minnesota population = 4.7 million).
Jakus et al. (92)	Issue mercury-related advisories on the Maryland portion of Chesapeake Bay (US)	IQ, AMI, ACM Recreational fishing Commercial fishing	COI VSL TCM	Benefits: Avoided illness 15.4×10^6 y^{-1} for consumers of Maryland–Chesapeake Bay fish. Lost recreation and commercial value: 9.1×10^6
Lutter et al. (83)	60%–90% reduction in power plant emissions (US)	Neurological deficiency	Benefits not monetized.	Total cost: $1.2–1.9 \times 10^9$ 120 000–190 000 per case averted
Palmer et al. (79)	Hg cap under CAIR for power plant emissions (US)	IQ, AMI, ACM	COI VSL	Cost: 3.4×10^9 Benefit: Same as Rice and Hammitt
Rae and Graham (84)	30%, 51%, and 100% reductions in power plant emissions (southeastern US)	IQ, nonfatal AMI, hypertension, ACM	COI VSL	Benefit: $619–2\,102 \times 10^6$ y^{-1} for four states in SE United States, only.
Rice and Hammitt (80)	26 t and 15 t US power plant emissions caps	IQ, alternatively assume with and without a threshold, nonfatal AMI, ACM	COI VSL	Benefits: IQ only (threshold): 0.075–$0.120 \times 10^9 y^{-1}$ IQ (no threshold) plus AMI plus ACM: $3.8–5.7 \times 10^9 y^{-1}$
Trasande et al. (81)	Evaluate costs of current emissions from all sources	IQ	COI	9.5×10^9 per birth cohort 1.4×10^9 due to power plants
US EPA (76)	Cap of 38 t in 2010, 15 t in 2018.	IQ	COI	Benefits: 0.25 to 1.56×10^6
US EPA (85)	Hg cap under CAIR and CAMR for power plant emissions (US)	IQ	COI	Costs: 750×10^6 y^{-1} by 2020 Benefits: Less than 168×10^6 y^{-1}

Abbreviations: ACM = all cause mortality; AMI = acute myocardial infarction; COI = cost of illness; CVM = contingent valuation method; IQ = intelligence quotient change; MACT = maximum achievable control technology; TCM = travel cost method; USD = US dollars; VSL = value of a statistical life.

distribution and consumption—remains a significant human exposure pathway in some populations, and can be associated with relatively high levels of chronic MeHg exposure (66). Subsistence fisheries are often held as common property with rules of conduct tending to be informal, local, and unwritten (67). Quantitative data on production and distribution of fish are rarely available, thus complicating the evaluation of MeHg exposure. The Arctic and sub-Arctic regions present a challenge on several fronts, including the finding that Hg from lower latitudes may be deposited by so-called "Hg-depletion events" (1), even though there are few anthropogenic emission sources. In some Arctic communities, marine mammals are also a significant dietary source of MeHg. In both Arctic and sub-Arctic settings, alternatives to locally harvested fish and marine mammals may be culturally untenable, unavailable, or not affordable (68).

ECONOMIC ANALYSES OF MERCURY USES AND POLLUTION

Economists often discuss a good's "opportunity cost"; that is, what must be sacrificed to obtain a good or service. For most goods, this is reflected in the price. But when the production of a good involves the release of a pollutant, such as Hg, the price may not include the associated environmental and social costs; these costs are called externalities. A negative production externality implies that individuals are adversely affected by production in ways that did not get factored into the product price; for anthropogenic Hg releases, this results when individuals are exposed to Hg or MeHg, as described in Figure 2. Economists have developed a number of methods to measure the costs of these externalities. We briefly review those methods here, focusing on methods to quantify the benefits to human health associated with reduced Hg exposure. Relative to humans, the effects of Hg on wildlife are poorly understood, so with the exception of the effect of consumption advisories on recreational fisheries, the economic value of reducing Hg pollution has seldom been quantified for wildlife and ecosystem functioning. As our review of existing studies shows, the scientific uncertainties even for humans lead to differing assumptions about health outcomes, which are translated into substantial variation in benefit estimates.

An additional consideration is that economic valuation methods do not work well when the implied tradeoff exceeds a person's or community's ability to pay. Economic analysis becomes very challenging if such tradeoffs are not possible, as might be the case when valuing Hg contamination to subsistence fishing communities with no practical dietary substitutes for Hg-contaminated fish.

Few economic studies have been conducted to quantify the benefits of reducing Hg pollution, and all of those have been conducted in the United States (Table 3). Among those few studies, there is only one that included wildlife benefits (69). Including the effects of Hg on wildlife and ecosystems is a daunting task; those studies that exclude such benefits will underestimate the full benefits of Hg reduction (70).

Economists employ two general approaches in measuring the human health benefits associated with a policy (71). Benefit–cost analysis (BCA) evaluates changes in health using monetary values, such as the cost of illness (COI) and willingness to pay (WTP) or willingness to accept (WTA) approaches. Cost-effectiveness analysis (CEA) evaluates these changes using summary measures of population health [e.g., disability-adjusted life years (DALYs) and quality-adjusted life years (QALYs), more generally known as health-adjusted life-years (HALYs)]. BCA collapses all health-related benefits and costs into a single, monetary metric from which economic efficiency can be evaluated. Those policies in which the incremental benefits exceed the incremental costs are beneficial to society. In contrast, CEA does not monetize benefits, instead this approach evaluates potential policies by comparing the ratio of a policy's cost to its health outcome, in cost per HALY. Policies with low cost per HALY ratios are typically preferred to those with high ratios.

Health Benefit Assessment Using Benefit–Cost Analysis

Cost-of-illness methods are used frequently to monetize the health improvement associated with a change in morbidity (illness). These methods measure the direct costs (e.g., treatment costs) and indirect costs (e.g., foregone income) associated with illness and injury, but do not measure losses associated with pain and suffering. For MeHg, COI methods link changes in the exposure of pregnant women to modeled changes in the IQ of their offspring. IQ changes are subsequently linked to changes in future income (throughout adulthood) and supplemental educational costs. Similarly, MeHg exposures can be linked to nonfatal heart attacks, with COI used to estimate the benefits of Hg reduction policies.

WTP methods measure an individual's willingness to exchange wealth for health. Economists consider such methods to be superior to COI methods because they include factors such as impairments to quality of life. For example, the value of a statistical life (VSL) measures an average individual's willingness to pay for a small change in the probability of dying sooner (72–75). Consider a Hg-reduction policy that could reduce the probability of death in a population from 2×10^{-5} to 1×10^{-5}, a reduction of one death per 100 000 people. If people are, on average, willing to trade 60 USD in exchange for this policy, then the VSL is 6 million USD (60 USD divided by 1×10^{-5}). Currently, the most common estimates for VSL used by researchers and policy makers in industrialized countries are between 3 and 7 million USD; the range arises, in part, because of the different values people hold for different types of mortality risks. VSL is positively related to income: a VSL estimated in a high-income country is generally greater than that estimated in a low-income country.

Table 3 summarizes a number of studies that attempt to monetize the benefits (usually human health benefits) associated with reduced MeHg exposure. The BCA conducted by the US Environmental Protection Agency's (US EPA) (76) as a component of the Clean Air Mercury Rule (CAMR) examined the costs incurred by US power plants to reduce Hg emissions and the monetized benefits associated with IQ increases in the children born to pregnant women whose MeHg exposures would be reduced as a result of the rule. Other groups also conducted benefit analyses of various Hg emissions reduction proposals under consideration during the development of this regulation (77–81). While the economic valuation models used are similar, assumptions regarding the impact of decreased Hg emissions on the changes in MeHg levels in different types of fish, and the health effects considered, differ markedly. All of the analyses emphasized the numerous uncertainties in evaluating specific policies for Hg reduction, including *i)* changes in Hg deposition rates, *ii)* changes in fish MeHg levels, *iii)* changes in MeHg intake by humans and the time it takes to observe this change, *iv)* changes in IQ due to fetal exposure, and/or *v)* changes in all-cause mortality and fatal and nonfatal heart attacks in adults. Some analyses assumed that Hg emissions markedly decreased only US freshwater fish MeHg levels; others assumed that marine fish levels, the primary source of MeHg exposure in the United States, could also decline as a consequence of decreased emissions. All analyses considered the impact of reduced fetal MeHg exposures on changes in IQ and lifetime earnings, although the slope of the MeHg IQ loss dose–response functions and lifetime earnings estimates vary. Some of these analyses also examined the impact of a toxicity threshold for the fetal neurotoxicity of MeHg that would be consistent with the US EPA's reference dose. Other studies included the possible economic impacts of decreased myocardial infarctions and premature mortality in adults. (See 11, 76, 80, and 82 for descriptions of the uncertainties in the epidemiologic data regarding these health end points.) The US EPA also simulated the time required for freshwater fish levels to change following an emissions reduction. These differences led to a large range of benefit estimates across the studies.

Much of the variability across the study results presented in Table 3 is a direct consequence of the differing assumptions that are made in response to uncertainties in the physical and health sciences of Hg and MeHg. For studies that have focused on nationwide programs, such as the emissions cap or the Clean Air Interstate Rule (CAIR) proposed in the United States (76–80, 83–85), we can see the impact of differing assumptions by comparing the results on a per capita basis. The EPRI study (77) and that by Gayer and Hahn (78) estimated costs of a 15-t cap-and-trade program at between 15 USD (Gayer and Hahn midpoint) and 21 USD (EPRI) per capita. Gayer and Hahn, focusing solely on IQ losses, estimate benefits of a Hg cap at less than 1 USD per capita. In contrast, the Rice and Hammitt study (80) , examining a similar program but including IQ, heart attack, and all-cause mortality effects, and assuming that there will be changes in both freshwater and marine fish, estimate benefits at about 16 USD per capita. The authors noted that heart attack and all-cause mortality effects and marine fish MeHg reductions are much less certain than the other factors included in their analysis. Given the uncertainties in the timing of the benefits, they did not discount the future benefits. Gayer and Hahn firmly conclude that the benefits of the Hg cap-and-trade program are less than its costs. Palmer, Burtraw, and Shih (79) , looking at Hg within the context of the CAIR, conclude that benefits (using Rice and Hammitt's estimate of 16 USD) exceed the estimated costs of CAIR (12 USD per capita). The primary factor driving the different conclusions is the decision on which health end points to include, a decision based on uncertainty in the physical and health sciences.

Economic benefits are based, fundamentally, on a person's WTP for reductions in Hg exposure. Whereas the studies in Table 3 represent a good start to a benefits literature, none of them address the theoretically correct, but difficult to estimate, WTP measures that incorporate uncertainty, such as "option price" (86). For example, consider exposure over time to a given level of Hg in commercially caught seafood. As a result of that exposure, one raises the risk of developing Hg-related health problems, such as AMI, above the baseline risk. Different people receiving the same Hg exposure will react differently: some will have a heart attack and others will not. The option price (OP) measures a person's WTP without resolution of this uncertainty, that is, without finding out if he or she is one of the people whose sensitivity to MeHg increases the likelihood of heart attack. The basic OP model can be augmented to incorporate uncertainty in the health risk itself (e.g., is the best estimate of MeHg-associated increase in AMI risk zero, or is it the dose-response slope 0.066 per ppm mercury in hair?); it can reflect endogeneity in the risk (e.g., risk estimates can be adjusted based an individual's actions, such as eating more or less fish), and it can include ambiguity about risks (a person may not have a good point estimate of their risk and instead consider their risk to be within a given range). An approach to economic analysis that explicitly incorporates uncertainty seems well suited for the case of Hg, in which policy choices must be made despite the presence of scientific uncertainty in environmental fate, exposures, and health effects.

The difficulty with such an approach is that different studies will produce different results. In most cases, a WTP measure such as OP would be elicited via stated preference methods, and WTP estimates will depend on the prior information that respondents have as well as that provided by the analyst. To the degree that researchers differ in the risks and uncertainties explained to respondents, study results will vary and must be evaluated within that context.

Health Benefit Assessment Using Cost-Effectiveness Analysis

The most commonly used HALY measures in CEAs are QALYs and DALYs. Different illnesses are associated with different degrees of severity; for these measures, severity is assessed by a utility weight (71, 73). The utility weights may be based on individuals' preferences for avoiding specific illnesses, or they may be based on expert opinions.

Both Ponce et al. (87) and Cohen et al. (88) examined neurocognitive deficiencies associated with fetal MeHg exposures, assuming that the deficiencies persist throughout the life of the affected individual. The benefit was assessed by multiplying the utility weight (i.e., the decrease in the quality of life that results from cognitive deficits) by the duration of the effect (persisting over the individual's lifetime). For QALYs, this calculation results in the prediction of the QALYs an affected individual experiences; they are compared with the increased number of QALYs an individual would experience if a policy to reduce MeHg exposures were put into place. The benefits are expressed as net QALYs gained by the population. For DALYs, the product of the utility weight and duration of the effect results in a prediction of disability-adjusted life years incurred. Population benefits of a policy are then evaluated by the decrease in the number of disability-adjusted life years incurred.

Both QALYS and DALYs are used as the denominators in cost-effectiveness analyses, with the numerator being the cost of the policy. The cost effectiveness of different policies can be compared; those that exhibit the largest gain in QALYs (or decrease in DALYs) for the lowest cost are preferred to those that exhibit smaller gains in QALYs for larger costs.

Benefits Assessment in Different Social Contexts

All of the BCAs and CEAs of Hg policies that we found have been conducted in developed countries, with monetary measures and HALYs used to address different economic questions associated with MeHg exposures that result from eating fish. While some of these analyses have attempted to identify subpopulations that benefit from implementation of a policy, most could be improved from additional analyses of the distribution of benefits and costs across the population. Finally, some of these analyses have examined the time frame over which anticipated MeHg exposure decreases and health-consequent benefits might occur. For many, benefits accruing soon after expenses are incurred are preferred to those same benefits accruing in the future (i.e., time value of money). While beyond the scope of this manuscript, both the manner and rate by which future health benefits are discounted is central to many policy analyses and may be particularly important for Hg, given the uncertain environmental response times implied by current research on the biogeochemistry of Hg (3).

In contrast to the number of evaluations in developed countries, we are not aware of a benefits assessment that examines the costs or benefits of reduced Hg releases and MeHg exposures in developing countries, or benefit assessments focused on those engaged in subsistence fishing or small-scale gold mining (Table 4). Such assessments could differ substantially from those in developed regions. Moreover, caution is warranted when applying these economic techniques in situations in subsistence societies where some Hg policies may greatly disrupt the social structure in a society with few alternatives to subsistence fisheries (Table 4; 89, 90), or in regions where small-scale gold mining is prevalent and there is no realistic alternative to using Hg to make a living. Table 4 also demonstrates that economic analyses of the costs and benefits of reducing mercury reductions are lacking for many of the Hg exposure pathways.

Assessments for Other Effects, Including Recreational Fishing and Environmental Degradation

Hg contamination may affect the quality of current recreational experiences, decrease future recreational use in this generation and future generations, and affect other values that one might hold irrespective of use. In a BCA, values for these impacts may be elicited directly by using stated preference techniques that rely upon choice in hypothetical situations (e.g., choice experiments or contingent valuation) or they may elicit value indirectly by using revealed preference approaches based on the observed choices of people (e.g., the travel cost model). Champ, Boyle, and Brown (91) provide an excellent introduction to these methods.

Jakus, McGuinness, and Krupnick (92) used observed human behavior to measure changes in commercial and recreational values due to fish and wildlife consumption advisories. For commercial fisheries, the cost of advisories was based on the market demand and supply for contaminated commercial species. Advice suggesting reduced consumption of striped bass means that at least some consumers will consume fewer bass at any given price. This "shift" in commercial demand is used to measure cost in terms of lost market value accruing to consumers and producers. A similar approach was used to measure impacts on recreational angling. Advice advocating restricted consumption of fish or wildlife altered the number of recreational trips or changed the species targeted. The travel cost method was used to calculate the change in the net value of fishing with and without consumption advisories. The method does not account for possible health impacts to those who do not change behavior in response to advisories.

Hagen, Vincent, and Welle (69) used a stated preference method, contingent valuation, to value changes in human health as a result of Hg-reduction policies, as well as the effects on recreational anglers and on wildlife. In their study, people were asked to estimate their willingness to pay for a policy designed to reduce environmental Hg levels. Respondents were asked to consider benefits from changes in their health, their family's health and, possibly, the health of their neighbors and others. As such, their analysis included cultural values, as in the case of a parent who would like his or her children to enjoy eating fish that they have caught as a family, irrespective of the health implications. Values may have been expressed for future

Table 4. Mercury exposure pathways and the extent of knowledge pertinent to cost–benefit analysis of reduction options. Benefit and cost methods that have been applied are in bold (references in parentheses); other possible approaches are listed. In many cases a necessary prerequisite is to quantify any connection between Hg releases and any endpoint.

Exposure pathway	Measurement tools (for benefits of reducing exposure)	Source of elevated Hg	Hg exposure reduction options	Measurement tools (for costs of reducing exposure)
FH—commercial fishing	**COI, VSL** (76, 78, 80, 81, 84, 85, 92)	VA—atmospheric deposition	a. Reduce Hg emissions from coal, ore refining, and small scale gold mining via: i. Incentives to develop control technology. ii. Incentives to transfer control technology globally. b. Purchase and consume low-Hg fish c. Consume nonfish source of protein	a. **COT** (77) b. **LMV (92)** c. COS
FH—recreational fishing	**COI, VSL (92)**	VA—atmospheric deposition	a. Reduce Hg emissions b. Consume low-Hg fish, release high-Hg fish. c. Fish low-Hg waters (e.g. different lake)	a. **COT (78)** b. **LRV (92)** c. **LRV (92)**
FH—subsistence fishing	COI, VSL	VA—atmospheric deposition	a. Reduce Hg emissions b. Reduce fishing & find alternate source of protein. c. Disseminate culturally appropriate fish consumption advice. d. Consume low-Hg fish, sell high-Hg fish.	a. COT b. QOL c. QOL d. QOL
FH—subsistence fishing	COI, VSL	DA—disposal of products and wastes to aquatic systems	a. Reduce Hg discharge to fishery b. Reduce fishing and find alternate source of protein c. Create incentives for switching to Hg-free products and processes for chlor-alkali and vinyl chloride monomer plants d. Disseminate culturally appropriate consumption advice. e. Consume low-Hg fish, sell high-Hg fish.	a. COT b. QOL c. COS d. QOL e. QOL
FH—subsistence fishing	COI, VSL	OA—ore refining discharges	a. Reduce Hg discharge b. Reduce fishing and find alternate source of protein d. Disseminate culturally appropriate fish consumption advice e. Consume low-Hg fish, sell high-Hg fish	a. COT b. QOL c. QOL d. QOL
FH—subsistence fishing and recreational fishing	COI VSL	Reservoir creation or operation	a. Evaluate impacts before reservoir creation b. Create and operate to minimize Hg in fish c. Reduce fishing & find alternate source of protein d. Disseminate culturally appropriate fish consumption advice e. Consume low-Hg fish, sell high-Hg fish f. Consume low-Hg fish, release high-Hg fish	a. COT b. COT COS c. QOL d. COT e. QOL f. **LRV (92)**
FH—subsistence fishing	COI VSL	SA—small-scale gold mining discharges	a. Provide incentives for efficient or reduced Hg use through: i. Reduce international supply of Hg through retirement, etc. ii. Transfer of culturally acceptable technology. iii. Build community capacity to reduce Hg-related problems. b. Economic development for opportunities other than gold mining. c. Reduce fishing & find alternate source of protein.	a. COS COT i. **COHR (62)** ii. COT iii. COT b. COED c. COS QOL
FW—wildlife consumption of fish	**SPM (69)**	VA—atmospheric deposition	a. Reduce Hg emissions.	COT
FW—wildlife consumption of fish	SPM	Reservoir creation or operation	a. Evaluate impacts before reservoir creation. b. Operate to minimize Hg in fish.	a. COT b. COT COS
FW—wildlife consumption of fish	SPM	OA—ore refining	Reduce Hg discharge	COT
FW—wildlife consumption of fish	SPM	DA—disposal of products, wastes to aquatic systems	Reduce Hg discharge to fishery	COT
FW—wildlife consumption of fish	SPM	SA—small-scale gold mining	a. Provide incentives for efficient or reduced Hg use through: i. Reduce international supply of Hg through retirement, etc. ii. Transfer of culturally acceptable technology iii. Build community capacity to reduce Hg-related problems b. Economic development for opportunities other than gold mining	a. COS COT i. COHR ii. COT iii. COT b. COED
SH—Inhalation exposure	COI, VSL	SV—inhalation while concentrating gold	a. Provide incentives for efficient or reduced Hg use through: i. Reduce international supply of Hg through retirement, etc. ii. Transfer of culturally acceptable technology iii. Build community capacity to reduce Hg-related problems b. Economic development for opportunities other than gold mining	a. COS COT i. COHR ii. COT iii. COT b. COED
MH—inhalation exposure	COI, VSL COI, VSL	MV—inhalation while manufacturing with Hg	a. Provide incentives for Hg-free processes b. Develop inexpensive Hg vapor monitoring	COS COT

Table 4. Continued.

Exposure pathway	Measurement tools (for benefits of reducing exposure)	Source of elevated Hg	Hg exposure reduction options	Measurement tools (for costs of reducing exposure)
PH—inhalation exposure	COI	PV—Hg vapor from Hg-containing product use and breakage	a. Choose Hg-free products (e.g., dental fillings, thermometers, medical devices, pharmaceuticals, barometers, paints, thermostats, lamps, etc.)	a. COS
			b. Create incentives for switching to Hg-free product production.	b. COS

Abbreviations: COED = cost of economic development; COI = cost of illness (including both MeHg and loss of protein and PUFA); COS = cost of substitute; COHR = cost of Hg retirement; COT = cost of technology, including the costs of research, and development and dissemination of fish consumption advice; LMV = lost market value; LRV = lost recreational value; PUFA = polyunsaturated fatty acids; QOL = quality of life; SPM = stated preference method; TCM = travel cost method; VSL = value of a statistical life (including both MeHg and loss of protein and PUFA).

generations and broader ecosystem services (so-called nonuse values), and thus WTP may or may not be tied to one's direct exposure to Hg.

While all of the previous analyses have been conducted in developed countries, both revealed preference and stated preference methods have been used in the developing nations on issues other than Hg. In less-developed regions, the suite of Hg impacts may be similar to those encountered in more-developed countries, but the values that these societies (e.g., subsistence fishing communities) place on these impacts could be very different from the values of those in more-developed countries (Table 4) and should be examined in future studies.

POLICY OPTIONS TO REDUCE Hg POLLUTION

Environmental Hg releases can be reduced by policies that reduce the supply or demand of Hg, implement technological controls (or processes) that reduce mercury releases during the production of goods that result in Hg releases (e.g., gold and electricity), or reduce the quantities of produced goods that result in such releases. In general, policy options used routinely to reduce pollutant emissions from industrial processes include technology requirements, emission performance standards, emission taxes, and cap-and-trade (CAP) approaches. Other policy options such as subsidies and restrictions on the sale and disposal of Hg (and Hg-containing items) could influence Hg releases from small-scale practices such as artisanal gold mining. Application of any of these alternative policies to Hg reduction will have benefits and costs. An economic approach to evaluating different policy options is to balance, at the margin, the benefits and costs of any policy option. Such policies are deemed economically efficient.

In the case of Hg, economic analysis is complicated by the need to track benefits and costs at various geographic scales, from local to global. While the costs associated with the implementation of new processes or control technologies can be estimated in a relatively straightforward manner, the assessment of benefits is complicated by the scientific uncertainties reported in the environmental literature [i.e., the linkages between reducing environmental Hg releases and lower levels of Hg in the atmosphere and in fish (1, 3)] and health science literature [i.e., linkages between reduced levels in the environment, reduced exposures, and health improvement (3, 11)]. Ideally, economic analyses highlight these uncertainties as well as those introduced in the benefit–cost component of the analysis, and researchers will conduct additional analyses to assess the sensitivity of the results to the assumptions associated with the uncertainties (93). Resolution of uncertainty—regardless of the source—will increase the reliability of the economic analyses.

Each of the main policy options has particular strengths and weaknesses. Technology requirements mandate a particular production or control technology, and can have the advantage of offering well-understood pollution reduction. On the other hand, for any specific level of reduction in the release of a given pollutant, economic models suggest that, when compared with other policy options, technology mandates generally have a higher cost than more flexible approaches and may provide less incentive for technological innovation (94, 95). Performance standards offer some flexibility by which firms can reduce costs; for example, firms have an economic incentive to develop less costly control technologies. Ideally, performance standards provide regulators assurance about the level of a pollutant released at each regulated source, an important advantage for pollutants that can have significant local impacts.

Market-based reduction policies can take the form of emission taxes or CAP. Under an emission tax approach, a source may emit any quantity of a pollutant desired but is taxed for each unit released. In CAP, the regulatory authority sets an aggregate emissions level and issues permits (that sum to the target level) to polluters by an auction or simple distribution. Polluters are free to trade permits, with the prevailing price naturally reflecting the incremental cost of control. Economic models suggest that market-based policies spur innovation of new production technologies that are more efficient or less costly than extant technologies (34, 94, 95). If sources of emissions face differing abatement costs, the emissions tax and CAP approaches generally offer lower total costs of control (when summed over all facilities) relative to technology or performance standards. This is because choices about how much to control are made by facility management based on the prices they face rather than by the regulatory authority. A requirement of either the emissions tax or CAP approaches is that emissions be accurately monitored and enforced. For pollutants with local impacts, a key disadvantage of the emissions tax and CAP approaches is the potential for local impacts to persist or increase where facilities deem it uneconomical to reduce pollution. Some have suggested that this problem can be addressed through differential trading rates in a CAP (96), differential taxes, or combining a CAP with a performance standard. Devising a policy to avoid local impacts under a CAP would require considerable knowledge about local factors that control exposure to such a pollutant.

With respect to large point sources of Hg emission to the air, reduction policies have generally relied on performance standards; for example, in the United States, performance standards were finalized for municipal waste combustors in 1995, for medical waste incinerators in 1997, and for hazardous waste incinerators in 2002 (43). However, in the case of coal-fired electric power plants, in 2005 the US federal government promulgated a CAP (5, 76). At the time of this writing, the regulation on Hg releases from both large and small sources, and strategies to address supply and demand of Hg, are rapidly evolving. This evolution is partly a function of the limits of economic analysis and uncertainties over the environmental fate, exposure, and health effects associated with Hg releases. While an economic approach may assess the relative economic efficiency of any set of potential policies, the choice of any one policy is subject to a variety of factors, only one of which is efficiency. For example, two different policies may be economically efficient, yet reduce very different amounts of pollutant, have different levels of benefits and costs, or have benefits and costs that are distributed quite differently across a population. Strictly speaking, benefit–cost analysis has little to say about a choice between these two policies. Thus, acceptable policies must also satisfy political, social, and cultural criteria.

POLICIES TO LIMIT EXPOSURES TO MERCURY THROUGH RISK COMMUNICATION

In addition to reducing Hg releases, human Hg exposures can also be reduced through risk communication policies, including fish consumption advisories, improved communication of the occupational risks associated with Hg releases during artisanal gold mining, and product labeling. In this section, we focus on consumption advisories and also provide a brief description of the risk communication challenges associated with small-scale gold mining. We note that the impacts of product labeling policies need additional study.

Fish consumption advisories are considered by many policy makers to be an unfortunate and, hopefully, interim public health necessity. In general, advisories are based on an assessment of the human health risks associated with pollutant exposures, including fetal exposures that result from consuming contaminated fish (e.g., 97). The primary policy goal of a fish consumption advisory is to reduce pollutant exposure by reducing the intake of a contaminant (MeHg, in this case), while maintaining recommended fish intake; this is accomplished by recommending consumption of different fish species, smaller fish, or fish from a different fishery (i.e., a different body of water that has less contaminated fish). The risk managers who develop fish consumption advisories consider multiple issues, including what level(s) of fish contamination should trigger the issuance of an advisory, the species of fish involved, and their availability to consumers. Consideration is given to identifying groups or individuals who should follow the advisory (e.g., fishers, women of reproductive age, or those responsible for food preparation). Techniques for communicating with different audiences need to be evaluated. Last, but certainly not least, the languages and concepts used by consumers to convey information should be studied, as well as aspects of local fishing economies, including distribution and sharing practices. The practical implications of advisories on fish consumption have seldom been documented, and most likely vary a great deal depending on the nature of the advice, how it is communicated, and the alternatives available to the community (e.g., 98, 99).

For public health officials, a fundamental tension exists in the development of fish consumption advisories: how to communicate to people that they should avoid eating highly contaminated fish, but that they should continue to eat fish because of its nutritional value and the associated health benefits. Fish are high in protein and low in saturated fat. Frequent fish consumption has been shown to reduce the risk of heart disease (100). Policy makers, thus, prefer to consider such advisories as "interim" in the expectation that other measures can be implemented that will effectively reduce the fish tissue MeHg concentrations (3). Knowledge of the impacts of fish consumption advisories on diet is quite limited, and this is an area that requires further research (88).

The contamination of fish by MeHg can be an elusive concept to convey because this toxicant cannot be detected visually in the fish and the fish do not appear to be diseased. Consumers can interpret consumption advisories in various ways; accurate communication of an advisory can be especially difficult when there are linguistic or cultural differences between the risk manager and the affected population (99). Since individuals who communicate advisories may differ in their views of the risks involved and their relation to the nutritional role of fish (e.g. 101), conflicting advice may be received by a fishing community. Those who develop advisories, therefore, require appropriate knowledge of the nature of the fishery itself, as well as fish sharing, preparation, and consumption rates and practices (97, 102, 103).

The use of fish consumption advisories presents additional challenges for remote and isolated communities dependent on subsistence fisheries, including some North American indigenous populations (99). In some subsistence societies, advisories have resulted in widespread avoidance of fish rather than reduced consumption of the most contaminated fish (104). The loss or substantial disruption of local fisheries can also have significant public health implications, as well as related cultural impacts (105). Alternative dietary choices available in larger population centers may simply not be available to subsistence populations, and the communities may already face significant diet-related public health problems (such as diabetes). In such settings, health service providers face the task of balancing the message of the consumption advisories against the public health consequences of significant changes in human nutrition (106).

In 2004, the US EPA and Food and Drug Administration (FDA) released a joint statement (107) that described fish and shellfish as important components of a healthy diet. It noted that "a well-balanced diet that includes a variety of fish and shellfish can contribute to heart health and children's proper growth and development," although "nearly all fish and shellfish contain traces of Hg ...." Finally, the statement advised women who may become pregnant, pregnant women, nursing mothers, and young children to avoid some types of fish (i.e., shark, swordfish, and king mackerel) because of the high MeHg levels and to eat up to two meals each week of fish or shellfish that are low in MeHg (e.g., shrimp, canned light tuna, salmon, pollock, and catfish). The joint statement also cautioned consumers to check local advisories about the safety of consuming fish caught in local bodies of water, noting that if no advice was available, to eat up to one fish meal of average size per week, but not to consume any other fish during that week. Several investigators have compared the risks associated with MeHg exposures and the nutritional value and health benefits of fish consumption (11, 87, 88, 108). Their findings generally are consistent with the EPA and FDA statement.

In the case of small-scale gold mining using Hg amalgamation, the primary toxicological issue is the inhalation of Hg converted to the gas phase during the heating of the amalgam. Heating often takes place inside or near the home. Artisanal workers and their families can be exposed to harmful levels of Hg vapor. Risk communication in the form of advice to avoid the Hg amalgamation technique or to reduce exposure during its use must take into account the limited options available to the gold miners and the widespread poverty and hardship associated with this occupation. Field researchers (e.g., 48, 53) emphasize that effective risk communication strategies need to be intertwined with strategies targeting improved profitability through better gold recovery methods or reduced losses of Hg, thus reducing the artisinal miner's production costs. Within each country, the industry is geographically scattered, so the logistical aspects of risk communication are a major challenge. Thus, to be effective, in each region, risk communication strategies may involve training a cadre of small-scale gold miners who can demonstrate and discuss the advantages of improved practices to their fellow miners (53).

CONCLUSIONS

Mercury is a naturally occurring element that can affect the health of humans and wildlife. Humans have historically found Hg to be a useful liquid metal for a variety of social and economic purposes, and currently release some 2400 t y^{-1} of Hg into the atmosphere. The best estimate is that almost 90% of anthropogenic emissions comes from the combustion of fossil fuels in electric power generation and from the release of Hg in large- and small-scale mining operations, although emissions associated with intentional Hg use are difficult to quantify and may be substantially underestimated. Some Hg emissions to the atmosphere are deposited relatively near the source, but a large portion enters the global atmospheric reservoir.

The most important pathways of human exposure to Hg are through the consumption of MeHg-contaminated fish and inhalation of Hg vapor. Worldwide, the greatest source of inhalation exposure likely is from small-scale gold mining. The release of Hg used in restorative dentistry can be a source of exposure, but the associated risks are not well understood. Exposure to environmental Hg is believed to have a number of potential negative effects on human health, including: *i)* cognitive deficits (e.g., reduced IQ) in children due to fetal exposure and in adults exposed to high concentrations of Hg vapors, *ii)* possible increases in fatal and nonfatal heart attacks, and *iii)* increases in premature death (i.e., some studies link Hg exposures to increased risk of premature mortality regardless of cause).

While the general pathways outlined in this paper are accepted, a great deal of uncertainty remains in the linkages between emissions and human health. Resolution of these uncertainties is important for analysis of Hg reduction policies but will be difficult to achieve. The key physical and health science questions include the magnitude of the environmental response, the environmental response time (i.e., the length of time between decreased Hg emissions and consequent changes in human health risks), to what degree decreased exposures will reduce the risks of cognitive deficits, heart attack, or premature death and, if so, in which populations. While some exposure pathways are better understood than others, the full extent of health damages in many of these pathways is not known. For example, while fetal exposures are relatively well studied (although uncertainties remain), the dose–response functions for health effects resulting from chronic exposure in adults, such as cardiovascular disease, remain uncertain.

Uncertainty with respect to health effects has implications for choices among many policy alternatives. Both of the primary approaches to economic evaluation, BCA and CEA, require that one be able to link changes in Hg emissions to changes in various health outcomes; uncertainty with respect to policy benefits implies uncertainty in the benefit–cost or cost-effectiveness metrics coming out of the analysis. The few economic studies of Hg policies all express concern about the degree of uncertainties in the physical and health science of Hg exposure, suggesting that a valuation approach that explicitly deals with uncertainty and ambiguity is warranted. Three other aspects of the economic and social analysis are also important for future research. First, all of the economic studies have been conducted in the context of a developed economy, but key aspects of Hg reduction policies affect people living in developing countries or regions (e.g., small-scale mining operations or subsistence fisheries). Second, little research has been done to quantify non–health-related benefits, such as nonuse values associated with benefits to future generations. Third, costs (both economic and social) associated with structural changes in local food production systems such as subsistence fishing are not well understood and, therefore, not well quantified in cost–benefit analyses. Given uncertainty with respect to benefits and costs, it is difficult to conclude *a priori* that any one Hg-reduction policy is "better" than any other from an economic point of view, or even if the benefits of such a policy exceed the costs.

Given the variety of sources and reduction options, many approaches to reduce Hg releases or exposures are being proposed and considered at multiple levels in governments around the world. Economic and comparative risk analyses need to be conducted to examine these approaches. Because Hg emissions in one part of the planet are transported globally, the efficiencies and risks associated with these approaches need to be evaluated in light of the local, regional, and global impacts. Likewise, international trade also moves elemental Hg globally and is linked to emissions and exposure; better data on country-to-country and in-country commercial flows of Hg (indeed, most countries have a poor understanding of their domestic use of Hg) will contribute to refining existing policies and developing new ones. Decision makers also need to analyze potential interrelationships between policies so that one policy does not reduce the efficiency of another. To the extent possible, effective and acceptable policies must satisfy political, social, and cultural criteria, as well as economic criteria.

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Edward Swain is a research scientist with the Minnesota Pollution Control Agency and an adjunct assistant professor at the University of Minnesota. His research on mercury ranges from the history of atmospheric deposition to factors that control methylation. His address: MPCA, 520 Lafayette Road, St. Paul, MN 55155, USA.
E-mail: edward.swain@state.mn.us

Paul Jakus is a professor in the Department of Economics at Utah State University. His specialty is nonmarket valuation, especially with respect to behavioral changes induced by fish consumption advisories. His address: Department of Economics, UMC 3530, Utah State University, Logan, UT 84322, USA.
E-mail: paul.jakus@usu.edu

Glenn Rice is a doctoral candidate at the Harvard School of Public Health. His research interest is human health risk assessment methods, a field in which he has worked for 15 years. His address: 16 Princeton Avenue, Ft. Mitchell, KY 41017, USA.
E-mail: grice@hsph.harvard.edu

Frank Lupi has a joint appointment as an associate professor in the Agricultural Economics and the Fisheries and Wildlife departments at Michigan State University. His recent research focuses on modeling Michigan fish and wildlife resource demand and value. His address: Department of Agricultural Economics, Michigan State University, East Lansing, MI 48824 USA.
E-mail: lupi@msu.edu

Peter Maxson is an engineer and economist who, after many years' work in developing countries, has focused for nearly 20 years on all aspects of commercial mercury flows, national policies, and other environmental issues. In the early 1990s he founded the small consultancy, Concorde East/West Sprl, 10 ave. René Gobert, 1180 Brussels, Belgium.
E-mail: concorde.ew@tele2allin.be

Jozef Pacyna is director of the Center for Ecological Economics at the Norwegian Institute for Air Research and Professor of Chemistry at the Gdansk University of Technology in Poland. His research on mercury includes assessment of mercury fluxes from anthropogenic sources, application of technological and nontechnological measures to reduce mercury emissions, and socioeconomic aspects of such reductions. His addresses: Center for Ecological Economics, NILU, P.O. Box 100, 2027 Kjeller, Norway, and Chemistry Faculty, Gdansk University of Technology, 11/12 Narutowicza Str., 80–952 Gdansk, Poland.
E-mail: jp@nilu.no

Alan Penn works as an advisor for a group of aboriginal communities (Cree) in northwestern Québec, Canada, who have had a long history of exposure to mercury and who have been the subject of several major epidemiological studies. The Cree experience encompasses mercury losses from chlor-alkali cells, forestry, mining—and for the last 25 years, large-scale hydro-electric development—as well as exposure to methylmercury from mercury in northern forest soils and peatlands. His address: Cree Regional Authority, 277 Duke Street, Suite 100, Montreal (QC) H3C 2M2, Canada
E-mail: apenn@gcc.ca

Samuel Spiegel is a policy analyst and researcher specializing in poverty and environment issues in Africa. He has worked with the United Nations Industrial Development Organization in Latin America, Africa, and Asia on legal and economic strategies concerning artisanal gold mining and mercury pollution. He is presently pursuing a Ph.D. as an interdisciplinary Trudeau Scholar at the University of British Columbia. His address: University of British Columbia, 6350 Stores Rd., Vancouver, BC, V6T 1Z4 Canada
E-mail: samspiegel@gmail.com

Marcello Veiga is the Chief Technical Advisor of the GEF/UNDP/UNIDO Global Mercury Project and an associate professor in the Department of Mining Engineering at the University of British Columbia. His address is: University of British Columbia, 6350 Stores Rd., Vancouver, BC, V6T 1Z4, Canada.
E-mail: veiga@mining.ubc.ca