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Benefits of mercury controls for the United States

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Mercury pollution poses risks for both human and ecosystem health. As a consequence, controlling mercury pollution has become a policy goal on both global and national scales. We developed an assessment method linking global-scale atmospheric chemical transport modeling to regional-scale economic modeling to consistently evaluate the potential benefits to the United States of global (UN Minamata Convention on Mercury) and domestic [Mercury and Air Toxics Standards (MATS)] policies, framed as economic gains from avoiding mercury-related adverse health endpoints. This method attempts to trace the policies-to-impacts path while taking into account uncertainties and knowledge gaps with policy-appropriate bounding assumptions. We project that cumulative lifetime benefits from the Minamata Convention for individuals affected by 2050 are \$339 billion (2005 USD), with a range from \$1.4 billion to \$575 billion in our sensitivity scenarios. Cumulative economy-wide benefits to the United States, realized by 2050, are \$104 billion, with a range from \$6 million to \$171 billion. Projected Minamata benefits are more than twice those projected from the domestic policy. This relative benefit is robust to several uncertainties and variabilities, with the ratio of benefits (Minamata/MATS) ranging from ≈ 1.4 to 3. However, we find that for those consuming locally caught freshwater fish from the United States, rather than marine and estuarine fish from the global market, benefits are larger from US than global action, suggesting domestic policies are important for protecting these populations. Per megagram of prevented emissions, our domestic policy scenario results in US benefits about an order of magnitude higher than from our global scenario, further highlighting the importance of domestic action.

mercury | policy | impacts assessment | Minamata Convention | economic benefits

Toxic contamination from human activities is a global problem. Although some countries have regulated toxic substances such as heavy metals and persistent organic pollutants for several decades, chemical contamination has still been identified as a key planetary boundary at risk for exceedance in the context of global change (1). To address this challenge, existing global environmental treaties try to manage the entire life cycle of chemical contaminants (2). The newest of these is a global treaty on mercury, the Minamata Convention. In November 2013, the United States became the first country to fulfill the requirements necessary to become a party to the convention.

In the United States, analyses to support domestic environmental decision-making include socioeconomic valuations of impacts as part of the regulatory process. However, these evaluations can be both scientifically challenging and politically contentious, particularly given uncertainties and knowledge gaps (as noted in arguments in a recent case heard in the US Supreme Court, *Michigan v. Environmental Protection Agency*, 2015, addressing analysis of the costs and benefits of mercury regulation). These challenges are especially difficult for contaminants such as mercury, which cross temporal and spatial scales and have both domestic and global sources. The chain of analysis from policies, through emissions, to impacts involves a complex pathway, which for mercury includes industrial activities, atmospheric chemistry, deposition processes, bioaccumulation, and human exposure. Existing approaches have not fully combined information and knowledge from these disparate fields, and

substantial gaps exist in scientific understanding of the processes that mercury undergoes through long-range transport. Thus, it has historically been difficult to quantitatively estimate prospective domestic benefits from global environmental treaty-making in ways that can be compared with socioeconomic analyses designed to support domestic environmental decision-making. Here, we use an assessment approach that enables tracing this pathway, accounting for best-available scientific understanding and addressing uncertainties and knowledge gaps with policy-appropriate assumptions.

Mercury is a naturally occurring element, but human activities such as mining and coal combustion have mobilized additional amounts, enhancing the amount of mercury circulating in the atmosphere and surface oceans by a factor of three or more (3, 4). Mercury previously deposited to land and water can revitalize over decades to centuries. Thus, human activities have fundamentally altered the global biogeochemical cycle of mercury (5). Deposited mercury in aquatic systems can be converted to more toxic methylmercury (MeHg), which bioaccumulates. People are then exposed to MeHg by eating contaminated fish. Effects of MeHg exposure include IQ deficits in prenatally exposed children (6–8) and may include cardiovascular effects in adults (7, 9). Scientific uncertainty and variability are substantial throughout this pathway, including but not limited to atmospheric chemistry, deposition patterns, methylation processes, bioaccumulation and food web dynamics, dietary patterns of exposure, and dose–response relationships. Despite these uncertainties, scientific analyses have been conducted to support decision-making, and state-of-the-art models exist for many of these steps.

Some studies have previously traced the pathway from mercury emissions to human impacts. These studies are limited in how completely they have represented physical processes, and how they have accounted for knowledge gaps. First, many do not explicitly consider spatial transport through the environment on a global scale, and so do not explicitly link emissions to exposure changes (10–14). Timescales associated with bioaccumulation through ecosystems also are often not taken into account, making

Significance

Mercury is a globally transported pollutant with potent neurotoxic effects for both humans and wildlife. This study introduces an assessment method to estimate the potential human health-related economic benefits of global and domestic mercury control policies. It finds that for the US population as a whole, global mercury controls could lead to approximately twice the benefits of domestic action by 2050. This result is robust to several uncertainties and variabilities along the emissions-to-impacts path, although we find that those consuming locally caught freshwater fish in the United States could benefit more from domestic action.

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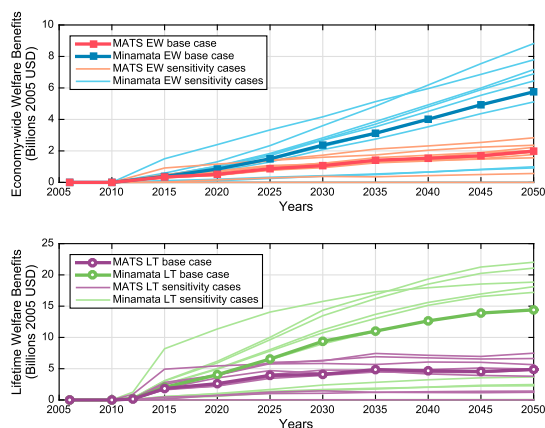


Fig. 2. Trajectories of welfare benefits under global and domestic policy until 2050, discounted at 3%. (*Top*) Modeled EW benefits realized in a given year. (*Bottom*) Projected LT benefits for that year's affected population. Base cases are indicated with markers. Unmarked lines show the range of trajectories from sensitivity cases.

in our sensitivity analysis) (30, 37). We specify base year blood MeHg, as a biomarker for MeHg exposure, by region, based on the National Health and Nutrition Examination Survey (40). We then scale blood concentrations based on the change in intake of fish MeHg (change in deposition plus time lag), taking into account consumption of domestic freshwater and imported fish species from global fisheries, using data from US seafood market studies (41) and data compiled by the US Environmental Protection Agency on noncommercial anglers (15, 42). Because of data limitations, we consider noncommercial mercury intake from local, freshwater fish only. We treat noncommercial marine anglers as average US consumers of marine and estuarine fish. This may slightly underestimate the benefits of MATS in our work; however, further data are necessary to quantify the MeHg intake of noncommercial anglers in different US coastal regions (see *SI Appendix, Changes in human exposure* for detailed methods).

Calculated average US mercury intake in 2050, assuming a 10-y time lag between deposition changes and fish response, as well as constant fish intake patterns, is 91% less under our Minamata scenario than under NP (*SI Appendix, Fig. S5*). Our MATS scenario reduces intake by 32% compared with the NP case. Although the deposition decreases over the United States are roughly equivalent between the MATS and Minamata scenarios, changes to modeled mercury intake are larger under the latter. More than 90% of the US commercial fish market, and the majority of US mercury intake, comes from marine and estuarine sources, particularly from Pacific and Atlantic Ocean basins (41, 43). These regions are heavily influenced by emissions from non-US sources, including East and South Asia. In addition, even locally caught freshwater fish are affected by the long-range transport of mercury emissions. Regional differences in the geographic source of dietary fish (*SI Appendix, Changes in human exposure*) and deposition lead to variations in intake change patterns across scenarios, as shown in *SI Appendix, Fig. S4*. The majority of modeled MeHg intake in the North Central region (*SI Appendix, Fig. S5*) is from self-caught, local freshwater fish, leading to a diminished intake benefit from the Minamata scenario relative to the MATS scenario. The opposite pattern holds for New York. These differences in intake lead to corresponding differences in IQ deficits and cardiovascular outcomes (see *SI Appendix, IQ effects; Cardiovascular impacts; and Health impacts* for health impacts methods and results, respectively).

Annual US economic benefits to 2050 (applying a 3% discount rate) from avoided health impacts under domestic and global mercury policies under our base case assumptions, relative to NP, are presented in Fig. 2. We use two economic valuation approaches: the first, a cost-of-illness and value of statistical life

(VSL) approach, estimates projected lifetime (LT) benefits of avoided exposure for those born by 2050 and is consistent with US regulatory practice; the second, a human capital approach, estimates economy-wide (EW) benefits realized by 2050 from avoided labor productivity and wage losses. Given differences in methodology, results from these two approaches are not directly comparable (see *SI Appendix, Economic modeling of health impacts* for more details). To estimate LT benefits of avoided health effects, we apply estimates of projected lost wages and medical costs for IQ deficits and nonfatal acute myocardial infarctions (heart attacks), and VSL for premature fatalities resulting from myocardial infarctions (see ref. 12 and examples listed in ref. 44 of studies that use this approach), for each year's projected birth cohort (IQ) and affected adult population (heart attacks). The second method uses the US Regional Energy Policy model, a computable general equilibrium model of the US economy (45). Consistent with previous work valuing economic effects of air pollution through computable general equilibrium modeling (46), we take into account the effects of IQ deficits and fatal and nonfatal heart attacks on the labor force, and its cumulative effect over time. Base case cumulative EW benefits of the Minamata Convention to the United States by 2050 are \$104 billion (2005 USD) (Fig. 2, *Top*, blue line), and cumulative LT benefits for those born by 2050 are \$339 billion (Fig. 2, *Bottom*, green line). EW benefits from our MATS scenario (Fig. 2, *Top*, red line) are \$43 billion by 2050, and LT benefits are \$147 billion (Fig. 2, *Bottom*, purple line). Both EW and LT benefits are dominated (>90% for LT and >99% for EW) by avoided cardiovascular effects, consistent with previous studies, including these health endpoints (12, 16). Relative to US domestic action, estimated cumulative benefits from the Minamata Convention are more than twice as large.

Considered per unit of avoided emissions, however, the projected benefits of MATS to the United States are larger than those of the Minamata Convention: \$324 million/Mg compared with \$46 million/Mg for EW benefits by 2050, and \$1.1 billion/Mg compared with \$150 million/Mg for LT benefits for those born by 2050. Given its global scope, the Minamata Convention is likely to prevent more emissions than MATS. However, as mercury pollution has effects on both local and global scales, avoided emissions within the United States, on a per unit basis, lead to larger benefits.

Policies-to-Impacts Sensitivity Analysis. We assess uncertainty and variability along the policies-to-impacts pathway by identifying key drivers of uncertainty in our base case integrated model, and calculating how changes in assumptions affect our quantification of US benefits from the Minamata Convention, MATS, and relative benefits. Key assumptions addressed here include the effect of atmospheric chemistry, ecosystem time lags, dietary choices, dose-response parameters linking MeHg exposure and health effects, economic costs, and discount rates. We run the integrated model for realistic and policy-relevant low and high bounds for these assumptions. Fig. 2 shows the range of calculated benefits from these sensitivity scenarios, described further here. The uncertain range spanned by these cases is illustrated by the lines in Fig. 2; however, the bounds delineated by these lines for the Minamata (blue/green) and MATS (red/purple) scenarios are not independent. Some sensitivity scenarios lead to the same directional change in benefits over the base case for both the domestic and global scenario, such that the magnitude of cumulative benefits for the Minamata scenario remain larger than for MATS. This result is illustrated in Fig. 3, which shows the range in ratio of benefits between Minamata and MATS, under different sensitivity scenarios. Details of the low and high cases addressed are presented in *SI Appendix, Table S7 and Sensitivity analysis*.

Our low and high cases for atmospheric chemistry bound uncertainty about the form of mercury emissions and atmospheric redox reactions. Although policies address total mercury emissions, emissions of mercury occur as different chemical species with different atmospheric lifetimes. Mercury emitted in its elemental form, Hg(0), has an atmospheric lifetime of 6 mo to a year, enabling it to transport globally before its oxidation and

Implications for Policy Evaluation. We developed and applied an assessment method to examine the complex pathways from policies to environmental effects for global toxic pollution from mercury that accounts for uncertainties and knowledge gaps in a structured way. We showed, using this method, that by 2050, the Minamata Convention could have approximately twice the benefit of our scenario simulating domestic actions (\$104 billion compared with \$43 billion in cumulative EW benefits, and \$339 billion compared with \$147 billion in cumulative LT benefits). The relative benefit is robust to several uncertainties assessed along the policies-to-impacts pathway, including atmospheric chemical processes, ecosystem time lags, and exposure–response relationships; however, we find that domestic action has a larger benefit when dietary fish is sourced from local freshwater bodies. Per megagram of avoided emissions, the benefits to the United States of domestic action are nearly an order of magnitude larger than global action, highlighting that although mercury is a global pollutant, local policies contribute strongly to local benefits. As shown in *SI Appendix, Fig. S4*, avoided emissions associated with the Minamata Convention outside of the United States may lead to large benefits in Asia and Southern Europe. Abatement costs will also vary by region.

Although we have conducted what is, to our knowledge, the first global-scale attempt to link future emissions trajectories to domestic impacts, our ability to incorporate detailed models of the entire pathway is limited by existing scientific knowledge. In addition to these knowledge gaps, there are also variabilities in mercury's behavior across ecosystems and regions, as well as in human responses (physical and social). Our approach uses bounding assumptions along the policies-to-impacts pathway as a proxy to assess the relative influence of various uncertainties, from a range of disciplines. In a number of previous analyses, range in the benefits of mercury reduction has been specified by the range in exposure–response functions (12, 13). Although our analysis underlines the importance of these uncertainties, particularly those related to cardiovascular effects, it also suggests that previous approaches miss other potentially large contributors to uncertainty in economic effects (particularly within a given time horizon), such as marine and freshwater ecosystem dynamics and dietary intake variabilities.

Although, all else being equal, mercury emissions reductions will ultimately result in exposure reductions, our analysis indicates that uncertainties in ecosystem dynamics affecting the timescale of these reductions will strongly influence benefits within a given time horizon. Many of the processes affecting the conversion of inorganic mercury to MeHg and subsequent uptake in biota are poorly understood, particularly in marine ecosystems (54, 55). In addition, there is variability among ecosystem types, both freshwater (37) and marine and estuarine (32), in how quickly these systems and biota within them respond to changes in deposition. As described previously, our analysis focuses on changes to mercury in surface reservoirs, and accounting for these effects could increase benefits estimates by ~30%. Future research should more fully address the timescales of reemissions from subsurface reservoirs, both land and ocean, and their effects on benefits estimates. Better understanding of mercury cycling, methylation and bioaccumulation processes, their variability, and the potential effects of global changes to climate, land use, and other environmental contaminants will be critical for improving policy evaluation (56), particularly for better understanding the distribution of benefits between current and future generations.

Our analysis also reveals the importance of social factors in estimating the absolute and relative benefits of different policies. Dietary choices, including fish selection and consumption rate, can have a potentially larger influence on the ratio of benefits from global compared with domestic action than substantial scientific uncertainties about mercury's environmental behavior. This sensitivity result suggests that domestic actions may be particularly important for reducing exposure for communities that consume mostly fish sourced from the contiguous United States, such as certain Indigenous peoples and immigrant groups,

subsistence fishers, and recreational anglers. In addition, it highlights the policy need for analysis and data collection on the evolving patterns in fisheries production and fish consumption (43). It has been noted that dietary guidance on fish selection and consumption frequency could be part of an adaptation strategy to minimize mercury exposure (57), and our results point toward their potentially large effect as a policy lever. However, dietary advice is highly complex. Fish consumption, and specific fish selection, can have substantial benefits, both nutritional (58, 59) and sociocultural (60). Balancing the risks and benefits of fish consumption therefore requires careful consideration of contextual factors. Even with such adaptive approaches, there is continued need to mitigate future emissions.

Although uncertainties related to chemical speciation of emissions reductions led to the smallest range in cumulative benefits for the Minamata scenario, interactions between these uncertainties and variabilities in dietary fish source could affect the relative benefits of global versus domestic action. At this time, our ability to constrain these speciation uncertainties is partially limited by measurement challenges (61). Improved measurement techniques could provide insight into distributional aspects of control policies.

Differences in valuation methods for health endpoints could lead to substantial variation in benefits estimates. Our two valuation approaches highlight some of these potential variations: Our EW approach emphasizes compounding economy-wide gains over time, but considers only effects to the economy (not individuals) realized within the 2050 time horizon; in contrast, our LT approach more closely resembles regulatory studies, taking into account projected lifetime and nonmarket effects to individuals (e.g., pain and suffering). As highlighted previously, economic benefits estimates are very sensitive to choices of temporal scope of analysis and discounting. Estimates are also sensitive to the endpoints considered: In addition to the health effects considered here, there may be other human and wildlife health endpoints not included in this study that, although not well characterized at this time (7), may also have economic effects. No less important, there may be dimensions of individual and community health and well-being that are not quantifiable within this economic framework, which should be considered in a holistic assessment of policy benefits (62).

Our assessment of US benefits from global and domestic policy is designed to be illustrative, drawing attention to uncertainties in estimating economic benefits and methods to take these uncertainties into account. As a consequence, our estimates should not be taken as a comprehensive projection of impacts. However, as scientific knowledge evolves, many uncertainties can be addressed using similar methodology. Policies-to-impacts analyses similar to the one presented here can be valuable for synthesizing available information, identifying its limitations, and when combined with sensitivity analysis, suggesting areas where scientific data collection to narrow uncertainty would lead to uncertainty reduction of importance to policy-making.

Materials and Methods

Brief explanations of methods have been included throughout *Results and Discussion*. In the *SI Appendix, Supplementary methods*, we provide a detailed description of methodology and data sources for emissions projections, chemical transport modeling, translating changes in deposition to changes in human exposure, IQ and cardiovascular impacts modeling, economic modeling of health impacts, and sensitivity analysis. Institutional review and informed consent were not necessary for this modeling study, as all human health and ecosystem input data were drawn from published sources.

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