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Integrating Mercury Science and Policy in the Marine Context: Challenges and Opportunities

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Abstract

Mercury is a global pollutant and presents policy challenges at local, regional, and global scales. Mercury poses risks to the health of people, fish, and wildlife exposed to elevated levels of mercury, most commonly from the consumption of methylmercury in marine and estuarine fish. The patchwork of current mercury abatement efforts limits the effectiveness of national and multi-national policies. This paper provides an overview of the major policy challenges and opportunities related to mercury in coastal and marine environments, and highlights science and policy linkages of the past several decades. The U.S. policy examples explored here point to the need for a full life cycle approach to mercury policy with a focus on source reduction and increased attention to: (1) the transboundary movement of mercury in air, water, and biota; (2) the coordination of policy efforts across multiple environmental media; (3) the cross-cutting issues related to pollutant interactions, mitigation of legacy sources, and adaptation to elevated mercury via improved communication efforts; and (4) the integration of recent research on human and ecological health effects into benefits analyses for regulatory purposes. Stronger science and policy integration will benefit national and international efforts to prevent, control, and minimize exposure to methylmercury.

Keywords

mercury policy; transboundary pollution; mitigation; total maximum daily load; benefits analysis

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1.0 Introduction

Mercury (Hg) pollution poses environmental challenges at local, regional, and global scales. Mercury is a naturally occurring element and centuries of human activity have released large amounts of inorganic mercury into the biosphere where it is readily converted to methylmercury. Methyl mercury is the organic form of mercury that bioaccumulates in fish at concentrations about ten million times greater than the concentration in the water in which they live. The form of methylmercury discussed here is monomethylmercury denoted as MeHg. MeHg concentrations associated with adverse impacts to fish, wildlife, and people (Mergler et al. 2007, Scheuhammer et al. 2007) have been observed worldwide, including in remote areas of the Arctic where no known major anthropogenic mercury sources exist (AMAP 2002).

Mercury cycling in coastal and marine ecosystems is understudied relative to freshwater systems (Chen et al. 2008). Processes such as mercury methylation are well-characterized for freshwater systems but may differ in the open ocean (e.g. Mason et al. this issue). In addition, most human and environmental (e.g., fish, wildlife) exposure to mercury is from the consumption of fish. Approximately 92% of the global fish harvest for human consumption consists of marine fish (UNDP et al. 2003). Thus, greater understanding of the connection between controls on mercury sources in particular regions and changes in MeHg concentrations in marine fish would be useful to national and international policy efforts.

Given recent advances in mercury research in coastal and marine systems, the opportunity exists to develop stronger science and policy linkages to inform national and international mercury abatement efforts. To that end, we draw on key findings from the policy-relevant scientific synthesis for six ocean basins as part of the Coastal and Marine Ecosystem Research Collaborative (CMERC) effort. We review several policy cases from the United States and highlight lessons from over a decade of policy implementation. Finally, we consider how scientific research can be more effectively integrated into mercury abatement efforts at the national and international levels.

1.1. Mercury Sources

1.1 Both human activities and natural processes mobilize mercury from long-term geologic storage to the biosphere, where it is available to cycle among air, soil, and water (Mason and Sheu 2002, Selin et al. 2008, Selin 2009), and a fraction bioaccumulates in biota as MeHg. The natural mercury cycle involves atmospheric emissions by volcanoes and thermal vents, and this mercury circulates between atmosphere and biosphere (Lamborg et al. 2006, Lindberg et al. 2007). Human activities, however, have dramatically increased the amount of mercury in circulation. At present, roughly two-thirds of mercury emitted to the atmosphere annually originates from direct (e.g., coal-fired power plants, chlor-alkali plants) and indirect anthropogenic sources (e.g., re-emissions of previously deposited mercury)(Bergan et al. 1999, Mason and Sheu 2002, Seigneur et al. 2004).

1.2 Sediment cores from lakes and results from modeling studies suggest that, as a result of the increased cycling of mercury associated with human activities, atmospheric mercury deposition has thus been enriched by about a factor of three compared to preindustrial conditions, with lower enrichment occurring in remote areas and greater enrichment (up to an order of magnitude) occurring in more industrialized regions (Swain et al. 1992, Fitzgerald et al. 1998, Selin et al. 2008, Drevnick et al. 2011). For example, sediment cores from the inland lakes of the Great Lakes region show peak enrichment factors of seven (Drevnick et al. 2011).

Mercury emissions to the atmosphere represent the largest present-day flux of mercury from anthropogenic sources to the biosphere globally (Mason and Sheu 2002, Selin 2009). In 2005, global atmospheric emissions of mercury were estimated to total 1930 tonnes (2127 short tons) (Pacyna et al. 2010). The largest source of emissions of mercury to the global atmosphere is combustion of fossil fuel for power and heating (45%). Other substantial sources include releases from artisanal and small-scale gold mining (24%), and metal production (10%). Asia contributed approximately 67% of the total global emissions in 2005, followed by Europe (~10%) and North America (~10%)(Pacyna et al. 2010). Globally, in 2005, China was the largest emitter of mercury, followed by India and the United States. Together these three nations released 60% of the total estimated global anthropogenic emissions (Pacyna et al. 2010). Power plants are the largest single emissions category in these three and many other countries. However, gold mining is the largest source in some countries, including Brazil, Indonesia, Colombia, and other countries in South America, Asia, and Africa (Pacyna et al. 2010). Future emissions scenarios suggest that in the absence of additional policy interventions, global mercury emissions could increase by roughly 25% from 2005 levels by 2020 (Pacyna et al. 2010), and potentially double by 2050 (Streets et al. 2009).

The distribution of mercury in the biosphere is dominated by transport during its atmospheric phase (Lindberg et al. 2007). Although the atmospheric chemistry of mercury is complex and incompletely understood, it is thought that emissions of gas phase divalent mercury (i.e., reactive gaseous mercury) and particulate-bound mercury, which have atmospheric lifetimes on the order of days or weeks, can deposit near emission sources or regionally. Emissions of elemental mercury, which has an atmospheric lifetime of approximately six months to a year, can be transported great distances and deposit far away from sources (Lindberg et al., 2007).

1.3 Increased understanding of the fate of mercury at the marine-sea boundary is an important research need from a policy context. Mercury is delivered to marine, coastal, and estuarine environments via (1) atmospheric emissions and deposition (e.g. Kirk et al. this issue, Mason et al. this issue), (2) watershed or coastal point sources (e.g. Horvat et al. this issue, Harris et al. this issue, Rice et al. 2009, Sunderland et al. this issue), and (3) legacy contamination sources, which are largely decommissioned historical point sources of mercury that continue to contaminate biota due to remobilization or persistence of mercury in the biosphere (e.g. Davis et al. this issue). Mercury is also delivered from submarine hydrothermal discharges, but this input is understood to be a minor component of the total marine mercury budget (Lamborg et al. 2006, Sunderland and Mason 2007). The global contribution of mercury from current point sources and legacy contaminated sites to the marine environment via the watershed or direct discharges into coastal waterways (i.e., the hydrosphere) has received less scrutiny compared to atmospheric processes, but a recent estimate found these sources to be significant (Kocman and Horvat 2011). From a policy context, increased understanding not only of the fate and equilibration of mercury at the atmosphere-sea boundary, but also further research on the relative contributions of mercury from contaminated sites and watersheds to the estuarine and coastal environment via the hydrosphere are needed.

1.2. Methylmercury Exposure

The dominant pathway for human exposure to mercury is through the consumption of MeHg in seafood, primarily fish (Fitzgerald and Clarkson 1991). In marine systems, MeHg enters the food chain at its base either in benthic fauna or in plankton in the water column and is retained with high efficiency in the bodies of organisms at higher trophic levels (Mason 2002, Chen et al. 2008). Top-down processes such as feeding ecology and diet preferences can influence MeHg exposure in top level predators. One such example is the beluga whale (*Delphinapterus leucas*) population in the Beaufort Sea where differences in feeding habitats account for a two-fold difference among groups (Loseto et al. 2008, Kirk et al. this issue). Top predator species that are commonly consumed by humans, such as tuna (*Scombridae* spp.) or swordfish (*Xiphias gladius*), tend to have high mercury concentrations in many regions of the world (Table 1).

Exposure levels to mercury vary widely from person to person and from region to region depending on individual seafood consumption patterns, anthropogenic mercury sources contributing to mercury in consumed seafood, and the geographic origin of the seafood consumed. In the U.S., more than 90% of human population-wide mercury exposure is from consumption of estuarine and marine fish (Sunderland 2007). Tuna and swordfish account for over half of the U.S. and Spanish population-wide mercury intake (Figure 1a, b) (Sunderland 2007, Sahuquillo et al. 2007). Total mercury concentrations in tuna and swordfish have been documented for different geographic regions (Table 1). However, for most consumers in the developed world the source of the fish and shellfish at retail venues is not known so it is difficult to link consumers to their regional seafood sources (Sunderland et al. 2007, Sunderland et al. this issue).

While fish consumption is the dominant mercury exposure pathway for many human populations, some people are exposed from consumption of traditional foods such as seal and whale meat (e.g. see Figure 1c for Greenland seasonal mercury intakes from Johansen et al. 2004, Choi et al. 2009, Kirk et al. this issue), from inhalation exposures to elemental mercury resulting from dental fillings that contain mercury amalgam, from releases from mercury-containing paints, from breakage of thermometers, from use of mercury in religious and cultural practices (Riley et al. 2001), and from artisanal gold production (Hilson 2006, UNEP 2006).

Exposure to elevated levels of MeHg from fish consumption or other exposure pathways can have adverse human health effects. Neurological effects in humans have been documented with MeHg exposure, as summarized in Mergler et al. 2007. Cognitive deficits in children exposed to mercury *in utero* through maternal transfer have been documented in several studies (e.g., Grandjean et al. 1997, Jørgensen et al. 2004, Trasande et al. 2005), although such deficits have not been observed in all epidemiologic studies (e.g., Marsh et al. 1995; Myers et al. 1995, 2000, 2003). Mahaffey et al. (2004) estimated that approximately 300,000 to 400,000 children were born each year in the U.S. exposed to *in utero* mercury levels that are associated with increased risk of neurological impacts (i.e., from a national U.S. survey of blood mercury levels in women of child-bearing age that exceeded US EPA’s reference dose). Some recent epidemiological studies link MeHg exposure to cardiovascular effects as summarized by Roman et al. 2011 and Karagas et al. in review; however, a subsequent, well-conducted epidemiologic study reported no association between MeHg levels and increased risk of coronary heart disease (Mozaffarian et al. 2011). There is also increasing evidence for effects due to low-level MeHg exposures, particularly on fetal growth (Karagas et al. in review). Adverse neurological, behavioral, and reproductive impacts from MeHg exposure have also been documented in many fish and wildlife species from both laboratory and field studies (Scheuhammer et al. 2007, Wolfe et al. 2007, Wiener et al. 2012).

In an effort to reduce dietary exposure to MeHg, several nations and international organizations have developed quantitative safety assessments using risk-based MeHg toxicity values, such as the “reference dose” (Table 2). A reference dose is an amount of chemical that can be consumed on a daily basis for a lifetime without expectation of adverse effect. Reference doses or similar estimates, such as minimal risk levels, tolerable weekly intakes and acceptable daily intakes, are expressed as a quantity of MeHg intake per kg body weight per unit time. For MeHg these are generally based on epidemiological studies of women of reproductive age and the developing fetus. The adopted toxicity values for MeHg have declined over time as understanding of exposure and effects has increased with research efforts (Stein et al. 2002, Oken et al. unpublished results). In addition to the nations listed in Table 2, many more nations have set limits on the maximum allowable or recommended level of MeHg or Hg in fish, which range from 0.2 up to 1.0 ug/g (or mg/kg, wet weight (ww))(e.g., see UNEP 2002, Health Canada 2007). The joint FAO/WHO Food Standards Programme (Codex Alimentarius Commission 2005), established a standard of 1.0 ug/g of MeHg for large predatory fish and a standard of 0.5 ug/g for all other fish. While seafood consumption guidelines based on maximum allowable levels of MeHg in commercial fish have the potential to reduce human exposure to MeHg, these have no impact on fish and wildlife exposure to MeHg through obligatory consumption of fish and other prey items.

2.0 Mercury Policy: Challenges and Opportunities

Mercury pollution has been a focus of international policy efforts since the 1970s and initially focused on limiting the direct dumping of mercury waste into certain binational or international waters (Selin and Selin 2006)(Table 3). Starting in the mid-1990s, agreements begin to address long-range atmospheric transport. Despite these advances, progress in coastal and marine ecosystems has been limited, suggesting the need for improving on the patchwork of policies that exist in some but not all countries. As of 2002, no country had developed a single comprehensive legislation that covered all aspects of the lifecycle of mercury (UNEP 2002). The resulting system of voluntary actions, policies, and regulations is not well harmonized and lacks a coordinated approach at national to international scales. This lack of an integrated approach limits the effectiveness of mercury reduction efforts across local, national, and international scales (Selin 2011).

A global legally binding mercury instrument is under development by over 140 participating countries through the United Nations Environment Program (UNEP). In 2001, the Governing Council of the UNEP called for a scientific synthesis on the extent to which mercury presented a global problem. This effort, the Global Mercury Assessment, was developed to inform future UNEP activities and was completed in 2002 (UNEP 2002). In 2003, at the 22nd Session of its Governing Council, UNEP was asked to help countries take action on global mercury pollution and in 2007 established the Global Mercury Partnership to develop an overarching framework. Then, at its 25th Session in 2009, the Governing Council agreed to negotiate a legally binding instrument on mercury. The Governing Council views the Global Mercury Partnership as a main mechanism to deliver immediate actions on mercury while negotiations are underway.

The stated goal from the 2009 framework is to “protect human health and the global environment from the release of mercury and its compounds by minimizing and, where feasible, ultimately eliminating global, anthropogenic mercury releases to air, water, and land” (UNEP 2009). The framework will address mercury supply, demand, unintentional releases, emissions, and the development of non-mercury technologies (e.g., non-mercury cell chlor-alkali production) where necessary (UNEP 2009). The goal has been set to complete negotiations before the twenty-seventh regular session of the Governing Council/ Global Ministerial Environment Forum in 2013.

The international treaty process and concurrent national policy efforts represent a major opportunity to address the full life cycle of mercury across multiple jurisdictions. The need for such a life cycle approach in international policy was first identified in the 2004 “daughter directive” that called on the European Commission to develop “a coherent strategy containing measures to protect human health and the environment from the release of mercury based on a life cycle approach” (European Parliament 2004). A life cycle policy approach to mercury entails intervening at multiple points in the mercury pollution cycle to reduce mercury sources, manage mercury outputs, and protect human and ecological health from the effects of MeHg (Table 4).

Some state and national scale policies have resulted in decreased mercury releases from anthropogenic sources (e.g., waste incinerators in the U.S.; see Schmeltz et al. 2011). Concurrent declines in mercury concentrations have been documented in some freshwater and coastal environments for which long-term records exist and response times are relatively short (e.g. Sager 2002, Atkeson et al. 2005, Bhavsar et al. 2011, Monson et al. 2011). There are limited time trend data evaluating the relative effectiveness of various policy and management options in place since the 1970s on mercury inputs to marine systems. To date, however, most longer-term time trends of mercury concentrations in marine-feeding biota show either no change or increases over time for species sampled in the Atlantic (Monteiro and Furness 1995, Thompson et al. 1998, Sunderland et al. this issue), Pacific (Vo et al. 2011), Arctic (AMAP 2002, Kirk et al. this issue) and Southern (Sun et al. 2006) oceans. Given that mercury pools in the ocean and atmosphere are currently not at steady state, it is likely that fish mercury concentrations will continue to increase in many ocean basins (Mason et al. this issue).

The increase in mercury concentrations in various environmental compartments in marine systems worldwide points to the need for stepped up efforts to address mercury pollution. We have reviewed the literature and assigned a range in the strength of the evidence for effectiveness of mercury policy or management options from high to low (Table 4). Cain et al. (2011) suggest that source control regulations tend be more effective at decreasing mercury inputs to the biosphere than voluntary efforts or “receptor-based” approaches. Voluntary efforts have been cited as important but do not set legally-binding regulatory requirements (Selin and Selin 2006). Efforts to minimize exposure to MeHg by changing fish consumption habits have had mixed results, and may have led to lower intake of important nutrients among pregnant women in the U.S. (Oken et al. unpublished results), and to reliance on less healthful non-traditional foods among many Northern peoples in the Arctic (Kirk et al. this issue).

3.0 Integrating Mercury Science & Policy: Examples and Case Studies

In order to advance a life cycle approach to mercury in coastal and marine systems, many policy and technical challenges must be overcome. These challenges include (1) the transboundary nature of mercury, (2) the lack of multi-media approaches, (3) the potential influence of cross-cutting issues, and (4) the need for interdisciplinary collaboration (Table 5). Research from several major ocean basins and examples from U.S. mercury policy provide important insights to help overcome these challenges and better integrate mercury science into national and international policy discussions.

3.1. Transboundary Challenges

State and national action alone is insufficient to address the transboundary movement of mercury in air, water, and biota. Fate and transport models have estimated that anthropogenic mercury emissions to the atmosphere from around the global contribute substantially to mercury deposition in the Arctic (Durnford et al. 2010)(Figure 2a), the U.S. (Selin et al. 2008) and the open ocean (Mason et al. this issue). Research in the Arctic has linked atmospheric emissions from more southern latitudes in the Northern Hemisphere to mercury deposition via mercury depletion events and to increasing concentrations of MeHg in biota in the Arctic despite the absence of any major local or even regional anthropogenic sources (AMAP 1997).

The transboundary nature of mercury in marine systems is further complicated by the lateral movement of mercury in ocean currents, which can transport mercury over interhemispheric distances. For example, a study of the eastern North Pacific estimated that mercury concentrations in the intermediate waters in 2006 were enriched compared to those observed in previous sampling efforts (Sunderland et al. 2009)(Figure 2b). The authors attribute the increase to the lateral transport of increasingly Hg-enriched waters from the western North Pacific (Sunderland et al. 2009).

The transport of fish in commerce adds to the transboundary challenge of reducing exposure to MeHg. Fish are a highly traded global commodity. Worldwide, imports of fish and fish products increased 95% between 1998 and 2008 (FAO 2010). The U.S. imported 84% of its seafood in 2009, with the largest portions from China (23%) and Thailand (16%)(NOAA 2011). Europe, dominated by the European Union, was the world's largest importer of seafood from 2006–2008 (Figure 2c), followed by Asia and North/Central America. The international mercury treaty process will have greater impact if it incorporates these transboundary processes that influence mercury in the atmosphere, in ocean waters, and in fish in commerce into the treaty.

3.2 Multi-media Challenges

Mercury is a multi-media pollutant and cannot be adequately addressed by single-media regulations that are common in most jurisdictions. By the mid-2000s, policy actions in the U.S. and related scientific research underscored the challenge of managing mercury as a multi-media pollutant. An example from the U.S. Clean Water Act highlights the challenge of reaching fish-tissue based water quality standards in atmospherically-dominated ecosystems using tools that are limited to regulatory controls over discharges to waterways.

The Clean Water Act (CWA; Section 303) requires states to adopt water quality standards, which contain three elements: designated uses, criteria to protect those uses, and an anti-degradation policy. When dealing with mercury, the primary designated use of relevance is fish consumption. States have established water quality criteria for mercury that are used to evaluate whether the designated use is supported. Many states base their water quality criteria and determination of impairment on either the U.S. EPA's recommended fish-tissue-based water quality criterion of 0.30 mg/kg (U.S. EPA 2009) or a similar fish tissue criterion calculated with state-specific data. Some states also use water column and sediment concentrations as water quality criteria for mercury (Rothenberg et al. 2008). Every two years, states must develop a list of impaired waters that are not supporting designated uses, known as the 303(d) list. States are then required to develop Total Maximum Daily Loads (TMDLs) for waters on the 303(d) list that they have identified as high priority waters for restoration. TMDLs establish the limit for a pollutant load that is necessary to meet applicable water quality standards, and apportions this load among sources.

Based on data provided by the states for 2002 through 2008, there were 5,004 waterbody impairments due to mercury and 6,946 EPA-approved TMDLs for mercury in U.S. waters (U.S. EPA 2011a, Driscoll et al. this issue). Of these, 196 waterbody impairments and TMDLs for 51 waterbodies occured in coastal waters, bays or estuaries (U.S. EPA 2011b, Driscoll et al. this issue)[1]. We reviewed the TMDL plans for these 51 waterbodies and found that atmospheric deposition was identified as a major source of the mercury load (defined here as >25% of the total load) in 36 (71%) of the coastal waterbodies with TMDLs. For the remaining 15 waterbodies, legacy pollution due to former mining sites or industrial practices was the major source of mercury to the system. Reductions in atmospheric deposition needed to attain the TMDL in atmospheric-driven systems ranged from 59% to 78%. TMDLs are a tool of the U.S. CWA and therefore do not have the regulatory authority to require controls on sources of atmospheric emissions. Furthermore, a portion of the mercury deposited in one state may originate from another state and the receiving state has no mechanism to force reductions from the contributing state. Consequently, TMDLs in many U.S. coastal waters are not attainable in the absence of additional federal level coordination to decrease atmospheric deposition both within and beyond the boundaries of the affected state.

Efforts have been made in the northeastern U.S. to confront this cross-media gap between water quality standards and atmospheric emissions. The northeastern states[2] developed a seven-state regional mercury TMDL that calls for a 98% percent reduction in anthropogenic mercury deposition in order to reach a target fish mercury concentration of 0.3 mg/kg (ppm) (NEIWPCC 2007). The states then filed a petition pertaining to mercury and atmospheric deposition under the Clean Water Act’s rarely utilized Section 319(g)(In Re: CWA 2008). This section of the CWA allows that if a state has waters impaired partially or completely by nonpoint source pollution (e.g. atmospheric deposition) from another state (or states), that state can petition the EPA Administrator to convene a conference of all the states involved. The purpose of that conference is to reach agreement on how to reduce pollution so that water quality standards can be met. The northeastern states’ 319(g) petition identified 11 states outside of the northeastern region that were significant contributors to mercury pollution in the Northeast. In June 2010, EPA convened those 11 states and the seven northeastern states at the nation’s first-ever Section 319(g) management conference. At that conference, the states requested that EPA take on a stronger role in addressing the multi-media policy challenges associated with mercury at the national level. Many states also requested that EPA develop a comprehensive national mercury reduction strategy to eliminate gaps in the current system and support greater integration of mercury control programs across different media.

Large-scale TMDLs and 319(g) conferences alone cannot solve the multi-media challenges associated with controlling mercury, but there are benefits to these approaches. TMDLs provide a calculation of the amount of mercury that needs to be reduced in order to meet water quality standards. The 319(g) petition provided a better understanding of the magnitude of the mercury contributions from states both inside and outside the northeast region. These two pieces of information combined provide evidence of the need for stricter controls on sources of mercury emissions. Information shared at the 319(g) conference demonstrated that there are diverse and sometimes conflicting approaches that states are taking to control mercury on a state-level, underscoring the importance of addressing

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[1] The number of TMDLs for coastal waters, bays and estuaries reflect only those for which the issuing state has provided information on waterbody type in the 303(d) listing.

[2] For the purposes of this discussion, northeastern states are defined as Connecticut, Maine, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont.

mercury pollution through a closely coordinated approach at the federal level (NEIWPCC 2007).

3.3. Cross-Cutting Issues

Cross-cutting issues refer to the challenges that arise due to the interactions between mercury and other pollutants. Two specific examples of cross-cutting issues are the interaction of mercury with changes in nutrient loading and climate. To address cross-cutting issues in coastal and marine environments, mercury policy and management efforts should consider (1) the potential impacts of pollutant interactions, (2) the need to mitigate mercury that is mobilized from legacy sources (e.g., Frederick et al. 2005), and (3) the importance of improved risk communication to help human communities adapt to elevated fish mercury concentrations.

3.3.1. Pollutant Interactions—Many estuaries near developed areas (U.S. east coast; San Francisco Bay; Mediterranean Sea) receive elevated nutrient inputs associated with wastewater discharges and agricultural runoff. In freshwater systems, the biodilution of mercury has been documented due to the lower concentrations at the base of the food web under conditions of high algal biomass (Pickhardt et al. 2002, Chen et al. 2005). In order to address eutrophication and hypoxia, efforts are underway to reduce nutrient loading to coastal waters. Reduced nutrient inputs could exacerbate mercury contamination in coastal waters by reversing biodilution effects and increasing mercury concentrations at the base of the food chain. A conceptual model and case studies have been developed to better understand these interactive effects and will be important to advance in order to ensure that both nutrient and mercury reduction efforts achieve their intended effect (Driscoll et al. this issue).

Climate change represents another environmental disturbance driven by atmospheric pollution that could alter mercury cycling, but its impacts are not yet well understood. For example, in the arctic changing temperature and precipitation patterns could impact mercury deposition, uptake and methylation due to loss of sea ice but it is not clear what the ultimate effect will be on mercury concentrations in fish and marine wildlife (Kirk et al. this issue). Ocean modeling by Booth and Zeller (2005) suggests that increased fishing mortality together with climate change may exacerbate increases in the trophic transfer of MeHg induced by climate change alone. To address the impact of multiple pollutants, focused research and expanded monitoring are needed to better understand the interactive effects of changing nutrient loadings and changing climate with mercury contamination in coastal waters (Driscoll et al. this issue, Mason et al. this issue).

3.3.2. Mitigation Measures—Mitigation refers to human interventions that moderate the force or intensity of mercury pollution of the biosphere. Mitigation includes resource management measures to decrease the mobilization and methylation of mercury from legacy sources through appropriate site-specific management activities. These activities may include curtailing and detaining urban and watershed runoff, dredging or capping contaminated sediments, and changing impoundment management to reduce anoxia and decrease organic matter accumulation (Wang et al. 2004, Warner et al. 2005, Driscoll et al. 2007, Davis et al. this issue).

San Francisco Bay (SFB) provides an interesting example of a coastal waterbody, contaminated from historic mining upstream, where mitigation measures could play an important role in decreasing MeHg concentrations in the food web to meet state water quality standards and protect endangered species (such as the California clapper rail)(*Rallus longirostris obsoletus*)(Davis et al. this issue). The methylation of mercury in sediments and the bioaccumulation of mercury in biota in SFB generate ongoing inputs to the food web, resulting in little or no improvement in food web concentrations of MeHg since the 1970s (Davis et al. this issue). To address this challenge, managers from the SFB Regional Water Quality Control Board have proposed to augment source control efforts with enhanced mitigation to control in situ production and delivery of MeHg to SFB (Davis et al. this issue). Importantly, the authors note that mitigation should not replace source reduction efforts and should be accompanied by comprehensive monitoring to evaluate their long-term efficacy.

3.3.3. Adaption Approaches—Adaptation measures refer to actions to modify human behavior and encourage lower-mercury seafood choices in light of the fact that high mercury concentrations in seafood persist in many regions (Selin 2011, Oken et al. unpublished results). A recent evaluation of the impact of fish consumption advisories suggests that they may not have yet achieved the positive behavioral change that they were intended to produce (Oken et al. unpublished results). Instead some may have led to an overall reduction in fish consumption, particularly among pregnant women, with the effect of reducing intake of nutritionally important omega-3 fatty acids. As such, advisories need to be improved and should be viewed as interim measures aimed at modifying behavior to minimize risk until such time that other interventions (pollution prevention and source control) result in fish mercury levels that are within safe thresholds.

3.4 Interdisciplinary Science & Policy Challenges

For mercury research to inform policy and management decisions, research from a wide range of scientific fields must be distilled and integrated into benefit cost analyses and other supporting assessments. The study of mercury exposure and effects cuts across many disciplines including these: atmospheric chemistry and modeling, paleoecology, oceanography, limnology, human toxicology and epidemiology, ecotoxicology and population ecology, natural resource economics, public health, and communications, among others. Fragmentation of knowledge across various peer-reviewed journals and lack of comprehensive synthesis limits the integration of science in many environmental pollution issues (Driscoll et al. 2011).

The policy impacts of the fragmentation of knowledge from various scientific disciplines are revealed through a case study of in recent efforts to regulate mercury emissions from major sources in the U.S. Mercury and mercury compounds are listed as Hazardous Air Pollutants (HAPs) under Section 112 of the U.S. Clean Air Act. The 1990 Clean Air Act Amendments regulates the emissions of HAPs by requiring the establishment of Maximum Achievable

Control Technology (MACT) standards for each major source in any listed categories. Major sources are those that emit 10 tons per year or more of mercury (or other HAP) or 25 tons per year or more of any combination of HAPs (U.S. EPA 2000). U.S. EPA rules to control mercury emissions through the establishment of MACT-based standards have achieved substantial decreases in emissions from 1990 levels in some source categories. Notable among these are standards for municipal waste combustors (date issued 1997; 95% reduction), medical waste incinerators (date issued 1997; 99% reduction), and hazardous waste combustors (date issued 1999; approximately 50% reduction)(U.S. EPA 2005). Further, emissions limits and voluntary actions by chlor-alkali plants have resulted in a 97% decline in emissions from this source category since 1990 (U.S. EPA 2005). The largest remaining source of anthropogenic mercury emissions in the U.S. are coal-fired electric utilities (52.3 tons in 2005)(U.S. EPA 2005).

A Regulatory Impact Analysis (RIA), or benefit cost analysis, conducted by federal agencies is required for all significant rules by Executive Order 12866 (U.S. C.F.R. 1993). During the rule-making process to address mercury emissions from major electric utilities that are subject to Section 112 of the Clean Air Act, the U.S. EPA completed an RIA for the proposed Clean Air Mercury Rule in 2005 (the rule has since been vacated) and updated the RIA in 2011 for the subsequent rule, known as the Mercury and Air Toxics Standards (MATS), that was finalized in December, 2011.

An RIA must consider both the health benefits and the welfare (i.e., social and environmental) benefits of the proposed rule. The 2011 RIA quantified human health benefits due to anticipated mercury reductions from utilities using avoided Intelligence Quotient (IQ) loss through fetal exposure based on a national-scale analysis for recreational freshwater anglers (exposure via marine and commercial fish was not included)(U.S. EPA 2011c). It provided a qualitative review of cardiovascular impacts but did not attempt to monetize the benefits of reduced cardiovascular effects due to its assessment that there were, “inconsistencies among available studies as to the association between MeHg exposure and various cardiovascular system effects” (U.S. EPA 2011c, p. 5-5).

The 2011 RIA also included a qualitative discussion of ecological benefits associated with decreased mercury emissions including effects on fish and wildlife but did not estimate the monetary value of welfare benefits associated with projected decreased mercury emissions. After a review of the ecological effects literature for mercury, the EPA concluded, “EPA is not, however, currently able to quantify or monetize the benefits of reducing mercury exposures affecting the provision of ecosystem services” (U.S. EPA 2011c).

The opportunity exists to expand current benefit analysis methods and account for the full spectrum of human health and ecological effects. Expanded benefits methods could apply to future significant rule-making to control mercury sources in the U.S. and elsewhere, to residual risk assessments related to such rules, and to negotiations underway through the UNEP process to establish a global legally-binding mercury treaty.

3.4.1. Considering the Full Spectrum of Health Effects—Many benefit analyses for mercury, including the 2011 RIA, focus on exposure based on consumption of recreationally caught freshwater fish (Swain et al. 2007) to estimate the potential benefit to human health of mercury abatement. Yet freshwater fish represent only 5% of the fish harvest in developed countries and 15% in developing countries (Swain et al. 2007). Studies that consider mercury exposure from marine fish suggest substantial increase in the estimated benefits of mercury emissions reductions where the regulatory actions decrease MeHg levels in marine fish (Rice and Hammitt 2005, Swain et al. 2007). Further advances in understanding of the change in fish methylmercury concentrations that would result from changes in mercury deposition and the timing of such changes in fish MeHg concentrations would improve benefits assessment models (Rice and Hammitt 2005).

Most mercury abatement benefits analyses for human health are based on Intelligence Quotient (IQ) improvements (Swain et al. 2007). However, recent studies suggest that other health effects, such as cardiovascular endpoints could be important. Taking these additional effects into account together with changes in exposure associated with both freshwater and marine fish would result in significantly higher estimates of benefit of mercury emissions reductions, if methyl mercury exposures do increase risk of cardiovascular diseases (van Wijngaarden et al. 2006, Swain et al. 2007, Rice et al. 2010). An estimate of the difference in societal benefits for an IQ-only approach compared to one that includes cardiovascular benefits suggests that the benefits could be seven times higher, based on a limited case study in the U.S. South Atlantic coast (Sundseth et al. 2010, Rae and Graham 2004).

Epidemiological and toxicological studies have evaluated the relationship between MeHg exposure and a number of different cardiovascular endpoints including myocardial infarction, oxidative stress, atherosclerosis, decreased heart rate variability, and hypertension. There is a range in the strength of epidemiological evidence for a causal association between MeHg and cardiovascular disease based on current research. Recent studies propose that sufficient evidence exists to include the link between MeHg exposure and acute myocardial infarction in regulatory benefits analyses (Roman et al. 2011, Karagas et al. unpublished results)(Table 6).

A positive association between methylmercury exposure and atherosclerosis also appears to be a plausible cardiovascular outcome. Three epidemiological studies in three different populations have examined the relationship between methylmercury exposures and atherosclerosis and all three reported evidence of a positive association between these exposure and measures of atherosclerosis (Salonen et al. 2000, Choi et al. 2009, Dewailly et al. 2009). Several studies report associations of methylmercury exposure with decreased heart rate variability in children and adults, but the relationship between this outcome and coronary heart disease in otherwise healthy adults and children is not well-understood.

Given the range in the strength of evidence for MeHg exposure and cardiovascular outcomes, one approach to expanding benefits assessment to account for evidence of a wider spectrum of health effects is to add a parameter to benefits models that reflects the strength of causal association (ranging from 0 to 1) for a range of health outcomes. For example, the Hill Criteria could be used to develop consistent parameters (e.g., Rice et al. 2010) and should include sensitivity analysis. Cormier et al. (2010) have proposed an alternate set of criteria for evaluating causality; some of these criteria could be applied to evaluate the strength of evidence from the studies of the cardiovascular effects of MeHg. Previous work suggests this parameterization can exert a very strong influence on benefits analysis of MeHg (Rice et al. 2010). Thus, as additional relevant studies are published (e.g., Mozzafarian et al. 2011), it is important to re-evaluate the values assigned to the strength of causal association parameters.

3.4.2. Accounting for Ecological Health Effects—As exemplified in the U.S. EPA 2011 RIA for the Utility Air Toxics Rule, the benefits of reduced mercury pollution to fish and wildlife are often excluded from benefits analysis. A review by Swain et al. (2007) of economic studies conducted on wildlife benefits from mercury pollution reductions found only one study that quantified such benefits (Hagen et al. 1999). Based on this willingness-to-pay study, Sundseth et al. (2010) estimated that the total value of environmental benefits of reduced mercury pollution to wildlife was approximately six times greater than IQ benefits to humans.

Research on the effects and sensitivity of mercury on fish and wildlife has increased substantially in the last decade (Wiener and Spry 1996; Scheuhammer et al. 2007, 2011; Wolfe et al. 2007; Evers et al. 2011a) and provides supporting evidence for integrating non-human health effects in benefit analyses. In fact, with increasing studies more species have been identified with elevated tissue mercury concentrations and adverse effects have been identified at increasingly lower mercury concentrations (Evers et al. 2011a). Elevated tissue mercury has been documented in fish, birds, and mammals across all of the geographic regions that were assessed as part of the CMERC effort (Davis et al., Sunderland et al., Harris et al., Kirk et al., Mason et al. this issue). A number of studies have linked tissue concentrations to effects levels for avian and marine mammal species (Muir et al. 1999, Hargreaves et al. 2010) and together with other research provide sufficient evidence to support the incorporation of ecological effects into benefits analysis.

Elevated body burdens of MeHg in wildlife can cause a variety of adverse effects, ultimately reducing reproductive success. Changes in blood chemistry, neurochemistry, hormones, and chromosome structure, as well as aberrant behavior and abnormal histopathology have been well documented in various species of fish, birds, and mammals (Eisler 2006; Scheuhammer et al. 2007, 2011; Wolfe et al. 2007; Sandheinrich and Wiener 2011). Local, regional, and intercontinental atmospheric mercury deposition to wetland and aquatic ecosystems is now known to significantly impact the reproductive health of free-living wildlife (Wolfe et al. 2007), in some cases it may be a primary driver for population-level declines in remote areas, such as the arctic (e.g., ivory gull [*Pagophila eburnea*]; Braune et al. 2006).

The common loon has been used as a standard bioindicator for characterizing spatial patterns and temporal trends of mercury in freshwater systems across North America (Evers et al. 1998, Meyer et al. 2011), including documenting biological mercury hotspots in the eastern United States and Canada (Evers et al. 2007, 2011b). Results from a robust study of a common loon (*Gavia immer*) breeding population in New England documented that 40% fewer fledged young were produced at mercury concentration thresholds of 3.0 ug/g wet weight (ww) in blood, 1.3 ug/g (ww) in egg and 40.0 ug/g in feather. A parallel, independent study in neighboring regions yielded similar results (Burgess and Meyer 2008). Piscivorous birds such as common loons are often used as environmental indicators for mercury exposure but are relatively tolerant of MeHg body burdens (Heinz et al. 2009). For example, strictly invertivorous birds, such as many songbirds, have effects concentrations that may be 2 to 4 times lower than the common loon (Jackson et al. 2011).

One approach to integrating ecological effects in benefits analysis is to consider the avoided economic cost of providing habitat that would be needed to offset effects on wildlife. The economic value of lost common loon years was determined in a precedent-setting injury assessment that quantified loon-years lost from a marine oil spill in Rhode Island as part of a Natural Resource Damage Assessment (NRDA) under the requirements of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) (Sperduto et al. 2003). The NRDA program provides a process for calculating the monetary cost of restoring injuries to natural resource that result from releases of hazardous substances or discharges of oil. The economic value of the impact to common loons in Rhode Island was estimated at approximately $1,000 per loon-year or $10,000 per individual loon. The value was based on the cost of purchasing shoreline habitat that would support an equivalent number of loon-years to the loon-years lost (Biodiversity Research Institute unpublished data). The resulting monetary value of lost common loon years was used to negotiate a $3 million settlement for damages compensated by the party responsible for the oil spill through the Natural Resource Damage Assessment and Restoration (NRDAR) program.

The NRDA approach to estimating the monetary cost of restoring injuries to wildlife using wildlife years lost and requisite habitat restoration costs could be used to develop an expanded, interdisciplinary approach to quantifying the wildlife benefits of pollution reduction for a range of species. In coastal marine ecosystems, *Ammodramus* sparrows (i.e., Saltmarsh, Seaside and Nelson's; *A. caudacutus, A. maritimus, A. nelsoni*, respectively) provide a useful correlate to the common loon. This group of birds is of high conservation concern and has been used as an indicator of the effects of mercury pollution in estuaries (Cristol et al. 2011, Lane et al. 2011, Winder and Emslie 2011). Because these songbirds are obligate estuarine species and they forage on invertebrates, they experience some of the highest risk for MeHg toxicity of birds on the Atlantic Coast. In one study, representing 25 distinct estuaries from Maine to New York, 60% of the estuaries had sparrow populations with mean blood mercury concentrations associated with at least a 10% nest failure rate (Lane et al. 2011). Some estuaries contained sparrow populations with blood mercury concentrations associated with higher than a 30% nest failure rate (Lane et al. 2011). An understanding of fish and wildlife mercury exposure patterns, their effect thresholds, taxonomic sensitivities, and emerging monetization approaches all support expanding benefits analysis to integrate the economic value of benefits to fish and wildlife of mercury pollution reductions.

4.0 Conclusions

Science has played an important role in informing and motivating mercury policy at regional, national and international scales. Several lessons emerge from this examination of the challenges that impede mercury policy progress and associated improvements in coastal and marine systems. These lessons include: (1) the need to address the full range of transboundary challenges in the international mercury treaty process; (2) the need for better federal coordination across air and water programs in the U.S. to address multi-media challenges in the current patchwork policy systems; (3) the need to address cross-cutting issues by confronting pollutant interactions and the impacts of on-going mercury inputs through expanded mitigation and adaptation measures; and (4) the need to enhance the integration of interdisciplinary research in benefits analyses in order to more fully represent the full range of human health and ecological benefits associated with mercury controls.

In addition, as national and international policy efforts advance, the relative effectiveness of different types of interventions in the mercury life cycle (e.g., product substitution, source reduction, risk communication) should be taken into account. Unfortunately, this area has been understudied; and further evaluation could play a significant role in science-based policy and management priorities. For example, existing information suggests that voluntary efforts and interim measures to minimize risk through fish consumption advisories and current risk communication strategies may be less effective than pollution prevention and source control efforts. Further, in systems with on-going inputs from legacy sources of mercury, *in situ* mitigation efforts to constrain methylation and bioaccumulation may offer an important supplemental management tool.

National and international policy efforts would benefit from an expanded framework to facilitate information exchange between scientists and policymakers. For example, the U.S Department of State leads the U.S. negotiation team in the UNEP global treaty process. The current consultation process emphasizes two major stakeholder groups: (1) tribes and states, and (2) nongovernmental organizations (NGOs)(primarily industry and environmental groups). Given the scientific complexities of the mercury issue, a third consultation group for academic research scientists who are not affiliated with a government agency or NGO should be established to facilitate the effective integration of mercury science and policy. A stronger science-policy system could support effective and on-going integration of rapidly advancing mercury research in coastal and marine systems with national and international policy efforts.

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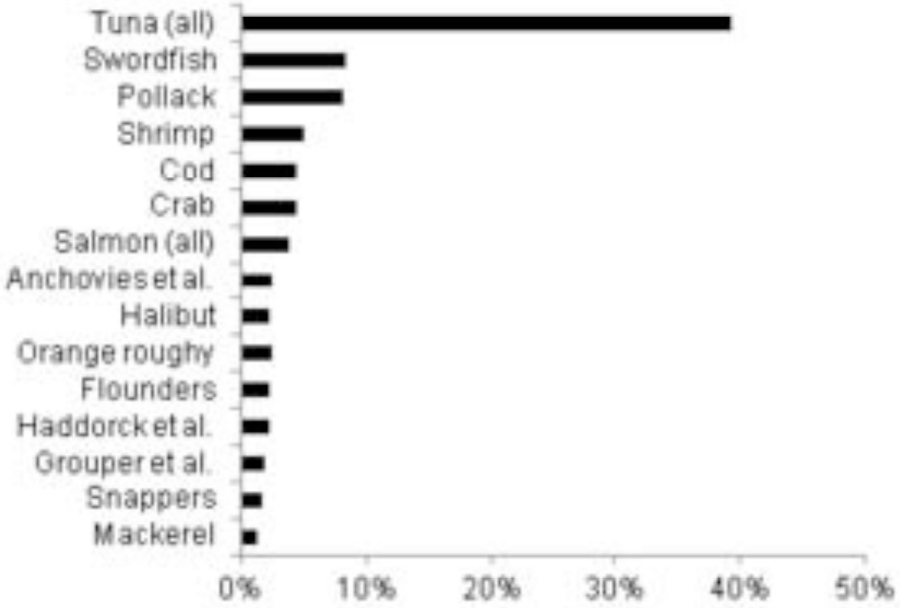
Research Highlights

- The patchwork of national and multi-national policy hinders mercury abatement.
- Reducing anthropogenic sources of mercury is an effective intervention.
- Policy challenges are transboundary, multi-media, cross-cutting and interdisciplinary.
- Intentional integration of emerging research will help address policy challenges.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Grouper et al.
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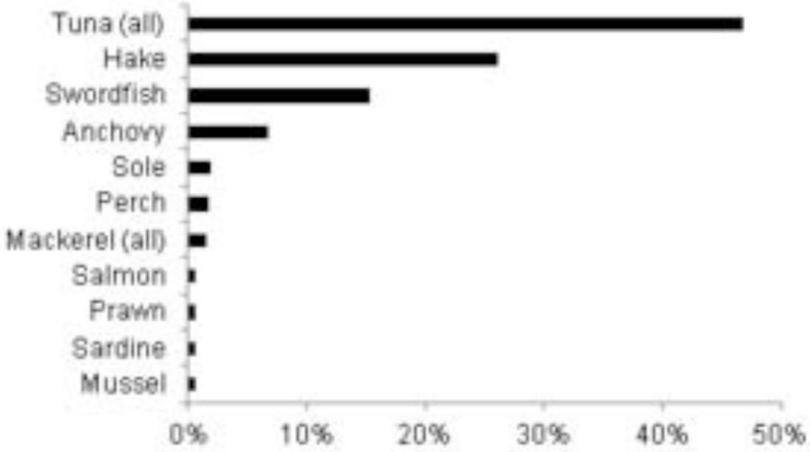
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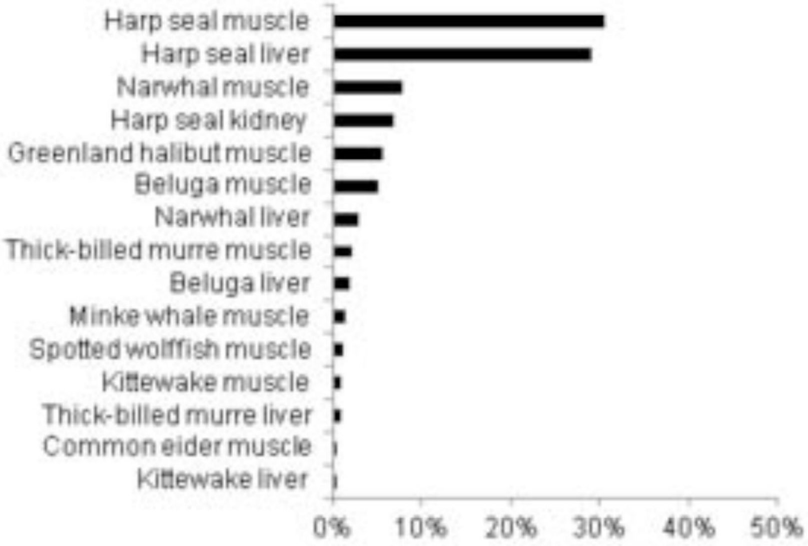
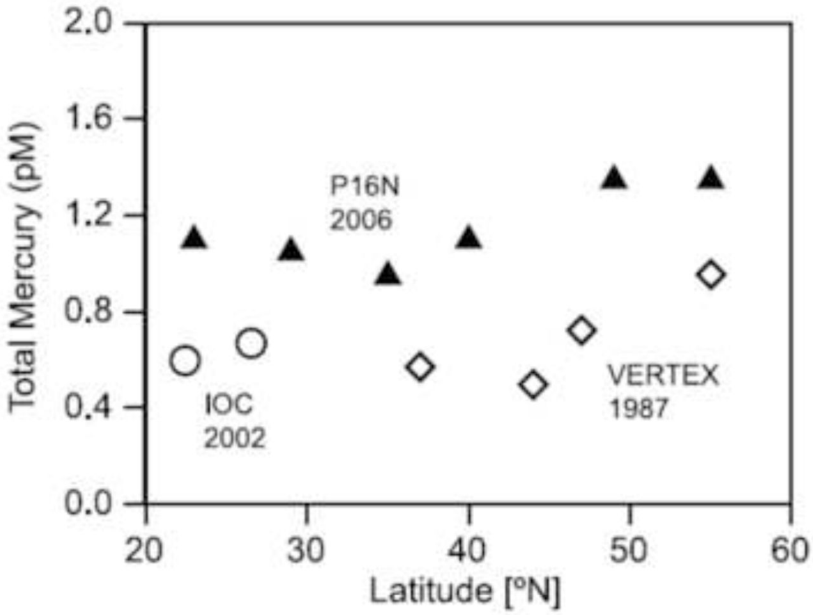


Figure 1.

Percentage of population-wide mercury intake from different seafood species in three geographic regions. (a) the United States (Hg intakes adapted from Sunderland 2007), (b) Spain (MeHg intakes adapted from Sahuquillo et al. 2007) and (c) Greenland (Spring season Hg intakes adapted from Johansen et al. 2004).

Figure 2a.

Source region	LRT events/year	Percent of total
Asia	201	43
North America	77	16
Russia	126	27
Europe	66	14
Total for 4 regions	470	100



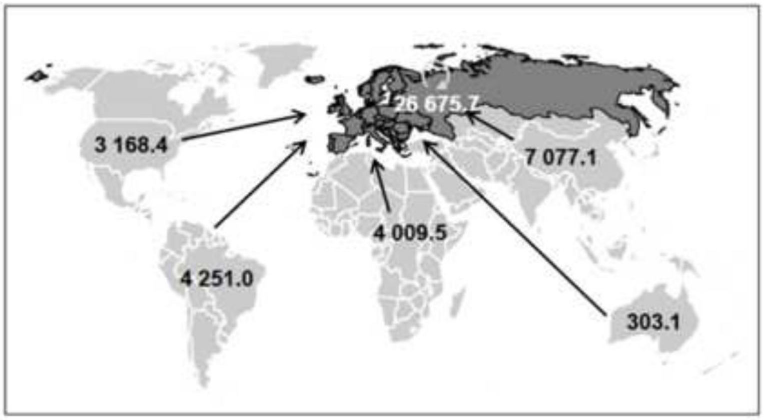


Figure 2.

Examples of the transboundary movement of mercury. 2a shows the number and percentage of annual long-range transport (LRT) events to the high Arctic attributed to region of origin for six stations during the period 2000–2008 (Durnford et al. 2010). 2b shows an increase over time in the lateral transfer of mercury in intermediate waters (0–1000 meters) in the eastern North Pacific Ocean based on average total Hg concentrations from integrated water samples taken along transects during three separate cruises (VERTEX, IOC, and P16N) during the period 1987–2006 (Sunderland et al. 2009). The increase is attributed to the lateral transport of increasingly Hg-enriched waters from the western North Pacific (Sunderland et al. 2009). 2c shows the transport of fish in commerce based on average import flows for Europe and Russia (2006–2008)(US $millions)(adapted from FAO 2010). Fish in commerce contributes to the transboundary movement of mercury in biota beyond source regions.

Table 1

Comparison of total mercury in tuna and swordfish by region (adapted from UNEP 2002 and FAO 2010).

Region	Fish species	Total Hg concentration mean (range) (mg/kg ww)	Sample size	Sources
United States	Swordfish	0.976	618	U.S. FDA 2010
	Tuna - caned albacore	0.353	399	
	Tuna - fresh/frozen, all	0.383	228	
	Tuna - bigeye	0.639	13	
United Kingdom	Swordfish	1.355 (0.153 – 2.706)	17	University of Bristol Survey
	Tuna	0.401 (0.141 – 1.5)	34	
Taiwan	Tuna - albacore	9.75 (dw)[1]	-	Han et al. 1998
Mauritius	Swordfish	(0.22 – 0.65)	17	National submission to UNEP
	Tuna	(0.10 – 0.70)	16	
Italy	Tuna - bluefin	(0 – 4.0)	-	Renzoni et al. 1998
France[2]	Swordfish	0.78	-	Thibaud 1992 in national submission to UNEP
	Red tuna	0.47	344	
Fiji	Tuna - caned	(0.01 – 0.97)	-	IAS, unpublished report 1992
Cyprus	Swordfish	0.54 (0.20 – 2.0)	21	National submission to UNEP
Cote d’Ivoire	Tuna - albacore	(0.30 – 0.36)	-	National submission to UNEP
	Tuna - large (80–91 kg)	0.8		

Maximum allowable and recommended levels in fish range from 0.2 ug/g (ww) total Hg (for high consumption populations in Canada) to 1.0 ug/g (ww) MeHg in predatory fish (e.g., tuna, swordfish)(Codex Alimentarius Commission (2005), U.S. FDA for fish in commerce).

[1] Taiwan data: dry weight (dw).

[2] Samples from France represent fish caught in Baltic and North Sea, English Channel, Atlantic Ocean.

- = sample size not available.

UNEP: United Nations Environment Programme.

IAS: Institute for Applied Studies.

FDA: Food and Drug Administration.

Table 2

Comparison of reference levels for methylmercury by nation and organization (adapted from UNEP/WHO 2008).

Nation/organization	Reference level (mg/kg week)[1]	Year	Agency
Australia/New Zealand	1.6	2004	Food Standards Australia New Zealand
Canada	1.4[2]	1997	Bureau of Chemical Safety
Japan	2.0	2005	Food Safety Commission
Netherlands	0.7	2000	National Institute for Public Health and Environment
United States	0.7	2001	US Environmental Protection Agency
WHO/FAO	1.6	2003	Joint FAO/WHO Expert Committee on Food Additives

[1] Units expressed as mg of MeHg intake per kg body weight per week.

[2] Original units expressed as ug/kg d and converted to weekly units by multiplication by $7*10^3$.

WHO: World Health Organization.

FAO: Food and Agriculture Organization of the United Nations.

Table 3

Advances in intergovernmental agreements relevant to mercury in marine environments (sources: UNEP 2002, Selin 2005, Selin and Selin 2006).

Time	Policy emphasis and examples	Scale
1970s	Dumping of mercury in international waters:	Basin
	International Convention on the Prevention of Marine Pollution by Dumping of Wastes	
	Convention for the Prevention of Marine Pollution by Dumping from Ships and Aircraft	
	Convention for the Prevention of Marine Pollution from Land-Based Sources	
	Protocol to a ban the dumping of mercury into the Mediterranean Sea	
1990s	Transboundary movement of mercury:	Regional
	UN Convention on Long-Range Transboundary Air Pollution (UNECE CLRTRAP)	
	Basel Convention on the Control of Transboundary Movement of Hazardous Waste	
	Hazardous Waste Protocol to virtually eliminate the generation of hazardous waste and the transboundary movement of such waste in the Mediterranean Sea	
2000s	Lifecycle approach to mercury abatement:	International
	European Commission presents strategy "on a life cycle approach"	
	European Parliament and Council bans export of metallic mercury and certain mercury compounds from EU with provisions for safe storage of elemental mercury	
	U.S. Mercury Export Ban Act prohibits the sale, distribution and export of mercury from the U.S. by 2013 and provides for safe storage of elemental mercury	

Table 4

Life cycle approach to mercury abatement: examples and evidence.

Category	Intervention	Examples	Strength of evidence for effectiveness	Sources
Sources	Pollution prevention	Product substitution Mercury-free technologies/processes Mercury export bans	High	UNEP 2002
Outputs	Waste handling	Consumer take-back programs Waste stream separation	High	U.S. EPA 2005, Cain et al. 2011, Schmeltz et al. 2011
	Controls	Atmospheric emissions standards Wastewater discharge limits	Moderate	Cain et al. 2011
	Mitigation	Manage urban runoff Enhance water circulation Reduce impoundment fluctuation Cap or dredge contaminated sediments	Moderate-low	Davis et al. this issue, Wang et al. 2004
Consumers	Adaptation	Fish consumption advisories Product labeling Healthcare provider education	Low	Oken et al. unpublished results

Table 5

Policy challenges and opportunities associated with mercury abatement.

Challenge	Description	Examples	Opportunities	Sources
Transboundary	State and national action is insufficient to reach goals	Atmospheric transport Ocean circulation patterns Fish migration Fish in commerce	UNEP global agreement Integrated models for coastal and marine systems	UNEP 2002, Sunderland et al. 2009, Durnford et al. 2010, FAO 2010
Multi-media	Single medium regulations impede environmental improvement	U.S. Clean Water Act – Total Maximum Daily Loads	Federal coordination Receptor-based approaches (e.g., critical loads)	U.S. EPA 2011a& b
Cross issue	Legacy effects and novel conditions complicate predictions and policy decisions	Climate change Nutrient loading Fishing mortality Risk communication	Comprehensive mercury monitoring Multi-pollutant approaches Mitigation measures	Booth and Zeller 2005, Schmeltz et al. 2011, Driscoll et al., this issue, Warner et al. 2005
Interdisciplinary	Isolated research communities limit linkages between sources and effects	Integration of full human health and ecological effects in regulatory impact analyses	Expanded benefits analysis	Swain et al. 2007, Roman et al. 2010

Table 6

Strength of evidence for cardiovascular outcomes related to mercury exposure (adapted from Roman et al. 2011).

Cardiovascular outcome	Overall strength of evidence[1]
Heart rate variability	Strong
Atherosclerosis	Moderate
Oxidative stress	Moderate to strong
Hypertension	Weak
Fatal and non-fatal myocardial infarction	Moderate

[1] Based on an assessment of biological plausibility of MeHg-related cardiovascular outcomes from epidemiological, animal and *in vitro* studies to 2010.