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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.

1. Introduction

Mercury (Hg) pollution poses substantial environmental and public health challenges locally, regionally, and globally. Although mercury is a naturally occurring element, centuries of human activity have released large amounts of inorganic mercury into the biosphere where it is readily converted to the organic form, methylmercury (MeHg). MeHg can bioaccumulate in fish at concentrations up to ten million times greater than MeHg concentrations in the surrounding water. MeHg concentrations in biota that are 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 sources of mercury exist (AMAP, 2002).

Mercury cycling in coastal and marine ecosystems is understudied relative to freshwater systems (Chen et al., 2008). This gap persists despite the fact that most human exposure to MeHg is from the consumption of fish; and marine fish constitute approximately 92% of the global fish harvest for human consumption (UNDP et al., 2003). State and federal policies (e.g., controls on air emissions from waste incinerators) have resulted in a 60% decline in atmospheric mercury emissions in the U.S. (Schmeltz et al., 2011; U.S. EPA, 2005). Concurrent declines in mercury concentrations in biota have been documented in several freshwater systems in the U.S. for which long-term records exist and response times are relatively short (e.g., Atkeson et al., 2006; Bhavsar et al., 2011; Monson et al., 2011). However, there are limited long-term data for coastal and marine systems and most trends show either no change or increases in mercury concentrations in marine-feeding biota from offshore areas of the Atlantic (Monteiro and Furness, 1995; Thompson et al., 1998; Sunderland et al., this issue), the Pacific (Vo et al., 2011), the Arctic (AMAP, 2002; Kirk et al., this issue) and the 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 there will be lag times in the response of many ocean basins to controls on anthropogenic mercury sources. As a result fish mercury concentrations may continue to increase for some time (Mason et al., this issue) even as beneficial policies are implemented. Thus, greater understanding of the connections between global mercury

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sources and MeHg concentrations in coastal and marine biota is necessary to both inform and accurately evaluate national and international policy.

We draw on key findings from the policy-relevant scientific syntheses conducted for six coastal ecosystems and ocean basins by scientists participating in the Coastal and Marine Ecosystem Research Collaborative (CMERC). We review several policy case studies from the U.S. 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

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 where a fraction bioaccumulates in biota as MeHg. Human activities have dramatically increased the amount of mercury circulating in the biosphere. Globally, mercury emissions to the atmosphere represent the largest present-day flux of mercury to the biosphere from anthropogenic sources (Mason and Sheu, 2002; Selin, 2009). Atmospheric mercury deposition has been enriched by a factor of three to ten compared to preindustrial conditions, in some regions of the world (Swain et al., 1992; Fitzgerald et al., 1998; Selin et al., 2008; Drevnick et al., 2011). It is estimated that roughly two-thirds of the mercury emitted to the atmosphere annually originates from direct anthropogenic sources (e.g., coal-fired power plants, chlor-alkali plants) and from indirect anthropogenic sources (e.g., re-emission of previously deposited mercury) (Bergan et al., 1999; Mason and Sheu, 2002; Seigneur et al., 2004).

In 2005, global atmospheric emissions of mercury were 1930 t (2127 short tons) (Pacyna et al., 2010). The largest source was the 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). The highest-emitting countries in 2005 were China; followed by India and the U.S. Together these three nations released 60% of the total estimated anthropogenic emissions to the atmosphere that year (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).

Mercury inputs to marine, coastal, and estuarine environments originate from atmospheric emissions and deposition (e.g., Kirk et al., this issue; Mason et al., this issue), but also from watershed or coastal point sources (e.g., Costa et al., this issue; Harris et al., this issue; Rice et al., 2009; Sunderland et al., this issue), and from legacy sources (e.g., Davis et al., this issue). Legacy sources are decommissioned historical point sources of mercury that continue to contaminate biota due to remobilization or persistence of mercury in the biosphere. 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 delivery of mercury to coastal waters via the watershed or from direct discharges into coastal waterways (i.e., the hydrosphere) has received less focus than atmospheric emissions. A recent estimate found these sources to be significant in some regions (Kocman and Horvat, 2011); suggesting the need for greater research and policy attention to these sources.

1.2. Methylmercury exposure

The dominant pathway for human exposure to MeHg is through the consumption of 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 it is retained with high efficiency in the bodies of organisms at higher trophic levels (Mason, 2002; Chen et al., 2008). Top predator species that are commonly consumed by humans, such as tuna (*Scombridae* spp.) or swordfish (*Xiphias gladius*), have high total mercury concentrations in many regions of the world (Table 1).

MeHg exposure varies widely by person and by region depending on individual seafood consumption patterns, the location and size of mercury sources, and the geographic origin of the fish and seafood consumed. In the U.S. more than 90% of human population-wide mercury exposure originates from the 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 (Fig. 1a and b) (Sunderland, 2007; Sahuquillo et al., 2007). For other populations, consumption of traditional foods such as seal and whale meat is the dominate source of mercury intake (e.g., see Fig. 1c for Greenland seasonal mercury intakes from Johansen et al., 2004; Choi et al., 2009; Kirk et al., this issue). Importantly, since the source of the fish and shellfish sold at retail venues in most areas of the developed world is not well-known; it is often difficult to link mercury sources to human exposure to MeHg via fish consumption (Sunderland et al., 2007, this issue).

Exposure to elevated levels of MeHg from fish consumption or other pathways can cause adverse human health effects. Neurological effects of MeHg exposure in humans have been summarized in Mergler et al., 2007. 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* MeHg levels that are associated with increased risk of neurological impacts. 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, often referred to as a "reference dose" (Table 2). The adopted toxicity values for MeHg have declined over time as understanding of mercury exposure and effects has increased (Stein et al., 2002; Oken et al., 2012).

2. Mercury policy: challenges and opportunities

Mercury pollution has been a subject of international policy since the 1970s. Initial actions focused on limiting the direct dumping of mercury waste into certain binational or international waters (Selin and Selin, 2006) (Table 3). In the mid-1990s, regional and international policies began to address the long-range atmospheric transport of mercury. In the 2000s, mercury export bans and calls for a life cycle approach to mercury emerged. Despite these advances, as of 2002, no country had developed a single comprehensive legislation that covered all aspects of mercury pollution (UNEP, 2002). The existing system of voluntary actions, policies, and regulations is not well harmonized and lacks a coordinated approach at national to international scales (Selin, 2011).

A global legally binding mercury instrument is under development by 128 countries through the United Nations Environment Program (UNEP). In 2001, the UNEP Governing Council called for a scientific synthesis on the extent to which mercury presented a global problem. The resulting Global Mercury Assessment was completed in 2002 (UNEP, 2002). In 2003, UNEP was asked to help countries take action on global mercury pollution

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	0.98	618	U.S. FDA, 2010
	Tuna-caned albacore	0.35	399	
	Tuna-fresh/frozen, all	0.38	228	
	Tuna-bigeye	0.64	13	
United Kingdom	Swordfish	1.36 (0.15–2.71)	17	University of Bristol Survey
	Tuna	0.40 (0.14–1.50)	34	
Taiwan	Tuna-albacore	9.75 (dw)[a]	–	Han et al., 1998
Mauritius	Swordfish	(0.22–0.65)	17	National submission to UNEP
	Tuna	(0.10–0.70)	16	
Italy	Tuna-bluefin	(0.0–4.0)	–	Renzoni et al., 1998
France[b]	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)	0.80	–	

–=Sample size not available.
Maximum allowable and recommended levels in fish range from 0.2 µg/g (ww) total Hg (for high consumption populations in Canada) to 1.0 µg/g (ww) MeHg in predatory fish (e.g., tuna, swordfish) (Codex Alimentarius Commission (2005), U.S. FDA for fish in commerce).
UNEP: United Nations Environment Programme.
IAS: Institute for Applied Studies.
FDA: Food and Drug Administration.

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

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

and in 2007 it established the Global Mercury Partnership to lead that effort. In 2009, the UNEP Governing Council agreed to negotiate a legally binding instrument on mercury. The stated goal for the legally binding instrument, or treaty, 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 international treaty process and concurrent national policy efforts represent a major opportunity to address the full life cycle of mercury. A life cycle policy approach to mercury entails intervening at multiple points in the mercury pollution cycle to decrease mercury sources, manage mercury outputs, and protect human and ecological health from exposure to MeHg. We reviewed the literature and assigned a range in the strength of the evidence for effectiveness of mercury policy and interventions from high to low (Table 4). Voluntary efforts have been cited as important to controlling mercury but are hindered by the lack of legally-binding regulatory requirements (Selin and Selin, 2006). Efforts to minimize human exposure to MeHg by using advisories to alter fish consumption habits have had mixed results. In some cases, fish consumption advisories have contributed to lower intake of important nutrients among pregnant women in the U.S. (Oken et al., 2012), and to reliance on less healthful non-traditional foods among many Northern peoples in the Arctic (Kirk et al., this issue). 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. Advancing source controls and other effective mercury abatement programs will benefit from drawing on past policy experiences to more effectively integrate mercury science and policy.

3. 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 globe contribute substantially to mercury deposition in the Arctic (Durnford et al., 2010) (Fig. 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 inter-hemispheric 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) (Fig. 2b). The authors attribute the increase to the lateral transport of increasingly mercury-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 (Fig. 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.

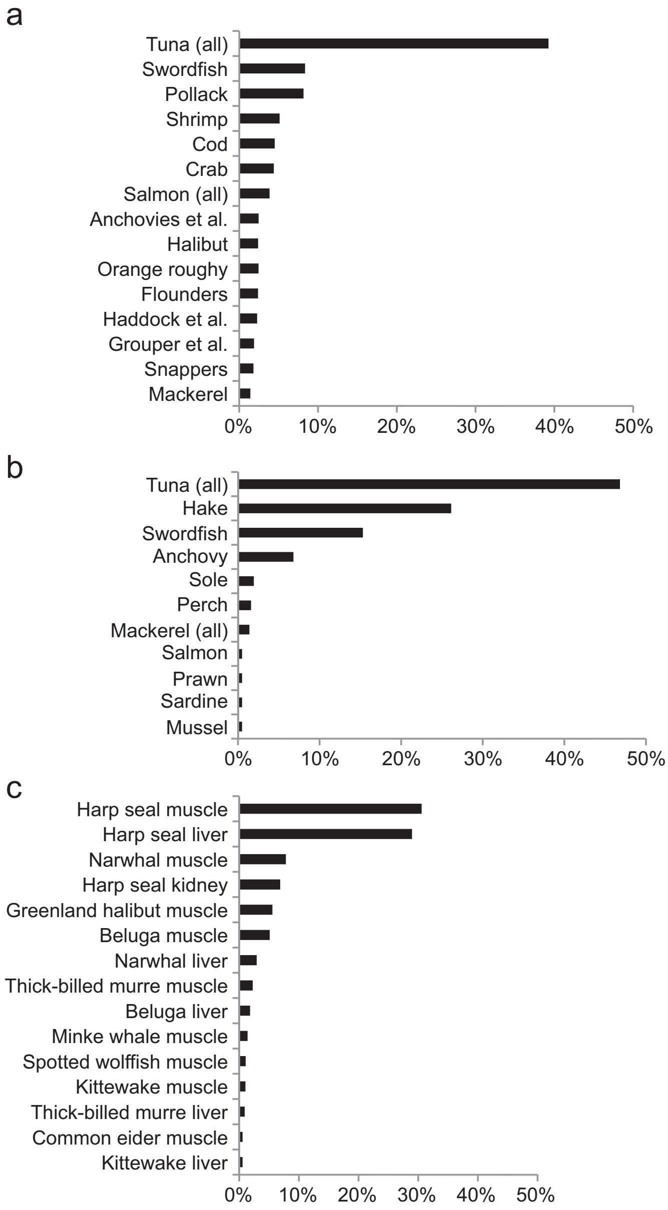

Fig. 1. Percentage of population-wide mercury intake from different seafood species in three geographic regions. (a) the United States (Hg intakes adapted from Sunderland (2007)), (b) Spain (MeHg intakes adapted from Sahuquillo et al. (2007)) and (c) Greenland (Spring season Hg intakes adapted from Johansen et al. (2004)).

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 that 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. A TMDL is an example of a receptor based approach to mercury control.

Based on data provided by the states for 2002 through 2008, there were 5004 waterbody impairments due to mercury and 6946 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

Table 2
Comparison of reference levels for methylmercury by nation and organization (adapted from UNEP/WHO, 2008).

Nation/organization	Reference level (mg/kg week)[a]	Year	Agency
Australia/New Zealand	1.6	2004	Food Standards Australia New Zealand
Canada	1.4[b]	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

WHO: World Health Organization.
FAO: Food and Agriculture Organization of the United Nations.

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

[b] Original units expressed as μg/kg d and converted to weekly units by multiplication by 7×10^3.

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: 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	Basin
1990s	Transboundary movement of mercury: 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	Regional
2000s	Lifecycle approach to mercury abatement: 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	International

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-high	Cain et al., 2011
	Mitigation	Manage urban runoff Enhance water circulation Reduce impoundment fluctuation Cap or dredge contaminated sediments	Low-moderate	Davis et al., this issue; Wang et al., 2004
Consumers	Adaptation	Fish consumption advisories Product labeling Healthcare provider education	Low	Oken et al., 2012

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 disconnect between water quality standards and atmospheric emissions. The northeastern states[2] developed a seven-state regional mercury TMDL that calls for a 98% reduction in anthropogenic mercury deposition in order to reach a target fish mercury concentration of 0.30 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, the U.S. 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 the U.S. 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 the U.S. 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

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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.

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, 2011b
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., 2011

a

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

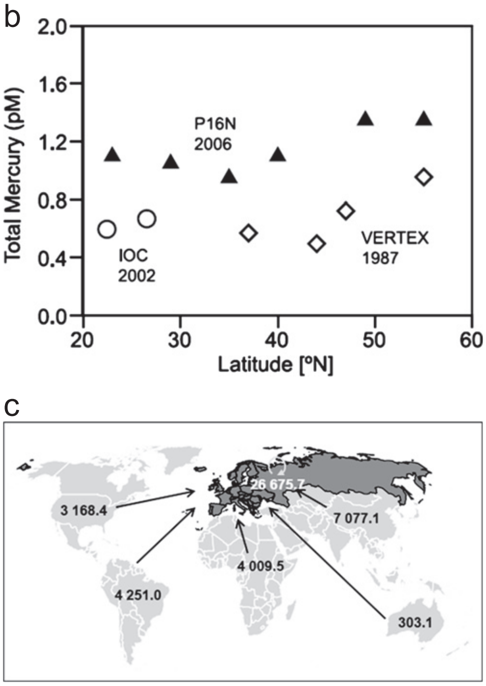

Fig. 2. Examples of the transboundary movement of mercury. Part (a) shows the number and percentage of annual long-range transport (LRT) events to the high Arctic attributed to region of origin for six stations during the period 2000–2008 (Durnford et al., 2010). Part (b) shows an increase over time in the lateral transfer of mercury in intermediate waters (0–1000 m) 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). Part (c) 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.

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

3.3. *Cross-cutting issues*

Cross-cutting issues refer to challenges that complicate efforts to reduce mercury sources and MeHg exposure. 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 the persistence of 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 where lower mercury concentrations occur at the base of the food web under conditions of high algal biomass, usually associated with high nutrient levels (Pickhardt et al., 2002; Chen and Folt, 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 could alter mercury cycling, but its impacts are not yet well understood. For example, in the Arctic changing temperature and precipitation patterns could alter 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 beyond that 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 climate on 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 releases to 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). The existence of legacy contaminated sites worldwide suggests that mitigation may be an important activity for developing and deploying technical assistance through the UNEP treaty process. Importantly, Davis et al. note that mitigation should not replace source reduction efforts and should be accompanied by comprehensive monitoring to evaluate its 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., 2012). 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., 2012). 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 recommended limits.

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. 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 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 regulate 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 t per year or more of mercury (or other HAP) or 25 t 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 t 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. CFR, 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 (U.S. EPA, 2011c). 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. (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 treaty process.

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 increases 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 MeHg 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 MeHg 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).

Cardiovascular research provides an interesting case study for how benefits analyses for mercury controls might be expanded to account for a wider range of effects. 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., 2012) (Table 6).

A positive association between MeHg exposure and atherosclerosis also appears to be a plausible cardiovascular outcome. Three epidemiological studies in three different populations have examined the relationship between MeHg 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 MeHg 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 assessments 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., Mozaffarian et al., 2011), it is important to re-evaluate the values assigned to the strength of causal association parameters.

Table 6
Strength of evidence for cardiovascular outcomes related to mercury exposure (adapted from Roman et al., 2011).

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

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

3.4.2. *Accounting for ecological health effects*

As exemplified in the U.S. EPA 2011 RIA for the Mercury 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, 2012; Wolfe et al., 2007; Evers et al., 2011a) and provides supporting evidence for integrating non-human health effects in benefits analysis. In fact, with increasing studies more species have been identified that have elevated tissue mercury concentrations and adverse effects have been reported at increasingly lower mercury concentrations (Evers et al., 2011a). Elevated mercury concentrations have 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, 2012; 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 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 μg/g wet weight (ww) in blood, 1.3 μg/g (ww) in egg and 40.0 μg/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 $1000 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. 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 coordination across air and water programs to address multi-media disconnects in the current patchwork policy systems; (3) the need to address cross-cutting issues by confronting pollutant interactions and by enhancing mitigation and adaptation measures; and (4) the need to integrate interdisciplinary research into benefits analyses in order to represent the 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. Existing information suggests that voluntary efforts and interim measures to minimize risk through fish consumption advisories and current risk communication strategies are 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 U.S. consultation process emphasizes two major stakeholder groups: (1) tribes and states, and (2) non-governmental organizations (NGOs) (primarily industry and environmental groups). Given the scientific complexities of mercury, a third consultation group for academic research scientists who are not affiliated with a government agency or NGO should be established. 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.

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