

# TECHNICAL INFORMATION REPORT ON MERCURY MONITORING IN BIOTA

November 2019



Proposed components towards a strategic long-term plan for monitoring mercury in fish and wildlife globally.



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## U.S. Acronyms for Mercury Monitoring in Biota

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Arctic Monitoring Assessment Programme	AMAP
Artisanal small-scale gold mining	ASGM
Biodiversity Research Institute	BRI
Caribbean Region Mercury Monitoring Network	CRMMN
Coordinated Environmental Monitoring Program	CEMP
Dissolved Organic Carbon	DOC
European Union	EU
Food and Agriculture Organization	FAO
Global Biotic Mercury Synthesis	GBMS
Baltic Marine Environment Protection Commission – Helsinki Commission	HELCOM
Joint Assessment and Monitoring Program	JAMP
Mercury	Hg
Methylmercury	MeHg
Northern Contaminants Program	NCP
Small Island Developing States	SIDS
Total mercury	THg
United Nations Environment Programme	UNEP
United States Environmental Protection Agency	USEPA
World Health Organization	WHO







# Executive Summary

Mercury (Hg) is a pollutant of global importance that adversely affects human health and the environment. Environmental concentrations of mercury have increased three-fold globally due to human industrial activities, and the world's freshwater ecosystems, estuaries and oceans are primary reservoirs where mercury is deposited and thereafter methylated.

People are commonly exposed to methylmercury through the consumption of fish, and some birds and marine mammals. However, there are gaps in our understanding about the relationship between anthropogenic releases of mercury and its subsequent bioaccumulation and biomagnification in freshwater and marine food webs, and how that may translate to exposure and risk at the local, regional, and global scale to fish, wildlife, and humans.

Monitoring mercury in biota (i.e., methylmercury availability) provides a pathway for understanding spatial gradients, temporal trends, and environmental magnitude of concern that cannot be ascertained in air, water, or sediment. Emphasizing upper trophic level biota for monitoring (i.e., trophic level 4 or higher) ultimately provides a confident ability to assess whether the global input of anthropogenic mercury into the environment is safe or harmful to fish, wildlife and humans. Because mercury methylation greatly

varies according to many environmental factors, identifying ecosystem sensitivity spots is critical for attaining resource efficiencies (i.e., low cost, high reward information in a timely way).

Our knowledge of mercury in biota is well known in the Northern Hemisphere as well as some ocean basins, however, large gaps remain in other geographic areas. To best track global and regional biotic mercury exposure over time and space, we need to synthesize existing information with new data in a structured and strategic way. Global models will be critical for understanding current needs and prioritizing future patterns.

The elements for a dual approach proposed herein is to conduct biotic mercury monitoring across continents and oceans basins using representative bioindicators that can confidently provide information for decision makers to assess the effectiveness of the Minamata Convention on Mercury at both regional and global spatial levels at temporal scales of interest.

Cost effective, standardized, and replicable monitoring of mercury in biota can be reliably conducted. Examples of existing networks and recent projects are given. This plan will provide the information needed for decision makers to protect human health and the environment.

## Three-step overarching framework for monitoring mercury in biota across continents and oceans.

### Step 1

Map ecosystem sensitivity spots for methylmercury availability



### Step 2

Identify sensitive and at-risk trophic level 4 or higher species



### Step 3

Select species and ecosystems to model and monitor globally



There are multiple steps in developing a framework for monitoring mercury in biota in a comprehensive, standardized, and replicable way. Models and mercury exposure information are well described for many places of the world, but there are important data gaps that still need to be defined, prioritized and filled.

# 1.0 Introduction: Why is it important to monitor mercury in biota?

Inorganic mercury enters ecosystems through the air (e.g., from coal-fired power plants and incinerators), water (e.g., from chlor-alkali facilities and artisanal small-scale gold mining), and land (e.g., from landfills and other contaminated sites; Kocman et al. 2017, Streets et al. 2017, Hsu-Kim et al. 2018, Martinez et al. 2018, Obrist et al. 2018, Mason et al. 2019). Once in the environment, mercury can be converted to methylmercury by bacteria and other microbes (Gilmour et al. 2013, Yu et al. 2013).

Methylmercury is toxic, and can accumulate in the tissues of fish, wildlife and humans, causing numerous negative health effects (Basu et al. 2018, Evers 2018, Buck et al. 2019). The extent to which mercury is methylated and made available in the environment is complex and can be influenced by many factors.

Specific ecological conditions can facilitate the production and bioavailability of methylmercury. For example, bacteria often produce more methylmercury under moderate amounts of sulphate and low oxygen conditions (Gilmour et al. 1998, Hsu-Kim et al. 2013); these conditions are especially prevalent in wetland ecosystems (Branfireun et al. 1996).

Furthermore, areas with certain types of dissolved organic carbon (DOC) from decaying terrestrial organic matter may generate and transport

methylmercury more readily than areas that are low in DOC (Schartup et al. 2015). Freshwater ecosystems that are acidified due to deposition of sulfur oxides from sources such as fossil fuel combustion may be important environments that methylate more mercury than others (Branfireun et al. 1999, Driscoll et al. 2007, Wyn et al. 2009).

In areas where wet and/or dry mercury deposition is relatively low or moderate, effects on biota may be disproportionately high if conditions promote methylmercury production. Conversely, ecosystems with low methylation potential may have low levels of methylmercury despite heavy anthropogenic mercury contamination.

The decoupling of inorganic mercury sources with methylmercury production and bioavailability is evident at local (Evers et al. 2007) and landscape levels (Eagles-Smith et al. 2016).

The complexity of mercury cycling makes it challenging to predict exposure levels in upper trophic level fish and wildlife from environmental mercury concentrations alone (Gustin et al. 2016, Sunderland et al. 2016). Therefore, identifying appropriate bioindicators based on their relationship with sensitive ecosystems is a critical first step in assessing risk to ecological and human health in response to the responsibilities of monitoring mercury under the Minamata Convention (Figure 1).

Freshwater wetlands in Northern Hemisphere biomes are good examples of areas with higher mercury methylation, especially habitats with elevated dissolved organic carbon, low pH, and fluctuating water levels.





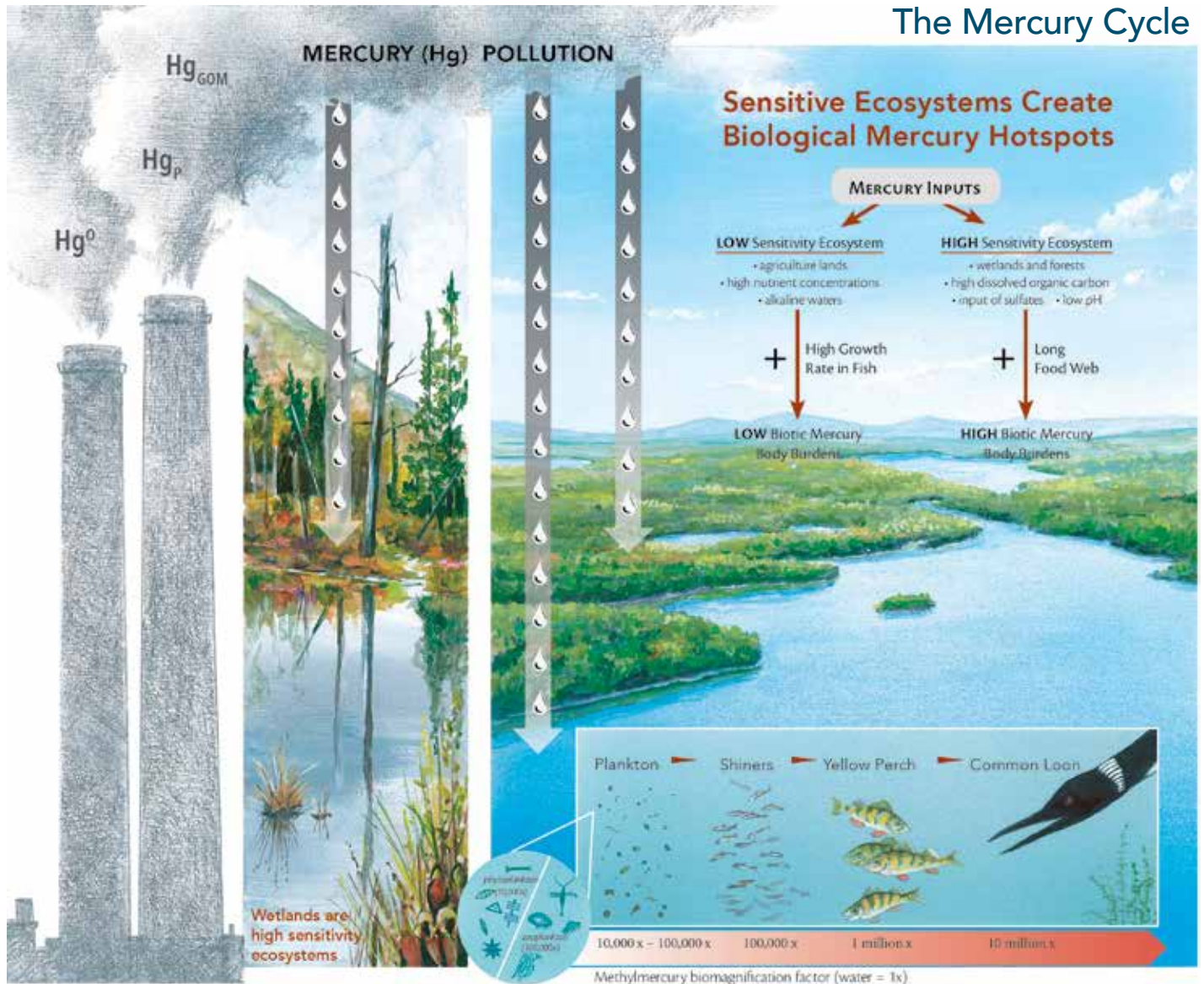


Figure 1. Mercury emissions can be transported hundreds and thousands of kilometers from their sources before being deposited on the landscape. Once deposited, the potential impact of mercury on the environment depends largely on ecosystem sensitivity. Understanding which ecosystems are most susceptible and also which organisms can serve as appropriate bioindicators is a critical component of effective mercury monitoring (Evers et al. 2007).

## Hg species

(from industrial sources)

- $Hg_{GOM}$  — gaseous oxidized mercury
- $Hg^0$  — elemental mercury
- $Hg_p$  — particulate mercury

## methylation

The conversion of inorganic mercury to its organic form (methylmercury). This step increases the bioavailability of mercury, its exposure to wildlife and humans, and ultimately its toxicity. Methylation occurs predominantly under oxygen-poor conditions. Sulfate-reducing bacteria are the primary agents of this process.

## bioaccumulation

Accumulation of substances, such as methylmercury, in an organism from various sources (e.g., food). Bioaccumulation occurs when an organism absorbs a substance at a greater rate than it is excreted over time. In food webs with elevated methylmercury, older individuals at high trophic levels are at greatest risk.

## biomagnification

Increase in concentration of a substance, such as methylmercury, from a lower to a higher trophic level in a food web. Organisms lower on the food web contain lower concentrations of methylmercury than the organisms that feed on them (e.g., phytoplankton < zooplankton < plant-eating fish < fish-eating fish < loons/eagles/humans).

## 2.0 Identification of biomonitoring information and data

### 2.1 Biotic tissues of interest

In assessing samples, it is suggested to assess muscle tissues for fish and marine mammals; for birds, blood should be used for short term data, muscle or eggs should be used for medium term and for feathers can be used for long term results (Table 1).

It is considered to be sufficient to assess total mercury for all keratin-based and muscle tissues (assuming greater than 90% of the total mercury, on average, is methylmercury) using either wet weight

or dry weight. Samples should be georeferenced, with the level of detail and choice of metadata varying according to the objective of the sampling.

Standard operating procedures are generally available through national/regional monitoring programs, however additional more universal protocols may need to be agreed on for other sampling which is not covered by this process. Intertissue conversions are generally feasible to help provide a way to have standardized, and therefore comparable, tissue mercury concentrations.

Table 1. Tissue types of interest for sampling by taxonomic group for understanding mercury exposure in biota.

Group	Matrix	MeHg* proportion	Sample prep type	Analysis type	Source reference for MeHg%	Comments
Fish	Muscle fillet	>95% (but varies)	ww or dw	THg	Bloom 1992	Dark muscle is significantly higher than white muscle (Bosch et al. 2016). New evidence indicates that %MeHg may be lower for some fish species and some cooking approaches (Wang et al. 2013) therefore 10% of fish should be analyzed for MeHg content
	Muscle biopsy	>95% (but varies)	dw	THg	Peterson et al. 2004	dw is best owing to moisture loss concerns. Muscle biopsy to muscle fillet has a $r^2 = 0.96$ . Biopsy plug depth may impact Hg measured – 5 mm plugs are best below dorsal fin (Cizdziel et al. 2002) and are without skin and adipose tissue
	Fin clips	unknown	dw	THg	Cervený et al. 2016	There is a significant correlation between fin clips and muscle fillet ( $p < 0.01$ )
	Blood	>95%	ww or dw	THg	-	Assumed to be >95% MeHg based on other vertebrates
Sea Turtles	Scutes	>95%	fw (or dw if scutes need washing)	THg	Schneider et al. 2015	Recommended and assumed nearly all MeHg as scutes are composed of keratin
	Blood	>95%	ww or dw	THg	-	Assumed to be >95% MeHg based on other vertebrates
	Muscle	>95%	ww or dw	THg	-	Assumed to be >95% MeHg based on other vertebrates

Group	Matrix	MeHg proportion	Sample prep type	Analysis type	Source reference for MeHg%	Comments
Birds	Blood	>95%	ww or dw	THg	Rimmer et al. 2005; Edmonds et al. 2010	Elimination of MeHg in blood comprises an initial fast phase, with half-time of 1 day, and a slow terminal phase with half-time between 44-65 days. Molt is a crucial factor in determining the rate of MeHg elimination (Monteiro and Furness 2001)
	Feather	~100%	fw (or dw if feathers are washed due to external contamination)	THg	Burger 1993	If feathers are not washed, fw = dw because mean feather moisture is <1%, n = 490; R. Taylor, Texas A&M, U.S.A. pers. comm.
	Eggs	>96%	ww or dw or fww	THg	Ackerman et al. 2013 (96% for 22 species)	ww and dw can be problematic if eggs are not collected immediately after laying (Dolgova et al. 2018)
	Muscle	>95%	ww or dw	THg		MeHg comprised over 99% of total Hg in breast muscle of waterfowl (Sullivan and Kopec 2018)
	Eggshells and membranes	>95%	dw	THg	Peterson et al. 2017	Membranes are assumed to be primarily MeHg, but shells are entirely inorganic Hg
	Liver and kidney	5–7% in loons and mergansers; 56–90% in egrets; 88% (20–100%) terns and shorebirds	dw	MeHg	Scheuhammer et al. 1998; Spalding et al. 2000; Eagles-Smith et al. 2009	These tissues are not recommended for monitoring; %MeHg can vary widely
Mammals	Skin	>90%	dw	THg	Wagemann et al. 1998	Muktuk (in marine mammals) includes layers of skin and blubber
	Fur or hair	>90%	fw (or dw if fur needs to be washed)	THg	Evans et al. 2000	Fur/hair may not relate to blood and muscle depending on growth patterns (Peterson et al. 2016)
	Muscle	>90%	ww or dw	THg	Wagemann et al. 1998	MeHg comprised over 95% of THg
	Liver and kidney	3–12% in whales/seals; 57–91% in mink/otter	dw	MeHg	Wagemann et al. 1998; Evans et al. 2000	These tissues are not recommended for monitoring; %MeHg can vary widely

\*MeHg = methylmercury; ww = wet weight; dw = dry weight; fw = feather weight; THg = total mercury

Inter-tissue conversions are available for many of these matrices, within and among the major taxonomic groupings (e.g., fish to birds or fish to mammals). Such conversions are important when

basing spatial gradients and temporal trends of biotic Hg concentrations when using trophic level 4 or higher bioindicators.



## 2.2 Biotic mercury data

Biodiversity Research Institute (BRI) has compiled mercury data from peer-reviewed published literature into a single database, the Global Biotic Mercury Synthesis (GBMS). This database includes details about each organism sampled, its sampling location, and basic ecological data. From each reference, mercury concentrations are averaged (using weighted arithmetic means) for each species at each location.

Data from the GBMS database can be used to understand spatial and temporal patterns of mercury concentrations in biota. This information can also help establish baseline concentrations for a particular species and identify ecosystems most at risk to mercury inputs.

The report, Mercury in the Global Environment, presents data on mercury concentrations in biota of concern in Article 19 of the Minamata Convention (i.e., marine and freshwater fish, sea turtles, birds and marine mammals), which are extracted from the GBMS database.

Data have been compiled from 1,095 different references, representing 119 countries, 2,781 unique locations, and 458,840 mercury samples from 375,677 total individual organisms (Table 2, Figure 2). For more information, visit: [www.briloon.org/hgpubs](http://www.briloon.org/hgpubs).

Together, these data can help raise awareness of potential risks and benefits of consuming key food items and thereafter help inform resource managers and decision makers about the species and places in

Table 2. Summary of mercury samples by major taxa across major ocean basins and continents as summarized by the Global Biotic Mercury Synthesis Database (Evers et al. 2018).

	Fish	Sea Turtles	Birds	Marine Mammals	Subtotal
<b>Ocean Basins</b>					
Antarctic	593		3,299	196	4,088
Arctic	1,776		2,613	2,693	7,082
Gulf of Mexico-Caribbean	6,515	259	45	169	6,988
Indian	3,264	60	1,447	180	4,951
Mediterranean	4,521	156	638	358	5,673
North Atlantic	12,770	955	13,624	2,381	29,730
North Pacific	14,590	211	17,116	1,024	32,941
South Atlantic	9,659	125	1,429	658	11,871
South Pacific	2,140		1,331	82	3,553
Subtotal	55,828	1,766	41,542	7,741	106,877
<b>Continents</b>					
Africa	5,877	391	865	253	7,386
Antarctica	564	49	2,881	196	3,690
Asia	11,978		1,535	1,029	14,542
Australia	1,887		906	64	2,857
Europe*	16,177	254	11,138	1,476	29,045
North America*	197,851	950	60,596	4,512	263,909
South America	28,940	363	685	546	30,534
Subtotal	263,274	2,007	78,606	8,076	351,963
Total	319,102	3,773	120,148	15,817	458,840

\*Fish sample sizes do not fully include available freshwater fish mercury data.

which mercury represents a potential risk to human health, which can be partly based on harvest data by the Food and Agriculture Organization.

The GBMS database also represents a valuable tool for: (1) integrating mercury science into important policy decisions related to the Minamata Convention on Mercury including contributions from the ad hoc technical expert group for effectiveness evaluation; (2) use by existing networks such as the Arctic Monitoring Assessment Programme (AMAP); and (3) protecting human health and the environment. GBMS was also the basis for biota chapter in UN Environment's *Global Mercury Assessment—2018* (see: <http://mercuryconvention.org/>).

### 2.3 Mercury monitoring programs for biota

AMAP is one of the best examples of how to operate a long-term mercury biomonitoring field program for the benefit of both human and ecological health (AMAP 2011, 2015). Whereas, the World Health Organization's (WHO's) Global Environment Monitoring System—Food Contamination Monitoring and Assessment Programme, commonly known as GEMS/Food, has one of the best global systems for collecting fish mercury data through their network of collaborating centers and recognized national institutions (WHO 2018).

A review of the geographical coverage of mercury biomonitoring networks reveals a general lack of regional initiatives around the world, especially in Africa and Australia (UNEP 2016). Most Asian countries are minimally involved with national initiatives to monitor mercury levels in biota, with notable exceptions being Japan and the Republic of Korea where more extensive programs exist.

In South America, regional initiatives are generally lacking, and while some countries have conducted many environmental assessments (e.g., Brazil), continuous biomonitoring is rare. Conversely, mercury biomonitoring is ongoing in many countries within Europe, Oceania and across the Western Hemisphere.

Environmental Specimen Banks can be used as monitoring tools to provide long-term trends for contaminants in the environment, including mercury, as outlined within the European Union (EU).

One of the better examples for a national mercury biomonitoring effort is Canada's Northern Contaminants Program (NCP)—an integrated

initiative for mercury monitoring throughout Canada's vast Arctic territory (NCP 2017). Since its establishment in 1991, the program has focused on the measurement of contaminants (including mercury) in fish and wildlife that are traditional foods of northern Indigenous peoples (Figure 3).

One of the strengths of the program is the interdisciplinary approach taken to assess and monitor risks of mercury to ecological and human health through the participation of indigenous organizations, government departments (at federal and territorial levels), environmental scientists, and human health professionals. Activities are managed under five subprograms:

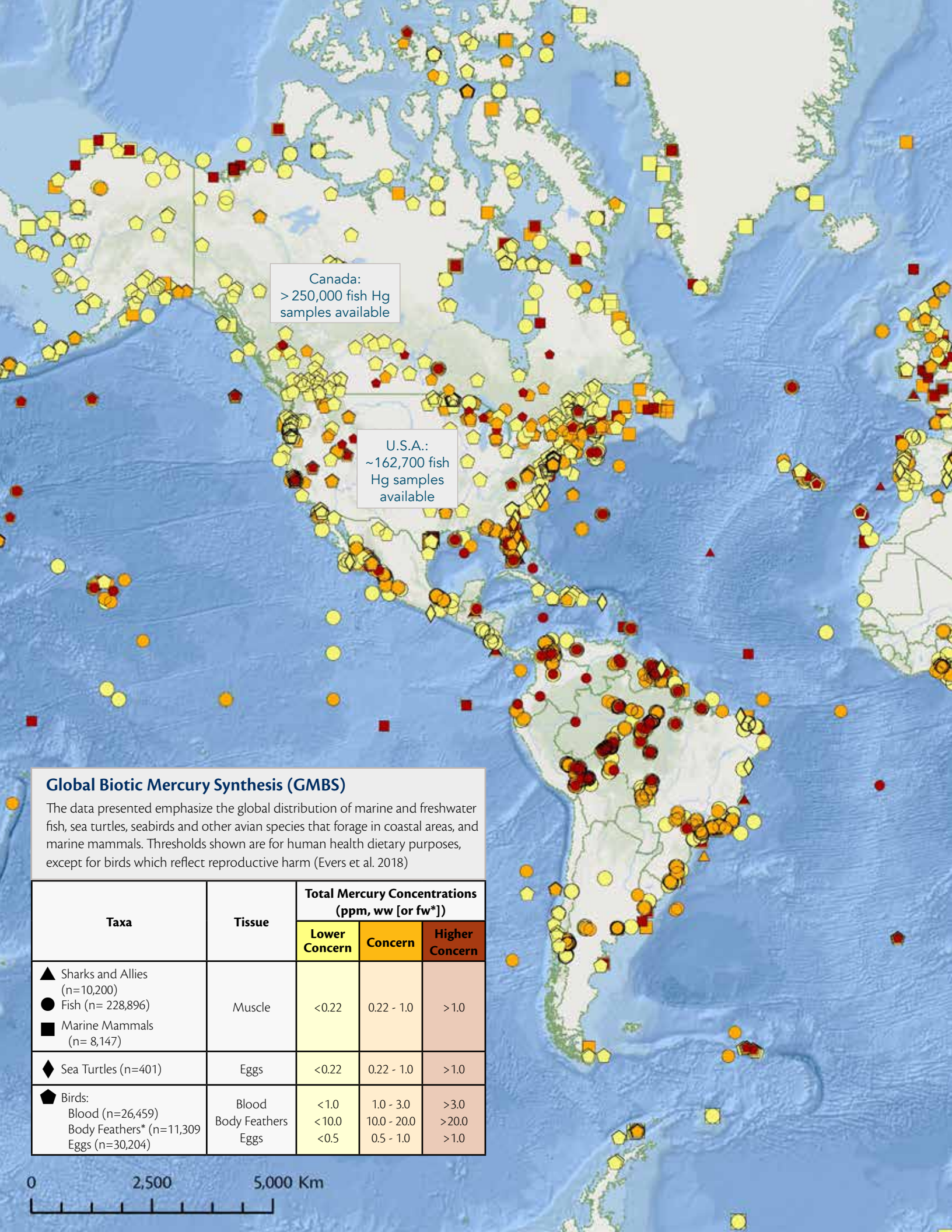
1. Human Health
2. Environmental Monitoring and Research
3. Community-Based Monitoring and Research
4. Communications, Capacity and Outreach
5. Program Coordination and Indigenous Partnerships

A strategic long-term plan guides the development of subprograms and the links between them. For example, monitoring of mercury in biota is supported by mercury measurements in air as well as focused research on environmental processes that control mercury bioaccumulation. Data generated on mercury in wildlife can be used for human dietary



Marine mammals, including the beluga whale (pictured), are important bioindicators for long term monitoring by AMAP.





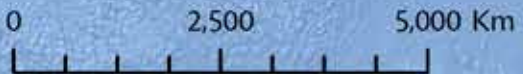
Canada:  
> 250,000 fish Hg  
samples available

U.S.A.:  
~162,700 fish  
Hg samples  
available

### Global Biotic Mercury Synthesis (GMBS)

The data presented emphasize the global distribution of marine and freshwater fish, sea turtles, seabirds and other avian species that forage in coastal areas, and marine mammals. Thresholds shown are for human health dietary purposes, except for birds which reflect reproductive harm (Evers et al. 2018)

Taxa	Tissue	Total Mercury Concentrations (ppm, ww [or fw*])		
		Lower Concern	Concern	Higher Concern
▲ Sharks and Allies (n=10,200) ● Fish (n= 228,896) ■ Marine Mammals (n= 8,147)	Muscle	<0.22	0.22 - 1.0	>1.0
◆ Sea Turtles (n=401)	Eggs	<0.22	0.22 - 1.0	>1.0
● Birds: Blood (n=26,459) Body Feathers* (n=11,309) Eggs (n=30,204)	Blood	<1.0	1.0 - 3.0	>3.0
	Body Feathers	<10.0	10.0 - 20.0	>20.0
	Eggs	<0.5	0.5 - 1.0	>1.0





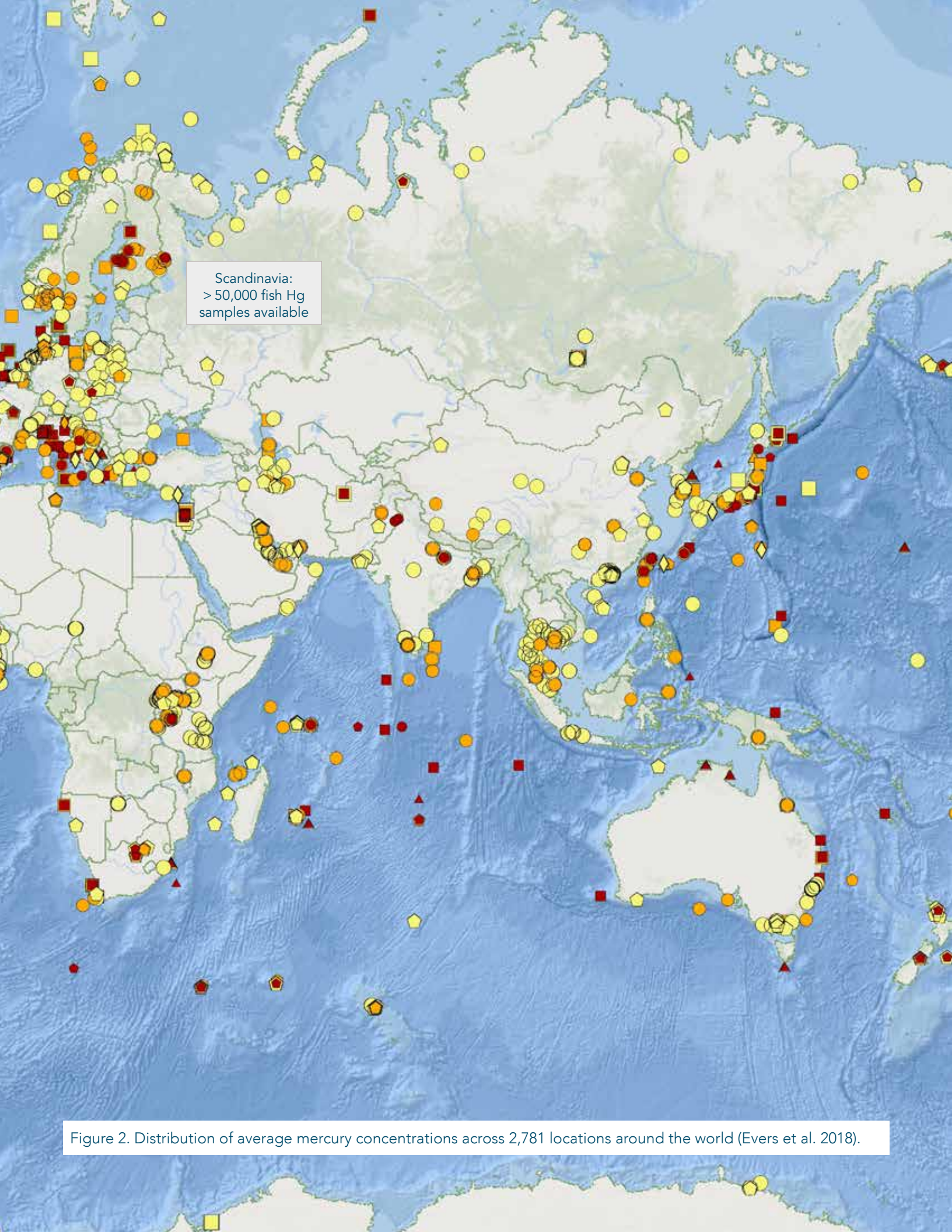


Figure 2. Distribution of average mercury concentrations across 2,781 locations around the world (Evers et al. 2018).



exposure assessments, while community-based projects may focus on species that are local priorities but not covered by routine monitoring.

Monitoring of mercury in fish and wildlife under the NCP includes terrestrial, freshwater and marine species in focal areas across northern Canada (Figure 3). Many of those samples are collected by indigenous hunters in nearby communities as part of their subsistence activities.

Annual measurements track temporal trends of mercury bioaccumulation, and retrospective analyses of archived tissues from government specimen banks have provided opportunities to extend some time series (e.g., Braune 2007). Intensive spatial sampling of several species including Arctic char (Evans et al. 2015) and ringed seal (Brown et al. 2016) have generated complimentary information on geographic variation.

Meanwhile, the hundreds of local studies conducted by the global scientific community that are reflected within the GBMS database provide a relatively comprehensive global data platform containing existing biotic mercury concentrations. Based on the GBMS database, some of the regions with the highest fish consumption are poorly covered by biomonitoring efforts (e.g., Central America and the Caribbean Sea, northern South America, western and central Africa, the southern Asian mainland, Indo-Pacific Asia).

Additional efforts are needed to develop and implement projects to fill geographic and ecosystem gaps. Although national efforts can serve as hubs for biomonitoring networks, local scientific studies can also make significant contributions toward better identifying what species, locations, and time periods to conduct biomonitoring.

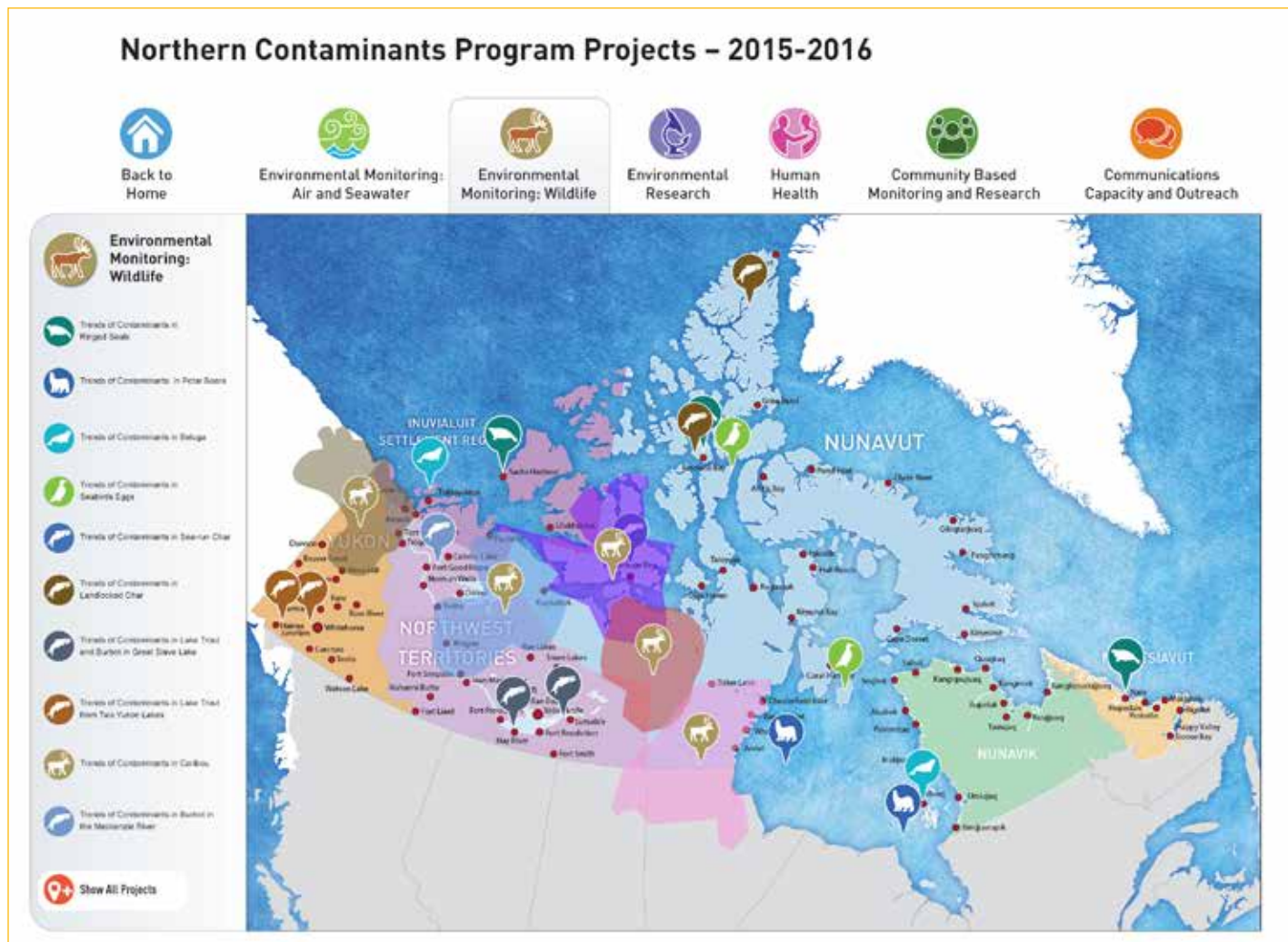


Figure 3. Map of long-term sampling sites for Arctic fish and wildlife monitored annually under Canada's NCP in terrestrial, freshwater, and marine ecosystems. Biotic monitoring is one of several interdisciplinary subprograms (identified at the top of the map) to assess and monitor risks of contaminants (including Hg) to ecological and human health.

## Screening Benchmarks

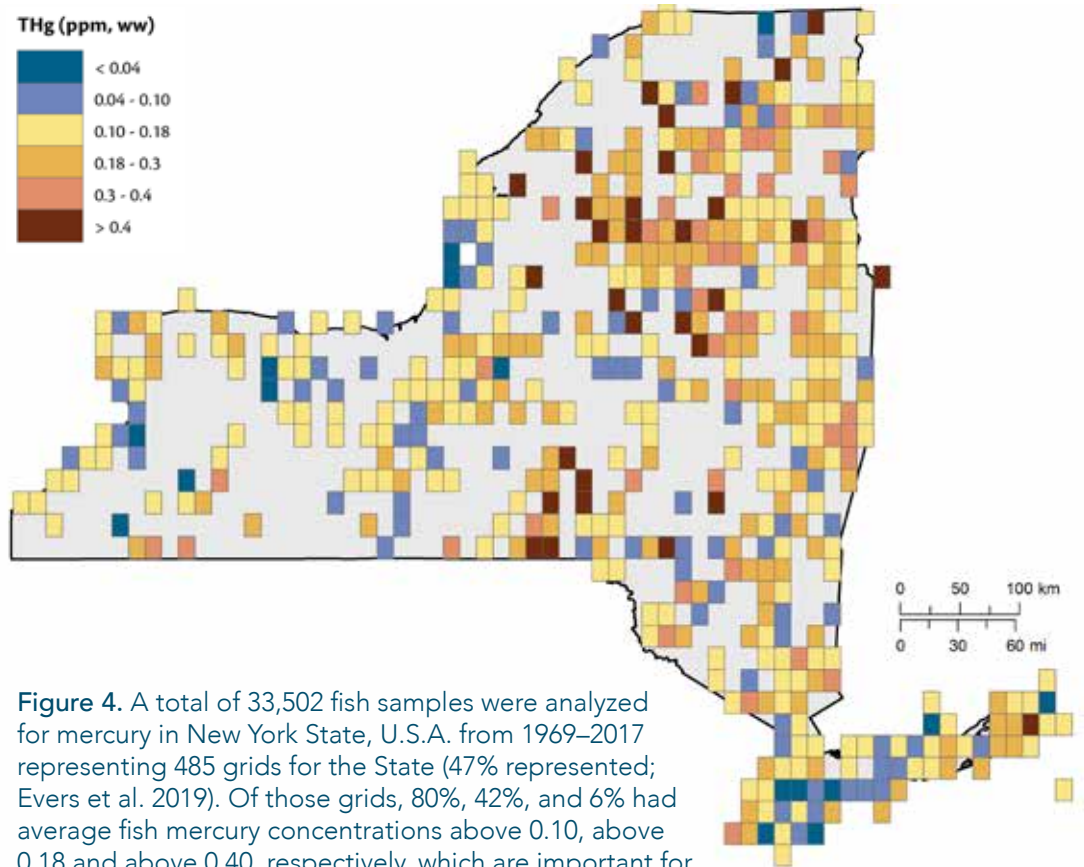
(whole body fish total Hg  
in ppm, ww)

### Fish:

- >0.04 ppm in diet of fish (Depew et al. 2012b—effects to fish reproductive success)
- >0.30 ppm in diet of fish (Scheuhammer et al. 2015—reduces reproductive success in fish)

### Birds:

- 0.10–0.18 ppm in diet of birds (Depew et al. 2012a—adverse effects on behavior for avian piscivores)
- 0.18–0.40 ppm in diet of birds (Depew et al. 2012a—significant reproductive impairment for avian piscivores)
- >0.40 ppm in diet of birds (Depew et al. 2012a—reproductive failure for avian piscivores)



**Figure 4.** A total of 33,502 fish samples were analyzed for mercury in New York State, U.S.A. from 1969–2017 representing 485 grids for the State (47% represented; Evers et al. 2019). Of those grids, 80%, 42%, and 6% had average fish mercury concentrations above 0.10, above 0.18 and above 0.40, respectively, which are important for the health and reproductive welfare of avian piscivores (Depew et al. 2012a).

One example of a local project that has established long-term monitoring of mercury using biota (e.g., fish and birds) is in New York State, U.S.A. (Evers et al. 2019). A 50-year dataset on freshwater fish mercury data (n=33,502 individuals) and birds (n=9,751) depicts exposure across nearly half of the state through the use of standard grids—in this case each grid represents 250 square kilometers.

Mercury exposure data can be placed in categories that are relevant to screening benchmarks. These benchmarks can then be related to risks to fish, birds, and humans for multiple endpoints from behavioral to reproductive impairments. Such standardized data can be comparably used for understanding spatial gradients (Figure 4) and temporal trends.

To provide sustainable and long-term biomonitoring capacity in key regions around the world—e.g., Arctic, tropical areas associated with artisanal small-scale gold mining (ASGM), and islands—the focus needs to be on expanding and stabilizing existing national initiatives that use relevant sample sizes that can meet statistical power for confidence in understanding spatial gradients (e.g., ecosystem

sensitivity spots; Evers et al. 2011) and temporal trends (Bignert et al. 2004).

Moreover, it is crucial to foster international collaboration and coordination among national or local projects to create harmonized regional approaches. Where possible, it is helpful to integrate biomonitoring activities into an interdisciplinary framework to assess ecological and human health risk that can be thereafter stitched together to represent regional and eventually global spatiotemporal patterns.



Freshwater fish, such as this large-mouth bass are important food items for recreational and subsistence purposes; poor nations depend far more on freshwater fishes than marine sources (McIntyre et al. 2016).



## 3.0 Comparability and gaps of mercury data

By identifying critical knowledge gaps and adopting quantitative and replicable approaches, a harmonized mercury monitoring effort for biota can be developed and made available to countries. A standardized approach that quantifies where, when, how, and what to monitor for tracking environmental inorganic mercury loads, their changes over time, and potential impacts on human and ecological health is feasible and has been described at a sub-regional level (e.g., mid-Atlantic coast of the U.S.) (Evers et al. 2008).

Although there are large biological mercury datasets available (as previously demonstrated), they do not provide the ability to determine changes in biotic mercury exposure at regional or global scales over decadal periods (with the important exception of the Arctic biome because of the AMAP).

Robust statistical approaches are critical for confidently tracking biotic mercury concentrations in the many different biomes around the world, and controlling for the effects of other factors. Such examples include global climate change, altered foraging habitat, changes in primary productivity and changing growth rates that can drive changes in biotic methylmercury concentrations with no

actual change in environmental mercury loads (Eagles-Smith et al. 2018).

### 3.1 Comparability of mercury data

An important element for a standardized global biotic mercury monitoring program is the selection of the proper species or groups within relevant geographic areas, such as biomes. Bioindicators most appropriate for assessing human health and the environment are those that are at the upper trophic levels, which best reflect the ability of methylmercury to biomagnify through the food web (Figure 5). For biotic mercury monitoring purposes, trophic level 4 (tertiary consumers) or 5 (top predators) bioindicator are best for evaluating the effectiveness of reducing environmental mercury loads around the world.

The choice of species or groups greatly varies because of their distribution and habitat preferences. However, the best way to standardize differences in mercury exposure levels is to base monitoring on trophic level 4 and 5 species. Species and groups have been categorized by trophic level for most taxa and subsequently bioindicators can be identified by the four major terrestrial biomes and associated aquatic areas to represent both human health and

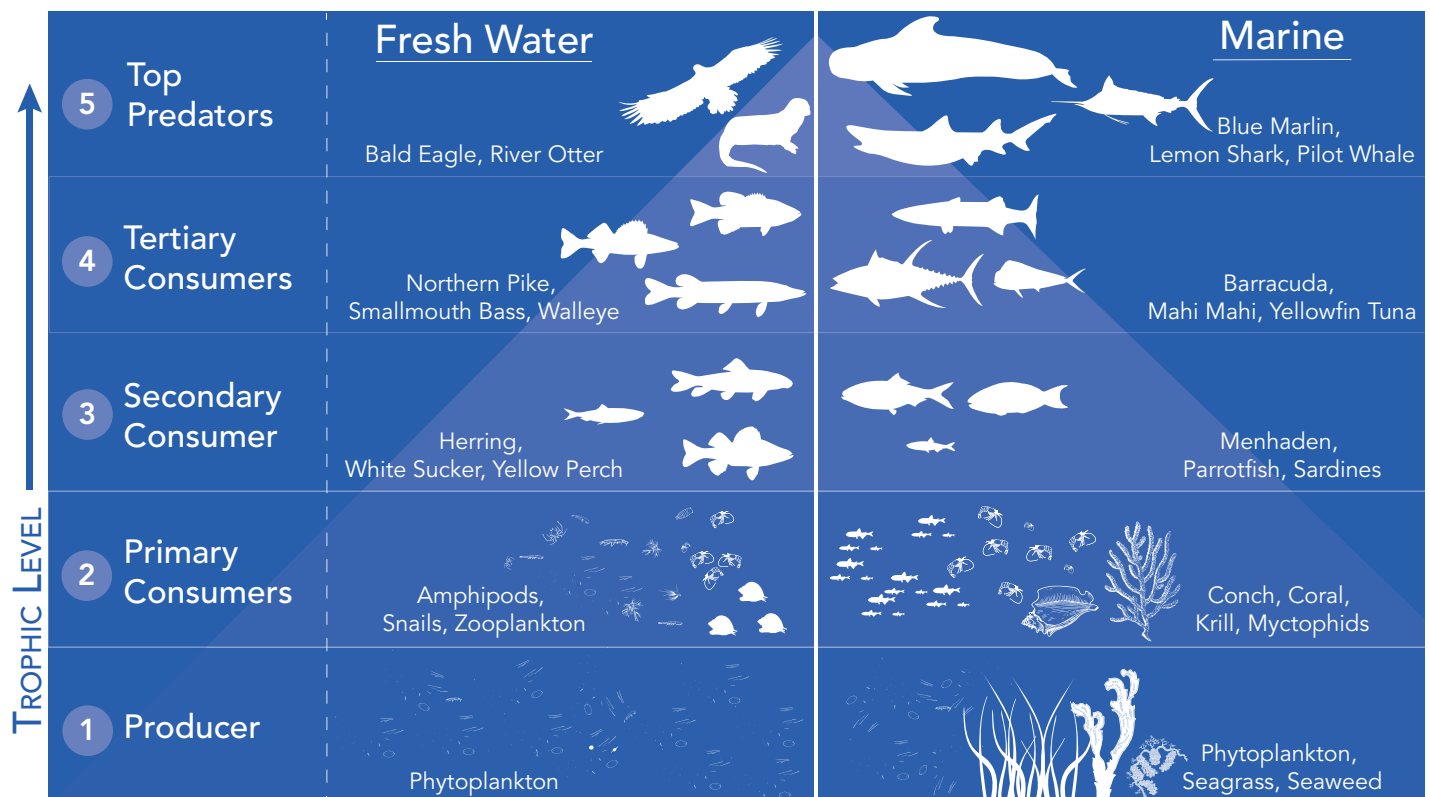


Figure 5. Trophic level categories for both freshwater and marine ecosystems with relevant associated bioindicators.

Table 3. Examples of trophic level 4 or higher biota that could serve as bioindicators within major biomes and associated nearshore areas (based on Evers et al. 2016, 2018).\*

Terrestrial Biomes and Associated Marine Areas	Ecological Health Bioindicators			Human and Ecological Health Bioindicators		
	Freshwater Birds	Marine Birds	Marine Mammals	Freshwater Fish	Marine Fish	Marine Mammals
Arctic Tundra and Arctic Ocean	Loons	Fulmars, Murres	Polar Bears, Seals	Arctic Char	Cod, Halibut	Beluga, Narwhal
Boreal Forest-Taiga and N. Pacific and N. Atlantic Oceans	Eagles, Loons, Osprey, Songbirds	Osprey	Mink, Otter, Seals	Pike, Walleye	Bluefish, Tuna	Pilot Whale
Temperate Mixed Forest and Pacific and Atlantic Oceans	Egrets, Grebes, Herons, Loons, Osprey, Terns, Songbirds	Cormorants, Osprey, Terns	Otter, Seals	Bass, Walleye	Barracuda, Mackerel, Sharks, Tuna	Pilot Whale
Tropical Rainforest and S. Pacific, S. Atlantic, and Indian Oceans	Egrets, Herons, Kingfishers, Songbirds	Albatrosses, Frigatebirds, Shearwaters, Terns, Tropicbirds	Otter, Seals	Catfish	Barracuda, Billfish, Grouper, Mahi mahi, Sharks, Tuna	Pilot Whale

\*Trophic level for some taxa may be specific to types of food webs, habitats and locations.

the environment. Many species and groups currently are characterized for mercury exposure and are therefore suitable choices (Table 3).

### 3.2 Gaps in mercury data: geographic, temporal, and taxonomic

Based on the knowledge of existing biotic mercury data and within the interest of using comparable data (i.e., trophic level 4 or greater), for relevant terrestrial biomes and associated aquatic areas, a matrix of available data that can respond to overarching questions related to temporal trends and spatial gradients can be developed (Table 4). Generally, data availability is sufficient for tracking temporal trends and spatial gradients for all major taxa as bioindicators for both human health and the environment in the Arctic (AMAP 2011, 2015), as well as for fish in North America and Europe (covering parts of the boreal and temperate mixed forests). There are some mercury monitoring programs that include birds within the U.S. and southern Canada. Data gaps are most notable within the tropical

rainforest biome and associated marine areas—they are most problematic when coupled with mercury releases from ASGM activities and other major mercury source types. Information for marine mammals is generally missing as well, except for the Arctic Ocean.



Invertivore foraging songbirds, such as this Prothonotary Warbler, are actually at a high trophic level and are now regularly used as a bioindicator for mercury monitoring and assessments in North America (Evers 2018).

Table 4. Generalized assessment of global mercury availability at poor (Data gap), good (X) and excellent (XX) levels for trophic level 4 or higher indicators within major biomes and associated marine areas for both ecological and human health indicators.

Terrestrial Biomes and Associated Marine Areas	Ecological Health Bioindicators			Human and Ecological Health Bioindicators		
	Freshwater Birds	Marine Birds	Marine Mammals	Freshwater Fish	Marine Fish	Marine Mammals
Arctic Tundra and Arctic Ocean	XX	XX	XX	XX	XX	XX
Boreal Forest-Taiga and N. Pacific and N. Atlantic Oceans	X	X	Data gap	XX	X	Data gap
Temperate Mixed Forest and Pacific and Atlantic Oceans	XX	X	Data gap	XX	X	Data gap
Tropical Rainforest and S. Pacific, S. Atlantic, and Indian Oceans	Data gap	Data gap	Data gap	Data gap	Data gap	Data gap

## 4.0 Options for filling gaps through existing mercury monitoring programs

The choice of trophic level 4 or 5 bioindicators by biome and general ecosystem type (i.e., land, freshwater, marine) is influenced by objective (e.g., tracking temporal trends or spatial gradients) and several other factors (Table 5). In the Arctic, standard bioindicators have been selected to monitor mercury for human health and the environment and represent a long-term existing dataset and confidence for future coverage. In the boreal and taiga biome, the NCP in Canada and various fish monitoring efforts in Scandinavia provide excellent examples of standardized programs, especially in freshwater lakes. For temperate biomes in the western hemisphere, existing efforts are primarily in place in the U.S. and Europe for freshwater ecosystems and some marine areas—although they rarely reflect long-term datasets.

In tropical biomes, there are few existing datasets and even fewer existing monitoring programs for land, freshwater and marine ecosystems. Across the open ocean basins (outside of the Arctic and

Antarctic Oceans), commercial fisheries for tuna and billfish provide an excellent potential platform for long-term, sustainable and cost-effective monitoring of mercury based on existing and regular capture.

The practicality, feasibility, sustainability, comparability, and cost effectiveness are all factors to consider for mercury monitoring in biota. For the Arctic biome, the AMAP has been meeting these needs since 1991 and is expected to continue to monitor mercury and other contaminants in the foreseeable future. In the taiga and boreal areas of the northern hemisphere comparable mercury data are very feasible (because of relatively similar taxa), and in Canada, the U.S. and Scandinavia the practicality and sustainability of Canada’s NCP and those directed by the other country’s respective governments makes running mercury monitoring programs cost-effective. The major exception for this region is Russia.

In the temperate biome, there are strong programs in monitoring biota in the freshwater ecosystems



Table 5. Practicality, feasibility, sustainability, comparability, and cost effectiveness of tracking mercury in trophic level 4 or higher bioindicators by biome and ecosystem.

Biome	Ecosystem	Influenced by MC* Article	Practicality & Feasibility Ranking	Sustainability Ranking	Comparability Ranking	Cost Effectiveness Ranking	Existing Monitoring Program/ Data Coverage
Arctic	Land	1, 8	5	5	5	5	AMAP provides full coverage
	Freshwater	1, 8	5	5	5	5	AMAP provides full coverage
	Marine	1, 8	5	5	5	5	AMAP provides full coverage
Taiga - Boreal	Land	1, 8	3	4	5	4	Continuous data sets available in Canada through NCP and in parts of Scandinavia
	Freshwater	1, 8	4	5	5	5	Continuous data sets available in Canada through NCP and in parts of Scandinavia
	Marine	1, 8	3	3	4	3	Some data sets, few monitoring programs
Temperate	Land	1, 8, 9	4	4	4	4	Some data sets, few monitoring programs
	Freshwater	1, 8, 9	5	5	4	5	State, provincial, and country long-term Hg monitoring programs for fish often in place in U.S. Europe, and some in eastern Asia
	Marine	1, 8	5	5	5	5	Very few data sets, no monitoring programs; however, commercial fisheries provide long-term monitoring abilities with tuna and billfish
Tropical	Land	1, 7, 8, 9	3	3	3	4	Very few data sets, no monitoring programs
	Freshwater	1, 7, 8, 9	4	4	4	4	Very few data sets, no monitoring programs; largest data gap and largest environmental impact from ASGM Hg sources
	Marine	1, 7, 8	5	5	5	5	Very few data sets, no monitoring programs; however, commercial fisheries provide long-term monitoring abilities with tuna and billfish

\* Minamata Convention on Mercury

(not as strong on land and marine areas, but still functioning) across the U.S., Europe and in parts of eastern Asia. Southern hemisphere mercury monitoring efforts for biota in temperate biomes are not as strong as the northern hemisphere and could significantly add to the knowledge of mercury cycling (e.g., Argentina, Chile, and Australia).

In tropical and subtropical areas, very few mercury monitoring efforts are in place. Environmental mercury-related research has been significant in some countries, such as Brazil and China, but are not as robust for monitoring mercury in biota as in temperate areas. The practicality, sustainability and comparability are also all challenging because of limited infrastructure and history of monitoring activities, however, the cost-effectiveness would likely be high.

Tropical and subtropical areas are especially important for monitoring mercury using biota for Article 7, because it is challenging to determine the effectiveness of the Minamata Convention in protecting human health and the environment from ASGM activities (Martinez et al. 2018; Mason et al. 2019).

One factor in particular, global climate change, will alter future mercury concentration levels across the landscape (Sundseth et al. 2017), especially in marine ecosystems (McKinney et al. 2015; Sundseth et al. 2015; Schartup et al. 2019), subarctic and temperate lakes (Chen et al. 2018), temperate estuarine ecosystems (Willacker et al. 2017), and

terrestrial ecosystems (Eagles-Smith et al. 2018). Specific effects of global climate change include: elevated mercury inputs from melting of polar ice caps, glaciers and permafrost, enhanced air-seawater exchange of mercury in ice-free polar waters (Fisher et al. 2013), changes in ocean circulation affecting mercury transport, shifts in productivity affecting methylation and uptake into the food chain, and direct impacts of temperature on fish metabolism increasing methylmercury (Shartup et al. 2019; Krabbenhoft and Sunderland, 2013). But, how these landscape processes relate to changes in biotic mercury exposure is relatively unknown.

Sunderland et al. (2018) showed global climate change is changing methylmercury exposures from fish species such as cod and pollock that are sensitive to climate driven warming of seawater. Schartup et al. (2019) showed that for a variety of commercially important fish species the direct effects of seawater warming will lead to substantial increases in methylmercury.

Iterative efforts to link realistic and applied biomonitoring efforts at local levels with science groups aimed at assisting the Conference of Parties of the Minamata Convention (e.g., ad hoc technical expert group for effectiveness evaluation) will ultimately help keep pace with the many emerging scientific findings that may fill existing information gaps that are key for global policymaking.

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Tropical ecosystems where mercury methylation is elevated often includes mangroves and other habitats that undergo regular wet-dry cycles.



## 5.0 Available modeling capabilities to assess changes in global mercury levels

The compilation of existing biotic mercury data is an important approach to understand broad spatial gradients and temporal patterns. Models based on existing data and scientific findings are useful for extending observations in space and time.

Recent global modeling efforts show 49% of global Hg<sup>II</sup> deposition occurs over the tropical oceans (Horowitz et al. 2017). The equatorial Pacific region is an essential commercial harvesting location for many large pelagic species such as tuna that are responsible for a large fraction of human exposure to methylmercury (Sunderland et al. 2018). Thus, linking elevated mercury deposition to methylmercury formation in the ocean and associated biological exposures is an important goal of ongoing research.

Similarly, understanding the relationship between enhanced deposition of mercury in India and China and other regions of intense coal use in Europe and the U.S. (Giang et al. 2015, Corbitt et al. 2011) and biological concentrations in inland food webs is essential for linking changes in benefits from future emissions reductions to human and ecological exposures.

In freshwater ecosystems, a global meta-analysis suggests that mercury biomagnification through food webs is highest in cold and low productivity systems (Lavoie et al. 2013), however large contaminated sites (e.g., ASGM areas) are likely important drivers of variability in tropical freshwater biota concentrations (Obrist et al. 2018).

One recent effort to characterize global aquatic mercury releases to inland ecosystems is therefore especially important for understanding the spatial distribution of these locations (Kocman et al. 2017). Our understanding of how mercury released from ASGM and associated conversion to methylmercury, exposures, and impacts on human and ecological health is poor (Affum et al. 2016).

It is expected that some of the ASGM-derived inorganic mercury into the air, water, and land reaches aquatic food webs and is transferred into upper trophic level organisms, but this may vary greatly across these continents. Yet, the associated patterns over time and space are critical to understand for developing biomonitoring activities in a time-efficient and cost-effective manner.

### 5.1 Spatial gradients

The availability of methylmercury to high trophic level organisms is not uniform. Some ecosystems are more sensitive to inorganic mercury input than others (Driscoll et al. 2007, Eagles-Smith et al. 2016) and it is in these areas that biological methylmercury hotspots can form and are especially pronounced in higher trophic-level organisms (Evers et al. 2007).

For terrestrial ecosystems, such areas are generally associated with wetlands and other temporally wetted habitats and can be particularly pronounced in ecosystems with water chemistry variables such as low pH, moderate to high DOC concentrations, and low to moderate primary productivity. In particular, fluctuating water levels can have a particularly important contribution in generating higher methylation rates and increases in methylmercury bioavailability (Willacker et al. 2016), and, may happen at daily (tidal), monthly (artificial reservoirs and pools), or seasonal (river floodplains and dry tropical areas flooded during the wet season) timeframes, as well as under managed areas (rice agriculture).

Therefore, the determination of areas that may have elevated methylmercury availability are generally not directly related to the deposition or release of inorganic mercury into the environment.



Rice fields, like all wetland habitats, are excellent mercury methylating environments. Rice fields in China were examined for methylmercury exposure to biota and demonstrated some of the highest songbird mercury levels known in the world, yet human exposure from a rice diet was low because the biomagnification of methylmercury is low unless it moves through multiple trophic levels (Abeysinghe et al. 2017).



For example, compared to the U.S., relatively low precipitation-weighted mean concentrations and deposition of total mercury are in Kejimikujik National Park in Nova Scotia, Canada (an average of <5 ng/L and <7.5 ug/m<sup>2</sup> of mercury per year for the past four years of available data, Dastoor and Larocque, 2004, Dastoor et al. 2015, NADP, 2017), yet the biotic methylmercury exposure is some of the highest in North America where fish (e.g., yellow perch) and birds (e.g., Common Loons) within the National Park well exceed ecological health thresholds (i.e., 0.30 and 3.0 µg/g ww, respectively, Evers et al. 1998, Burgess and Hobson, 2006, Burgess and Meyer, 2008, Wyn et al. 2009, 2010). This is because most lakes in the area are sensitive to inorganic mercury input and have high methylation potential and methylmercury bioavailability owing to a combination of low pH, high DOC, high percentage of shoreline wetlands, and low primary productivity.

Ultimately, identification of biological methylmercury hotspots (also known as ecosystem sensitivity spots) can be made through the collection of existing biotic data (Evers et al. 2011, Ackerman et al. 2016, Eagles-Smith et al. 2016) and modeling ecosystem sensitivity at regional or global scales.

In marine regions, spatial patterns in biological methylmercury concentrations are less resolved but will be facilitated by the development of a global biotic database of mercury concentrations in marine species and supporting modeling efforts to help

explain observed spatial patterns. Differences in methylmercury concentrations across ocean basins are apparent in the literature. The highest reported concentrations of methylmercury in seawater have been reported in some regions of the Southern Ocean, which also have elevated concentrations of methylmercury in some food webs (Cossa et al. 2011).

Considerable spatial variability in seawater methylmercury concentrations has been reported among other ocean basins, with highest levels in subsurface waters of the most biologically productive areas (Bowman et al. 2014, 2016, Cossa et al. 2009, Kim et al. 2017, Munson et al. 2015, Sunderland et al. 2009). The Arctic appears to have higher concentrations of methylmercury in near-surface seawater, which may reflect unique microbial activity resulting from the combination of stratification, freshwater discharges and ice cover (Lehnherr et al. 2011, Heimbürger et al. 2015, Schartup et al. 2015).

Several modeling approaches are available for linking atmospheric deposition of mercury to concentrations in food webs. In addition to the empirical approaches for characterizing spatial patterns in concentrations, a variety of ecosystem models and global models are available. Ecosystem models are usually forced by measured atmospheric inputs for a specific system and then linked to a hydrological model and food web models.

Examples of past applications include lakes (Knights et al. 2009, Harris et al. 2007) and coastal



Research vessels such as the RV Navicula of the Royal Institute for Sea Research in the Netherlands (pictured) can provide cost effective and efficient means of collecting samples for mercury testing.

ecosystems (Sunderland et al. 2010, Schartup et al. 2015, Calder et al. 2015). Global food web models are under development and include ocean models for inorganic mercury (Zhang et al. 2015, 2016), methylmercury (Dastoor and Laroque, 2004, Zhang et al. in review), and fish bioaccumulation models (Schartup et al. 2019).

For the global oceans, simulated methylmercury concentrations in seawater (Figure 6) and data

on fish mercury concentrations in the commercial seafood market (Karimi et al. 2012) allow estimations of the flow of mercury in marine biota to different regions globally. Fisheries catch data are available globally. Such an approach can be used to better understand the types of fish harvested in different countries globally, the consumption preferences by subsistence consumers, and associated methylmercury exposures from dietary intake.

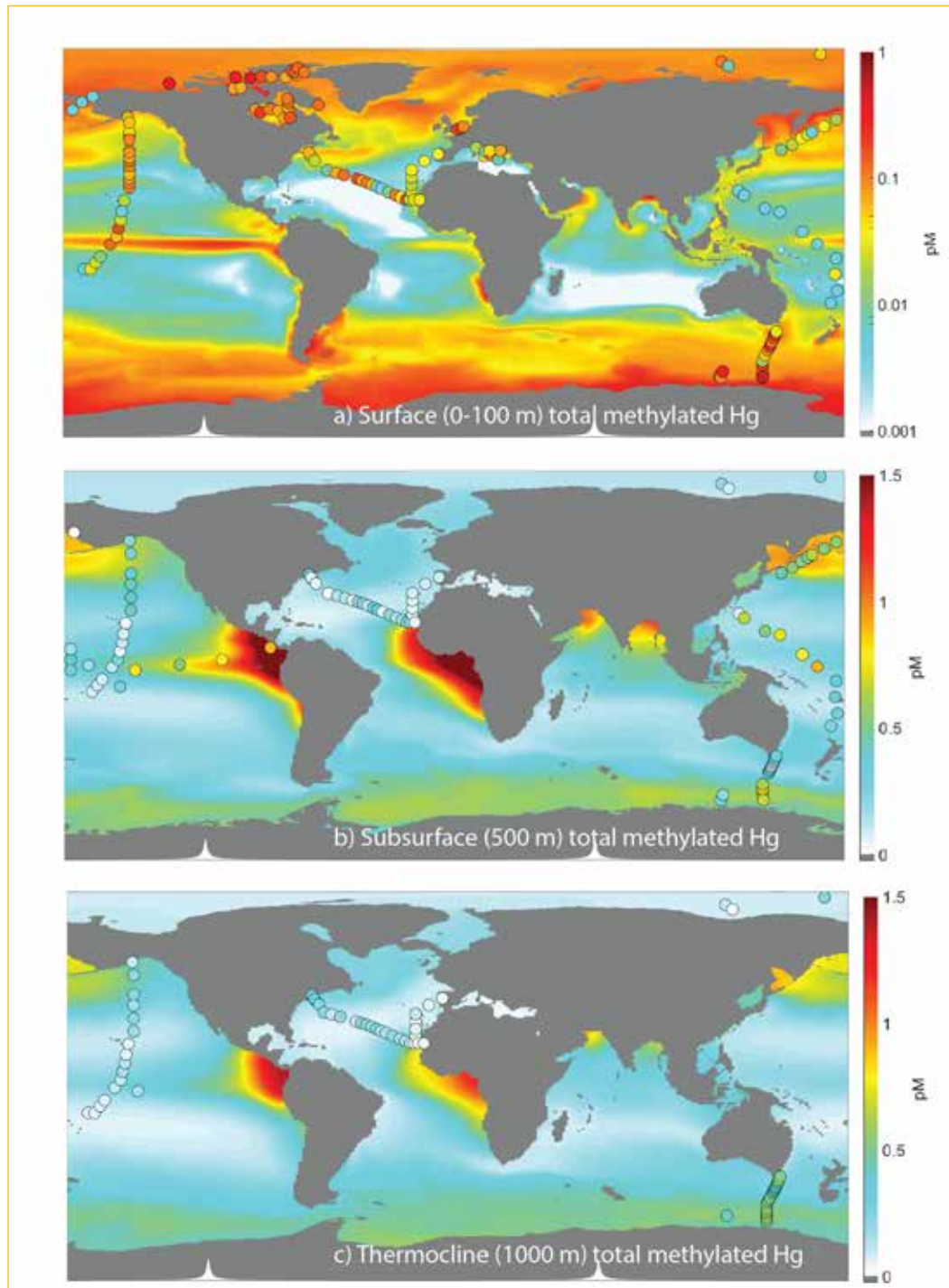


Figure. 6. Example of simulated methylmercury concentrations in seawater from Zhang et al. in review

## 5.2 Temporal trends

Models simulating the deposition of mercury from anthropogenic emissions at global scales (using three anthropogenic emissions scenarios) indicate a best-case scenario of a decrease of up to 50% in the Northern Hemisphere and up to 35% in the Southern Hemisphere by 2035 (Pacyna et al. 2016). Although tracking mercury emissions, deposition, and releases are important tools for understanding patterns of environmental mercury loads (Sundseth et al. 2017) the relationship between modeled (or measured) deposition and methylmercury concentrations in biota is poorly understood.

Trends in inorganic mercury concentration are thought to differ among ocean basins because anthropogenic emissions have strongly declined in North America and Europe, leading to large declines in atmospheric concentrations, especially in the Atlantic Ocean (Zhang et al. 2016). Lee and Fisher (2016) postulated that this may also explain observed declines in Atlantic bluefin tuna methylmercury concentrations between 2004 and 2012 in the North Atlantic Ocean—which are supported in measured mercury concentrations in blue marlin (Barber and Cross 2015).

The relationship of changing fish methylmercury concentrations in different ocean basins is germane to a better understanding of the geographic origins of seafood by country or region. For example, for the U.S., 45% of population wide methylmercury exposure originates from open oceans (particularly the Pacific Ocean), 37% from domestic coastal ecosystems, and 18% from aquaculture and freshwater fisheries (Sunderland et al. 2018).

By contrast, both atmospheric emissions and freshwater discharges of mercury have been growing on the Asian continent leading to increased mercury pollution in the North Pacific Ocean (Amos et al. 2014, Streets et al. 2009, Sunderland et al. 2009, Zhang et al. 2015). Most recent data indicate the rate of growth in mercury emissions has been slowed by widespread implementation of emissions controls on new coal-fired utilities (Streets et al. 2017).

Temporal data on fisheries in the North Pacific are more limited but some researchers have suggested that there is evidence for increases in tuna methylmercury concentrations over recent decades (Drevnick et al. 2015), which is further supported by additional analysis of bigeye tuna for the same area (Drevnick and Brooks, 2017).

In North America, long-term biomonitoring in Arctic freshwater (Chételat et al. 2015) and marine (Rigét et al. 2011, Braune et al. 2015) ecosystems provides an important regional platform for examining temporal trends through Canada's NCP and the AMAP. In addition, in the Canadian province of Ontario projected temporal trends in over 200,000 game fish analyzed since 1970 indicate increasing methylmercury concentrations in more than 250,000 lakes (which, when including the Great Lakes, represents about a third of the world's freshwater).

Using one of the largest consistent mercury biomonitoring efforts in the world, a robust long-term trend in fish mercury concentrations can be determined. Using mercury concentrations in the muscle of walleye, northern pike, and lake trout, it is projected that 84–100% of the 250,000+ lakes will have “do not eat” advisories by 2050 for sensitive

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Monitoring mercury in trophic level 4 bird groups (e.g., loons) in North America has been in place across temperate and tundra biomes since 1990 (Evers et al. 1998, 2003, 2011, 2014; Scheuhammer et al. 2016).





human populations (Gandhi et al. 2014, 2015).

Although inorganic mercury emissions in North America are declining, other factors such as global emissions, climate change, invasive species, and local geochemistry may be impacting the response time and magnitude of biotic methylmercury trends for this region (Gandhi et al. 2014). Climate drivers such as higher precipitation rates may be especially important in this area causing increased methylmercury concentrations for both cool and warm water gamefish (Chen et al. 2018).

Experimental data have suggested increased discharges of terrestrial natural organic matter, due to climate change, may drive trophic shifts at the base of aquatic food webs that lead to increased biomagnification of methylmercury (Jonsson et al. 2017). Recent work on methylmercury uptake and trophic transfer of marine food webs in the Northwest Atlantic Ocean suggest that most variability in methylmercury concentrations in marine plankton can be explained by differences in DOC (Schartup et al. 2018), similarly, there are relationships with changing seawater methylmercury and temperature with tuna mercury concentrations (Figure 7).

The influence of climate change on mercury cycling

only increases the importance of generating baseline data for methylmercury in bioindicators. An example can be found in Canada where total mercury levels in aquatic birds and fish communities have been monitored across the Canadian Great Lakes by Environment and Climate Change Canada at 22 stations for the past 42 years (1974–2015) (Blukacz-Richards et al. 2017). For the first three decades, mercury levels in gull eggs and fish declined at all stations.

In the 2000s, trend reversals were apparent for many stations and in most of the Great Lakes, although the specific taxa responsible varied (e.g., walleye, Common Loons). While strong trophic interactions among birds and fish are apparent, there also appears to be a high likelihood of trophic decoupling in some ecosystems. This indicates the importance not only of long-term mercury biomonitoring efforts, but also study designs that include other parameters such as food web structure (Pinkney et al. 2015), watershed disturbances including novel factors such as beaver activity (Brigham et al. 2014), and especially those related to climate change (magnitude and frequency of storm events, increasing wildfire activity, etc.; Sundseth et al. 2015).

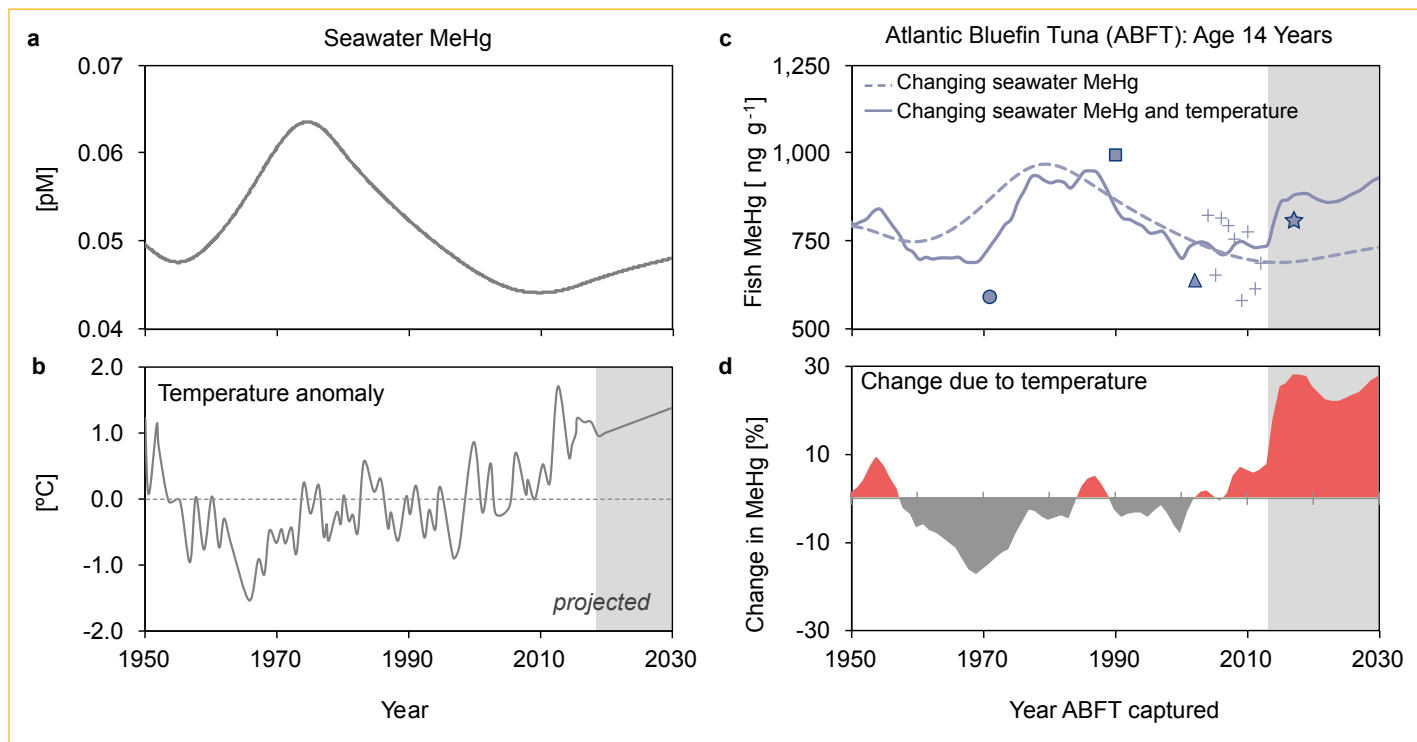


Figure 7. Illustration of the impacts of changing seawater temperature in the northwestern Atlantic Ocean on Atlantic bluefin tuna. Figure from Schartup et al. (2019)

## 6.0 Baselines

Environmental conditions and biotic mercury concentrations are well known for many areas of the world and for many taxa. Baseline identification of biotic mercury concentrations will ultimately need to represent the geographic areas and taxa that best

respond to the many objectives within the Minamata Convention. The *Global Mercury Assessment* provides an important source of information for baseline biotic mercury exposure (AMAP/UN Environment 2019).



Existing tuna mercury concentrations, such as from yellowfin tuna, are especially important potential long-term baseline bioindicators for oceans.

## 7.0 Other technical input

The biotic section of this report is based on the GBMS database that was developed and is currently maintained by BRI, Portland, Maine, U.S.A. and was partly funded through UNEP's Scientific and Technical Advisory Panel. This database and parts of this report were used as the basis for:

- UN Environment's *Global Mercury Assessment* (AMAP/UN Environment 2019). Information in GBMS is useful for developing spatial and temporal baselines.
- The technical report of the ad hoc effectiveness evaluation (Minamata Convention Secretariat 2019).

- Developing principles and recommendations for the next steps in evaluating the effectiveness of the Minamata Convention (Evers et al. 2016).

A data repository could be embedded within Environment Live (<http://environmentlive.unep.org/>) or with other existing global data repositories, such as within Global Earth Observation System of Systems.

The biotic mercury database that represents scientifically peer-reviewed information could be queried to permit quick access by Parties of available data. Results from queries could be in tabular and visual forms (e.g., bar charts, histograms, maps etc.).

## 8.0 Proposed monitoring arrangements

Two overarching biotic mercury monitoring approaches proposed herein differ for continents and oceans. They follow some of the recommendations described in Evers et al. (2016).

### 8.1 Continental framework for integrated mercury monitoring

To identify the best locations for global mercury monitoring requires multiple defined steps (Figure 8). Step 1a is to understand the complexities of a landscape and its ability to methylate mercury and make it available in the food web. Mercury methylation is highest in wetlands—and, potentially greatest in estuarine wetlands such as mangroves. Forested areas are also an important factor for

increasing dry deposition rates of atmospheric mercury, while agricultural areas tend to dampen methylation rates (Driscoll et al. 2007). Many of the most important wetland areas in the world are identified and protected through the Ramsar Convention for Wetlands (<https://www.ramsar.org/>) and their 2,341 locations covering 252,489,973 ha will be identified through Step 1b.

The mapping of ecosystem sensitivity spots for each continent at a global level will depend on the resolution of interest. Watersheds are the most relevant base area (i.e., polygon) for mapping and they can greatly vary in size—as an example, mapped herein are drainage basins within each continent (Figure 9).

### Three-step overarching framework for monitoring mercury in biota across continents.

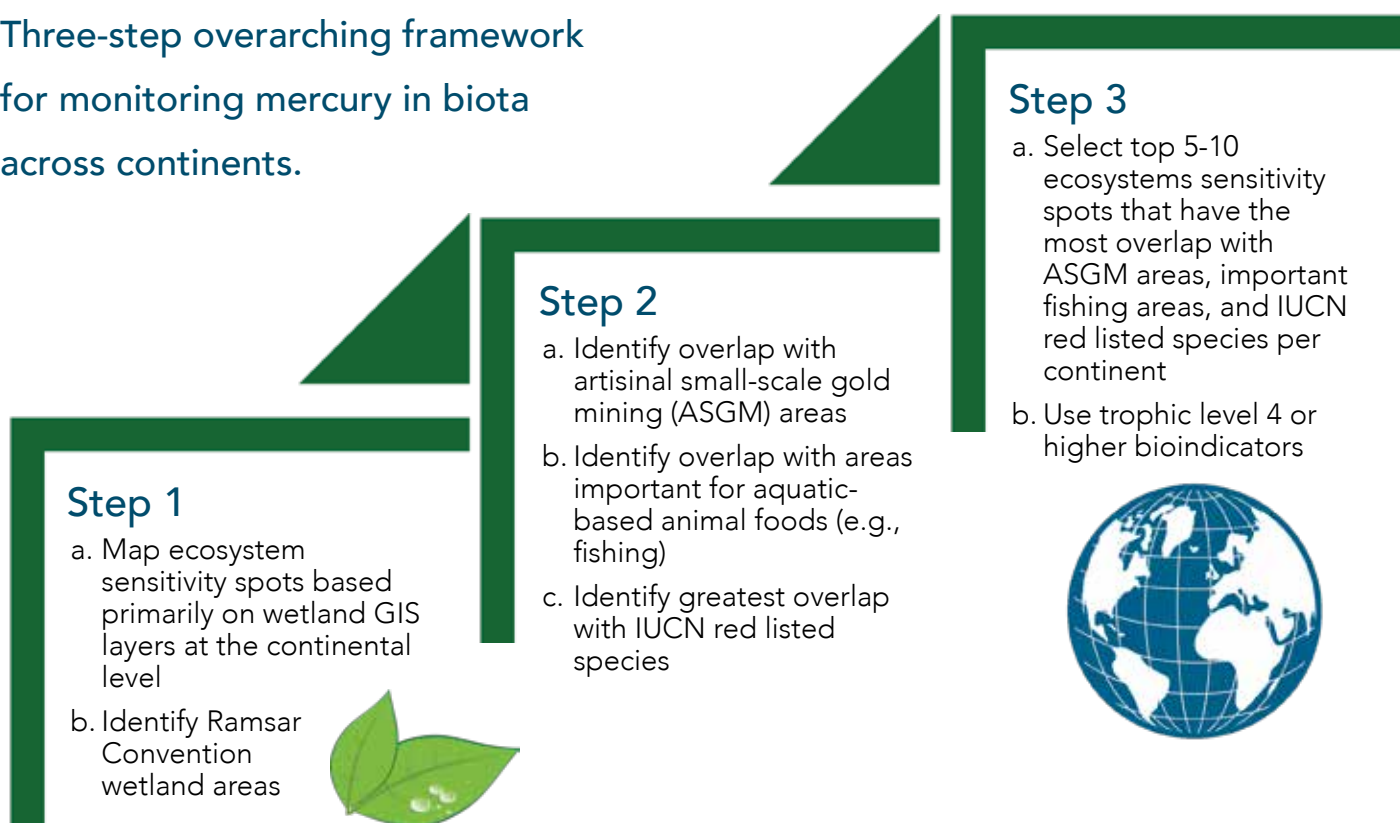


Figure 8. Stepwise components for developing a continental approach using biota for mercury monitoring.



## Step 1

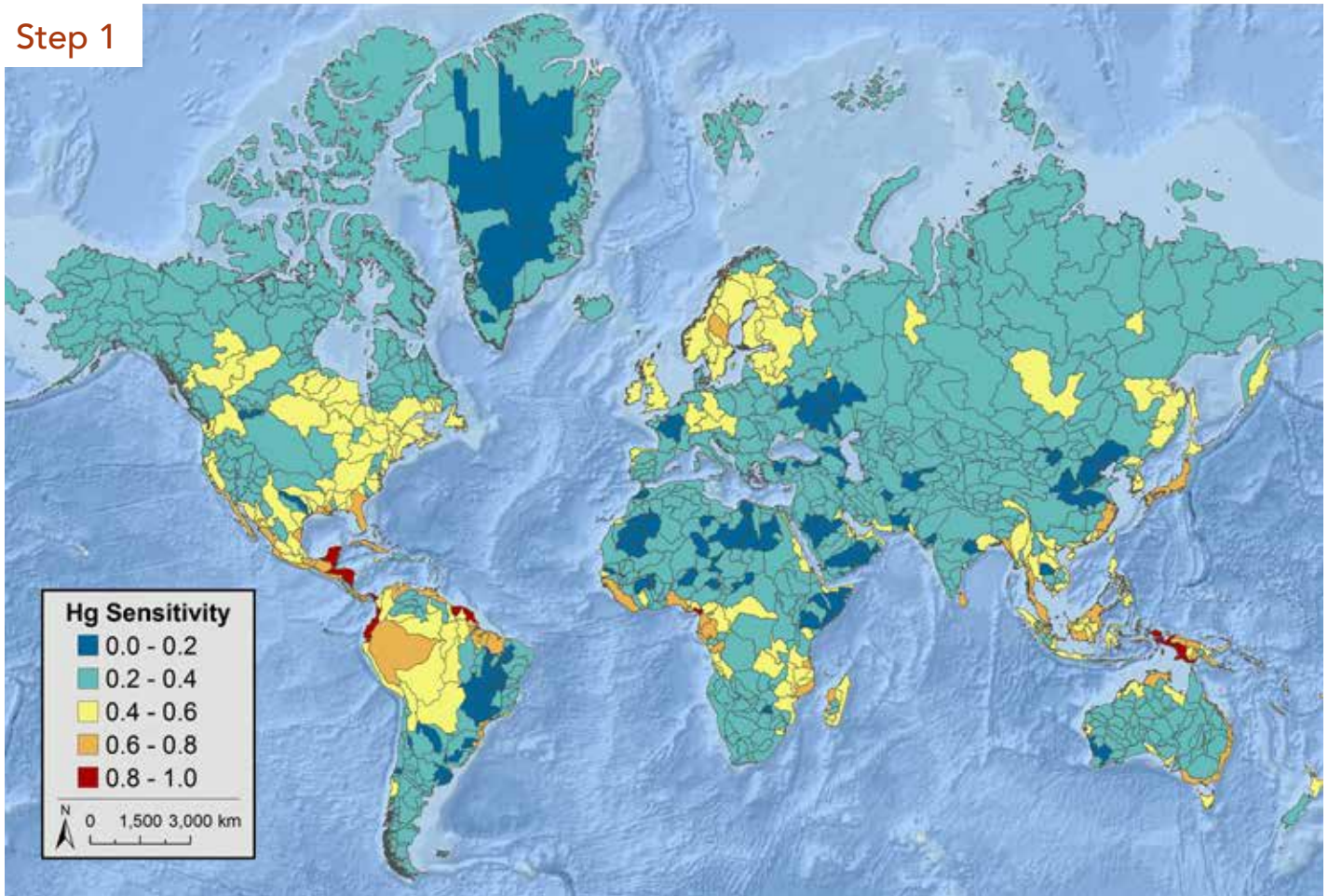


Figure 9. Illustration of potential sensitivity of ecosystems to mercury input in five categories within river drainages at a global level (northern latitudes are not included at this time and are covered by the AMAP).

## Step 2

Step 2 includes the identification and potential overlap with ecosystem sensitivity spots of three important elements that will help prioritize areas of greatest concern for protecting human health and the environment. Step 2a includes the mapping of ASGM as it is the top mercury source in the world (AMAP/UN Environment 2019), with particularly high activities in parts of South America, Africa and Asia (Figure 10). The level of existing biotic mercury data in many of these ASGM areas is minimal based on the GBMS database, which creates an elevated priority in better understanding the potential impacts to human health and the environment.

Step 2b responds to the need of which ecosystem sensitivity spots overlap with areas important for extracting aquatic-based animals for human consumption – this generally represents fish but can include many other vertebrates such as river turtles, crocodiles, birds, and mammals. Such areas are not easily captured by existing GIS layers, therefore

discussions at the national level will need to be conducted.

Step 2c includes the need and the ability to reflect protection of the environment from the impacts of mercury at the highest importance of conservation through the identification of rare, threatened and endangered species of animals as identified by the IUCN Red List. Only species that are at trophic level 4 or higher will be considered for this element.

Following the analyses and prioritization of where the three Step 2 elements overlap with ecosystem sensitivity spots for mercury within each of the six continents of concern (not including Antarctica), Step 3 will involve the selection of 5-10 of the highest ranked areas in each continent (see Figure 11 for an example). The ranking system will quantitatively define each of the Step 2 elements by their intensity and extent within the drainage areas that are most sensitive to the methylation of mercury released or deposited.



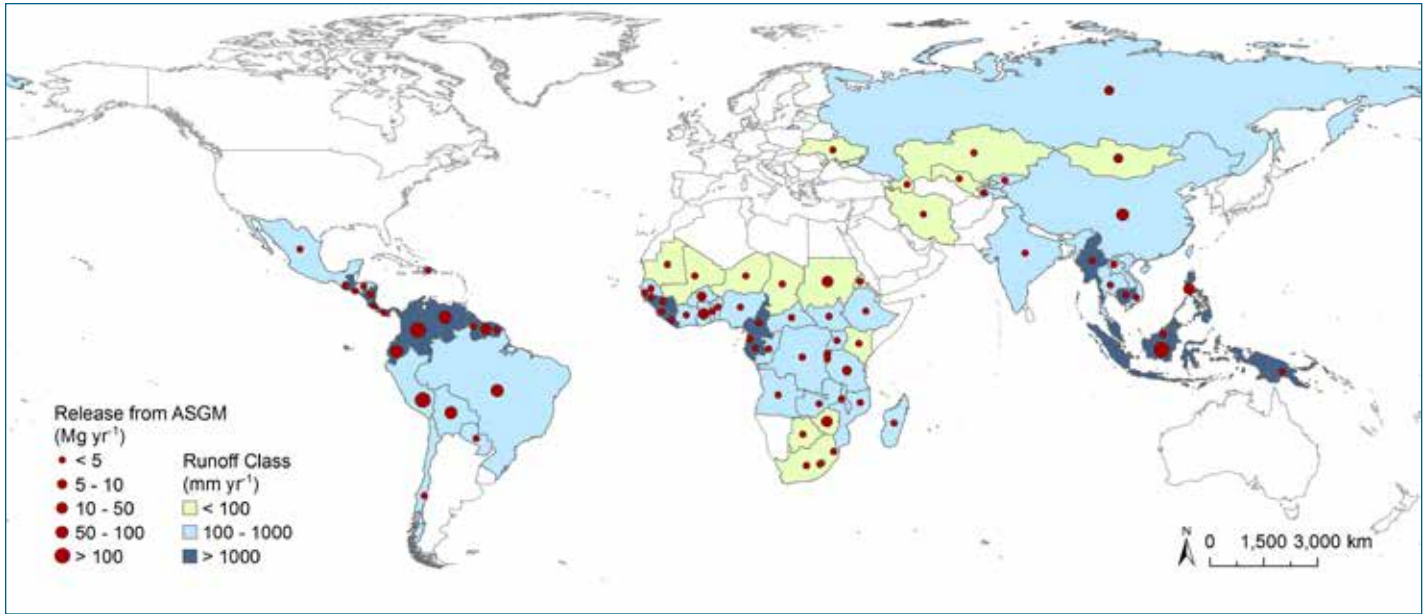


Figure 10. Level of ASGM activities (Kocman et al. 2017).



Artisanal small-scale gold-mining activities can have severe environmental effects, where the impact area of mercury contamination may be over 100 miles downstream from the point source. Key bioindicators for assessments still need to be identified for human and ecological health purposes.



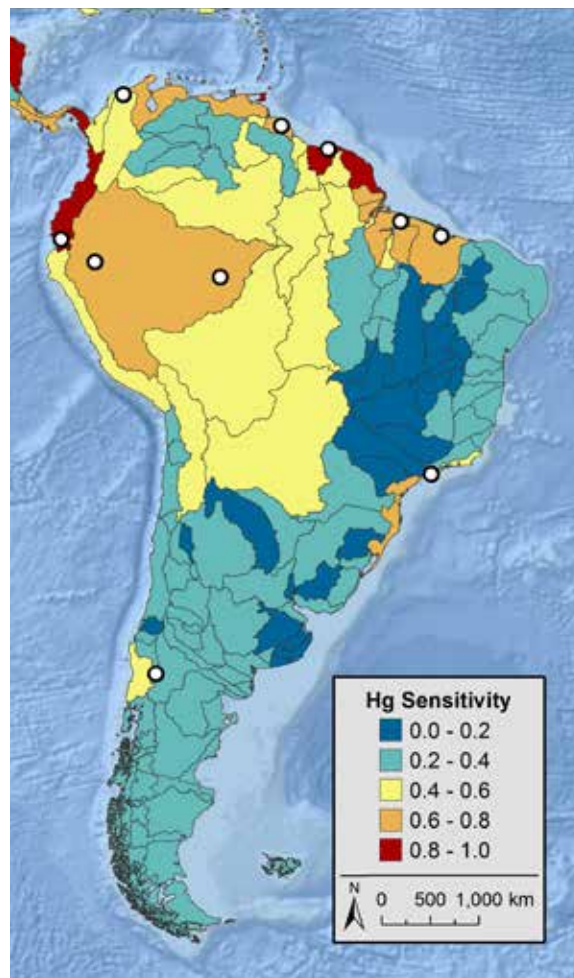
### Step 3

The selection of 5-10 ecosystem sensitivity spots for Step 3a that are made on this basis will also include an internal mercury monitoring design that has both intensive and cluster sites—as described in the U.S. Environmental Protection Agency's *MercNet* (USEPA 2008).

Within each ecosystem sensitivity spot there will be an intensive site (or hub) where there will be a greater ability and interest to monitor mercury in multiple compartments (e.g., air, biota and humans, with an emphasis on trophic level 4 or higher bioindicators under Step 3b), to account for annual variation (e.g., wet vs. dry seasons), and measurements/models of mercury loading.

Whereas cluster sites include less intensive sampling and are chosen to expand the geographic relevance of the intensive site measurements (e.g., include habitats and ecosystems that may differ from the intensive site to better inform geographic scaling of temporal trends, spatial gradients and risk to biota). The number of cluster sites may range from 3-5, depending on local ecosystem variability and objectives.

Figure 11. An example of the potential selection of intensive sites in South America based on the three-step process and knowledge of the elements within each step. Most of the proposed sites, identified as white dots, would be in association with intensive ASGM areas. Note this is only an exercise to understand potential process—these are not sites chosen for mercury monitoring in biota.



Areas downstream from ASGM activities, such as in the Amazon River basin, are important for consolidating upstream mercury input, are conducive for high methylation rates, and are crossroads for human activities for food.



### 8.1.1 Summary of continental sampling framework

As part of the sampling framework for tracking mercury within and adjacent to continents, a matrix that details existing and needed coverage by mercury monitoring networks is possible for seven regions in the world (Table 6). A range of 5-10 intensive sites (n=30 samples) across three broad ecosystems (i.e., freshwater, nearshore marine, and terrestrial [wetlands]) would adequately cover large landscapes, when associated with three cluster sites (n=20 samples) with each intensive site. Wetlands chosen should be prioritized as being part of the Ramsar Convention for Wetlands. The approximate coverage using existing mercury data within monitoring programs is estimated for each of the seven regions.

Sampling timing should be coordinated at times of the years that match similar seasonality (i.e., summer) and/or wet-dry cycles (i.e., wet season). Sampling frequency can be every year for intensive sites and every three years in cluster sites to best capture local variability of methylmercury availability within different habitat types. For example, using this approach in the Central American and Caribbean Region (for 10 sites) would result over a three year period of an analyses of 300 samples/year for intensive sites (n=900 samples over three years) and 600 samples for the three-year period for cluster sites (n=600); therefore, 1,500 samples over three years or 500 samples/year.

### 8.1.2 Summary of sampling framework by region of interest

For North America, each of the three broad ecosystems can be covered through existing mercury monitoring programs for biota – which include AMAP, NCP, the USEPA and various efforts by U.S. states and Canadian provinces.

Site selection is needed and should be distributed across three biomes including Arctic tundra, boreal forest-taiga, and temperate mixed forest. There can be 100% coverage using existing mercury data collection.

For Europe (especially western and central), freshwater and marine ecosystems can be covered through existing mercury monitoring programs for biota, which include: the Coordinated Environmental Monitoring Programme (CEMP); the Joint Assessment and Monitoring Programme (JAMP); and Baltic Marine

Environment Protection Commission—Helsinki Commission (HELCOM) efforts. Gaps could be filled for freshwater Ramsar wetlands. There can be 80% coverage using existing mercury data collection.

For Asia, there is a mix of coverage for each broad ecosystem, but only covers a limited number of countries and is mostly outside of ASGM area. Existing mercury monitoring programs for biota are primarily in China, Japan, and the Republic of Korea (new ones are being explored in Indonesia).

There are many gaps in countries with sensitive ecosystems (e.g., tropical rainforests, mangroves and estuaries) that are associated with major ASGM point sources. There may be approximately 50% coverage using existing mercury data collection.

For South America, there have been many studies emphasizing biotic mercury concentrations in the Amazon River basin, but existing mercury monitoring programs are generally lacking. Because ASGM activities are common and are often associated with wetland communities, there are many high priority gap areas that need more information to better protect human health and the environment. There is less than 20% coverage using existing mercury data collection.

For Central America and the Caribbean, there are very few mercury monitoring studies or programs. One new effort, the Caribbean Region Mercury Monitoring Network has generated new mercury concentrations for key seafood bioindicators and serves as a good platform for long-term monitoring. There is less than 10% coverage using existing mercury data collection.

For Africa, there are very few mercury monitoring studies or programs, with some countries such as Ghana, that have had recent robust efforts. Because of numerous and large ASGM activities and the lack of existing mercury data coverage, many African countries represent major data gaps. There is less than 10% coverage using existing mercury data collection.

For Australia, New Zealand and Small Island Developing States (SIDS; except the Caribbean Region) there are very few mercury monitoring programs. Heavy reliance in seafood and the large data gaps of mercury concentrations exist. There is less than 10% coverage using existing mercury data collection.

Table 6. Sampling strategy for trophic level 4 or higher biota (see Table 3) for the **Continental Sampling Framework**. Listed are the number of intensive sites (with a sample size of 30 at each site); each which should include another 3 cluster sites (with a sample size of 20 at each site) to account for local variability. Monitoring program coverage based on UNEP (2016).

Region of Interest	Freshwater (lakes/rivers)	Nearshore Marine (estuaries/reefs)	Terrestrial (freshwater wetlands)	Estimated number of samples (based on 30 samples per trophic level 4 or higher bioindicator)	Approximate coverage (%) using existing Hg data and monitoring programs*
North America (not including Mexico, Central America, and Caribbean Islands)	3 sites – existing coverage by U.S. states and Canadian provinces, NCP, and AMAP	5 sites – existing coverage by USEPA, NCP and AMAP	2 – existing coverage by U.S. states, NCP and AMAP	None needed – provided by existing entities	>90% (official existing site selection will be needed)
Europe	3 sites – existing coverage by the EU and specifically Norway, Poland, Spain, Sweden, and United Kingdom	5 sites – existing coverage by CEMP, JAMP, and HELCOM	2 sites – no or minimal existing coverage	None needed – provided by existing entities	>80% (official existing site selection will be needed)
Asia	3 sites – existing coverage in China and Republic of Korea; further coverage need near ASGM sites	5 sites – existing coverage in Japan and Republic of Korea	2 sites – existing coverage in China; further coverage needs near ASGM sites and rice fields	150 in intensive sites 300 in cluster sites	<50% (official existing site selection; new sites will need to be identified)
South America	3 sites – existing coverage is minimal and especially needed near ASGM sites	5 sites – existing coverage is minimal, some by Brazil and Colombia	2 sites – existing coverage is minimal and especially needed near ASGM sites	250 in intensive sites 500 in cluster sites	<20% (new sites will need to be identified)
Mexico, Central America, and Caribbean Islands	3 sites (Mexico and Central America) – no existing coverage	3 sites – beginning coverage by CRMMN	2 sites (Mexico and Central America) – no existing coverage	240 in intensive sites 480 in cluster sites	<10% (new sites will need to be identified)
Africa	3 sites – existing coverage is minimal and especially needed near ASGM sites	5 sites – existing coverage is minimal outside of defined studies	2 sites – existing coverage is minimal and especially needed near ASGM sites	300 in intensive sites 600 in cluster sites	<10% (new sites will need to be identified)
Indo-Pacific Region (including all of Australia and New Zealand)	3 sites – existing coverage is minimal and especially needed near ASGM sites	5 sites – existing coverage is minimal in Australia and by SPREP	2 sites – existing coverage is minimal and especially needed near ASGM sites	300 in intensive sites 600 in cluster sites	<10% (new sites will need to be identified)

NCP=Northern Contaminants Program (Canada), AMAP = Arctic Monitoring Assessment Program, USEPA = United States Environmental Protection Agency, CRMMN = Caribbean Region Mercury Monitoring Network, SPREP = Secretariat of the Pacific Regional Environment Programme, CEMP = Coordinated Environmental Monitoring Programme, OSPAR Commission's JAMP = Joint Assessment and Monitoring Programme, HELCOM = Baltic Marine Environment Protection Commission – Helsinki Commission

## 8.2 Oceanic framework for integrated mercury monitoring

The approach for monitoring mercury in oceanic areas greatly differs from the continental approach. The cycling and movement of mercury in the world's oceans varies by hemisphere, basin and juxtaposition with the continental land masses. Therefore, mercury concentrations in fish, birds, and marine mammals varies significantly.

For example, bluefin tuna (representing three sibling species—the Atlantic, Pacific and Southern) have average mercury concentrations in their muscle tissue across six ocean regions that may vary three-fold (Figure 12). Reasons for this variation differ and need to be accounted for when globally monitoring mercury in oceanic areas.

Therefore, recommended is a three-step approach for a global mercury monitoring framework for marine biota (Figure 13). Step 1a is related to Step 1b, to best define the distinctions among the ocean basin limits (and the number of ocean basins of interest), likely related to the United Nations' Food and Agriculture Organization (FAO) interest and how they define commercial fishing areas (Figure 14).

These bluefin tuna (right) are an important commercial commodity for many countries, although mature individuals generally exceed mercury concentrations deemed acceptable for human health standards.

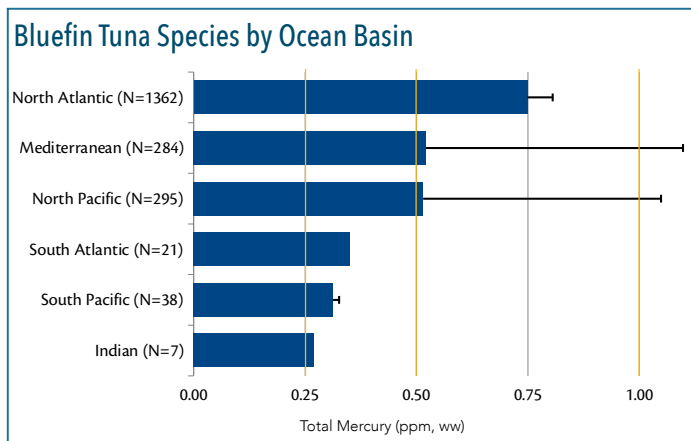


Figure 12. Average ( $\pm$  SD; N=sample size) THg concentration in muscle tissue of three bluefin tuna species (Atlantic, Pacific, and Southern bluefin) from six ocean regions. Data Source: Global Biotic Mercury Synthesis Database.



### Three-step overarching framework for monitoring mercury in biota across oceans.

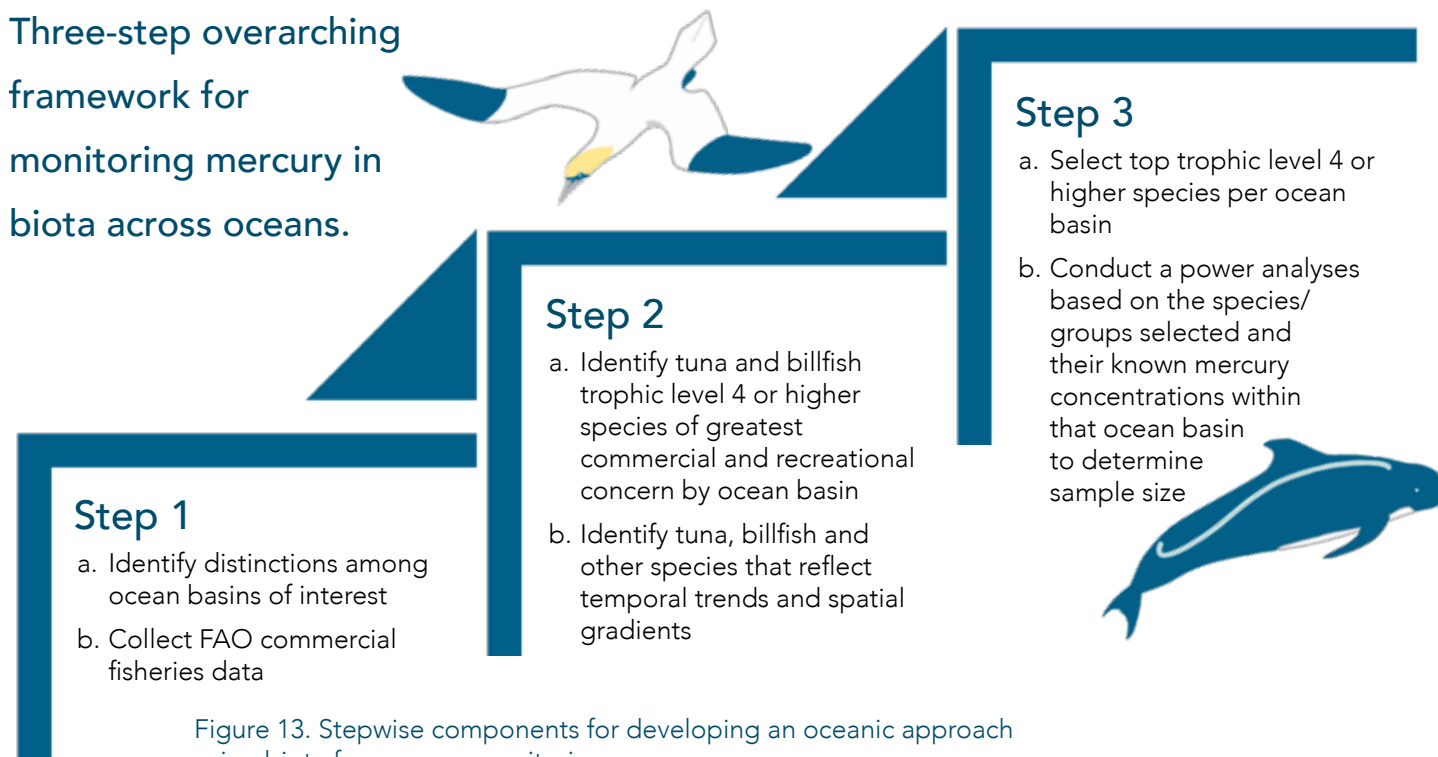


Figure 13. Stepwise components for developing an oceanic approach using biota for mercury monitoring.



## Step 1

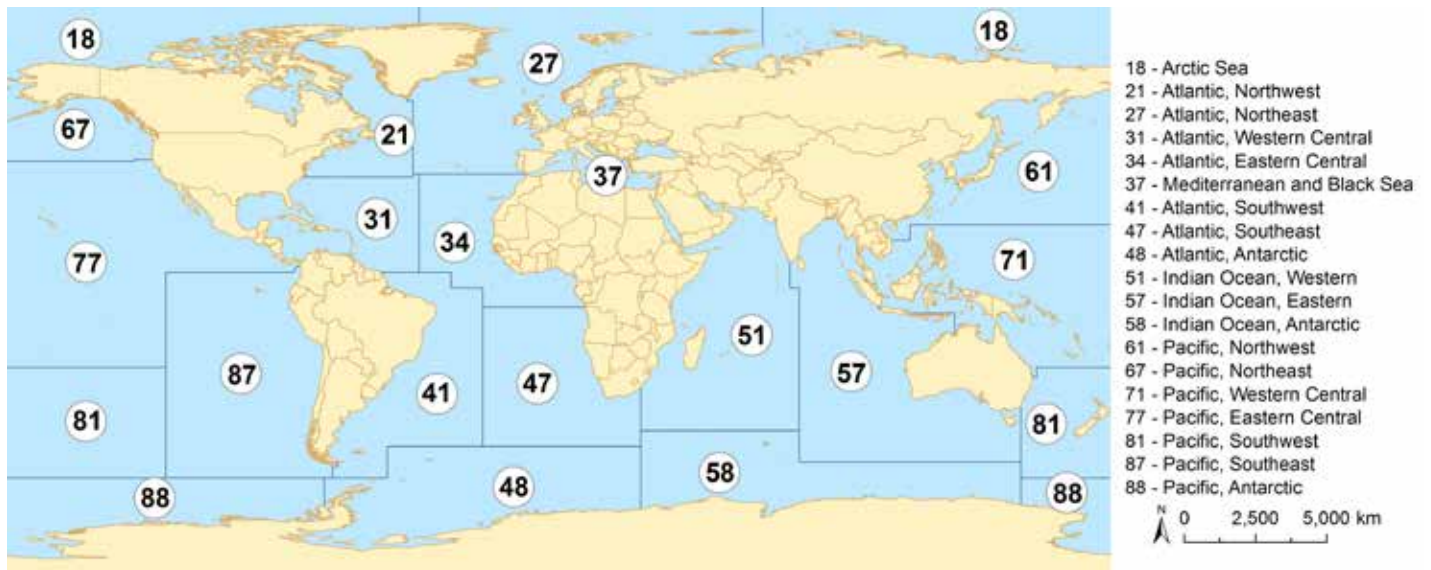


Figure 14. Food and Agriculture Organization of the United Nation's defined fishing areas.



Most sharks, such as these hammerhead sharks, are categorized as trophic level 4 or higher and can be important bioindicators for determining spatial gradients in methylmercury across most of the world's oceans.

## Step 2

For Step 2a, based on the GBMS database, the species of highest mercury concern with the greatest interest for human consumption are tuna and billfish (e.g., swordfish, sailfish, and marlin species). The mercury concentrations in tuna vary greatly by species because of their growth rates, ultimate size, age, trophic level, and ocean basin (Figure 15).

Smaller commercially captured species, such as skipjack and yellowfin tuna have lower mercury concentrations, while larger species tend to have higher levels, such as bluefin species. Tuna species with the greatest commercial interest are skipjack and yellowfin (Figure 15).

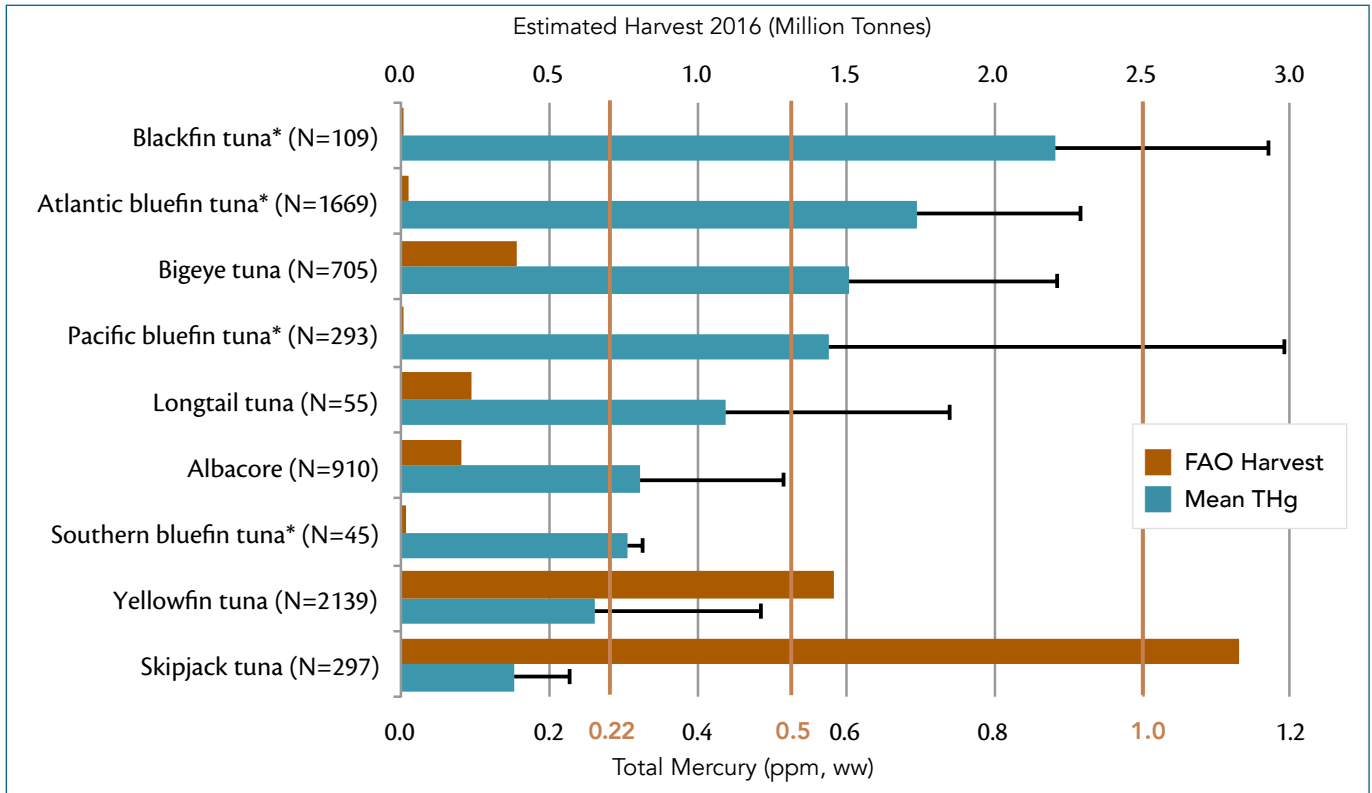


Figure 15. Average (+/- SD; N=sample size) THg concentration in muscle tissue of nine tuna species compared with the FAO harvest estimate in tonnes. \*FAO harvest is less than 15,000 tonnes.



The global commercial tuna harvest is greatest for the skipjack tuna, one of the smallest tuna species. This tuna species also has the lowest average body burden of mercury and is regularly used for canned tuna purposes.



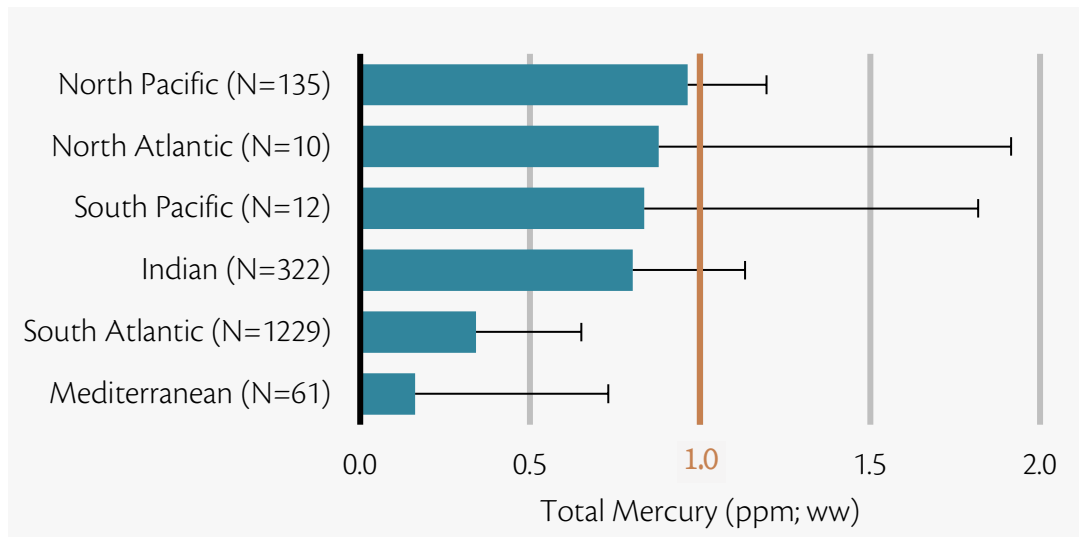
Billfish, such as the striped marlin, are important trophic level 4 or higher bioindicators for monitoring mercury in open oceans. Nonlethal biopsies of muscle tissue can be used from recreational or sport catch-and-release fisheries.

### Step 3

For Step 3 and assuming the use of trophic level 4 species that are within the tuna and billfish groups, spatial gradients are best determined through similar species that have global ranges. The bluefin tuna complex (representing three sibling species) is present in the Atlantic (north and south), Indian and Pacific (north and south) oceans, as well as the Mediterranean Sea and Caribbean Sea. The bluefin tuna complex tends to have some of the highest

mercury concentrations, which when properly adjusted for size and age, can be compared across the world's temperate and tropical oceans. Billfish, in particular swordfish, are also relevant for making comparisons across the world's oceans (Figure 16). Lastly, to best track mercury concentrations in trophic level 4 fish in the Arctic Ocean, Atlantic cod are used by the AMAP and are the best species for regional comparisons.

Figure 16. The mercury concentrations in six ocean basins for swordfish.





## 8.2.1 Summary of oceanic sampling framework

As part of the sampling framework for globally tracking biotic mercury in oceanic basins, a matrix that details existing and needed coverage by mercury monitoring programs is possible for eight ocean basins of interest (Table 7). A range of 4-6 sampling sites may adequately characterize ocean basins of interest for both temporal and spatial objectives.

To track temporal changes, especially those that may happen within a decade, smaller commercially and regularly captured species, such as the skipjack and yellowfin tuna, are good bioindicators for measuring changes in environmental mercury loads (Drevnick et al. 2015, Drevnick and Brooks 2017); bluefin tuna can be used for decadal changes (Lee et al. 2016). For Step 3a, a matrix of trophic level 4 or greater marine fish species that could be globally monitored for spatial gradients and temporal trends is feasible (Table 7). Determining the ultimate sample size through a power analyses (Step 3b) is dependent of the species chosen, their range of mercury concentrations, the defined ocean basin distinctions, and the home range of the fish populations. Initial sample sizes are 30 individuals per site.

Because there are known significant differences in muscle mercury concentrations in same-tuna (Nicklisch et al. 2017) and same-billfish species (Figure 15) among major ocean basins of interest, understanding spatial gradients is an important component for incorporating into tracking temporal changes. The co-location of sites that can provide fish muscle mercury concentrations for tracking both temporal changes and spatial gradients requires careful consideration.

Timing of sampling should be coordinated at times of the years that match similar seasonality (i.e., summer) and/or weather patterns (e.g., El Niño). Sampling frequency can be rotated every other year. For example, using this approach in the Pacific Ocean (for three sites in the north basin and three sites in the south basin) would result over a two year period of an analyses of 180 samples for tracking temporal changes and 180 samples for characterizing spatial gradients (or 360 samples).

Sampling efforts for tuna and billfish species can be coordinated with existing commercial (and potentially recreational) fisheries around the world. Therefore, access to known-sized fish, from known waters, and at selected times can realistically be

coordinated in a cost-effective way. Once a global sampling design is defined, sample handling, shipping and analyses can be globally coordinated (as show by a recent global effort for measuring mercury in fish; Buck et al. 2019).

## 8.2.2 Summary of sampling framework by ocean basin of interest

For the Arctic Ocean, there is existing coverage of sampling and mercury analyses by the AMAP program and national entities, such as Norway. There can be 100% coverage using existing mercury data collection.

For the Mediterranean Sea, there is existing coverage of sampling and mercury analyses, but there may need to be a need for harmonizing analytical standards for meeting EU needs. The Adriatic Sea has especially elevated biota mercury concentrations and should be a long-term tracking site. There can be 80% coverage using existing mercury data collection.

For the Indian Ocean, there is existing coverage of sampling and mercury analysis as coordinated by the Indian Ocean Commission, especially with SIDS on the western side, such as the Seychelles and Mauritius. Further efforts are needed on the eastern side. There may be 50% coverage using existing mercury data collection. Swordfish may be an important focal bioindicator.

For the Caribbean Sea, there is no existing coverage of sampling and mercury analyses other than some island countries measuring mercury in a small number of individuals (usually yellowfin tuna). The new Caribbean Region Mercury Monitoring Network provides a newly established structure for harmonized efforts across many countries, which are increasingly exporting tuna to the EU. There is < 10% coverage using existing mercury data collection.

For the Pacific Ocean–North, there is existing coverage of sampling, but not a coordinated effort for analyzing mercury. Both Japan and the U.S. have commercial fisheries in this basin and could provide a cost-effective platform for collecting samples for future mercury analyses. There is 100% coverage for sampling and <10% coverage using existing mercury data collection.

For the Pacific Ocean–South, there is existing coverage of sampling, but not a coordinated effort for analyzing mercury. The U.S. have commercial fisheries in this basin and could provide a cost-effective platform for collecting samples for future

mercury analyses. There is 100% coverage for sampling and <10% coverage using existing mercury data collection.

For the Atlantic Ocean–North, there is existing coverage of sampling, but not a coordinated effort for analyzing mercury. Both the U.S. and the EU have commercial fisheries in this basin and could provide a cost-effective platform for collecting samples for future mercury analyses. There is 100% coverage for

sampling and <10% coverage using existing mercury data collection.

For the Atlantic Ocean–South, there are limited existing coverage of sampling, and no coordinated efforts for analyzing mercury. Commercial fisheries in this basin are less common than the northern part of the Atlantic Ocean and the Pacific Ocean. There is <10% coverage for sampling and <10% coverage using existing mercury data collection.



In Madagascar and other coastal African countries, seafood fisheries within the Indian Ocean are important food sources and need to be monitored for mercury to best understand and characterize potential human health risk.

Table 7. Sampling strategy for trophic level 4 or greater biota (see Table 3) for the **Oceanic Sampling Framework**. Listed are the number of sites (with an initial sample size of 30 fish at each site) for both objectives of monitoring temporal trends and spatial gradients of mercury.

Ocean Basin of Interest	Monitoring Temporal Trends <sup>1</sup>	Monitoring Spatial Gradients <sup>2</sup>	Estimated number of Hg samples (based on 30 samples per trophic level 4 bioindicator)	Approximate coverage (%) using existing Hg data and monitoring programs*
Arctic Ocean <sup>3</sup>	3 sites – existing coverage of sampling and Hg analyses by AMAP and Norway	3 sites – existing coverage of sampling and Hg analyses by AMAP and Norway	180	>90% (official existing site selection will be needed)
Mediterranean Sea	2 sites – existing coverage of sampling and Hg analyses	2 sites – existing coverage of sampling and Hg analyses	120	>80% (official existing site selection and analytical standards will be needed)
Indian Ocean	3 sites – existing coverage of sampling and Hg analyses by Mauritius, Seychelles, and the Indian Ocean Commission	3 sites – existing coverage of sampling and Hg analyses by Mauritius, Seychelles, and the Indian Ocean Commission	180	<50% (official existing site selection and analytical standards will be needed)
Caribbean Sea	2 sites – beginning coverage by the CRMMN	2 sites – beginning coverage by the CRMMN	120	<20% (new sites will need to be identified)
Pacific Ocean - North	3 sites – existing coverage of sampling by Japan and the U.S., but not Hg analyses	3 sites – existing coverage of sampling by Japan and the U.S., but not Hg analyses	180	100% coverage for sampling and <10% for Hg (new sites will need to be identified)
Pacific Ocean - South	3 sites – existing coverage of sampling by U.S., but not Hg analyses	3 sites – existing coverage of sampling by U.S., but not Hg analyses	180	100% coverage for sampling and <10% for Hg (new sites will need to be identified)
Atlantic Ocean - North	3 sites – existing coverage of sampling by U.S. and EU, but not Hg analyses	3 sites – existing coverage of sampling by U.S. and EU, but not Hg analyses	180	100% coverage for sampling and <10% for Hg (new sites will need to be identified)
Atlantic Ocean - South	3 sites – existing coverage of sampling, but not Hg analyses	3 sites – existing coverage of sampling, but not Hg analyses	180	<10% for sampling and Hg (new sites will need to be identified)

<sup>1</sup> Focal bioindicator – Yellowfin Tuna (*Thunnus albacares*)

<sup>2</sup> Focal bioindicator – Bluefin Tuna species (*Thunnus spp.*) and Swordfish (*Xiphias gladius*)

<sup>3</sup> Arctic Ocean focal bioindicator - Cod (*Gadus spp.*) – because tuna are not regularly distributed in the Arctic Ocean.



## 9.0 Generalized budget considerations

An attempt was conducted to estimate the possible cost for a five-year period of monitoring mercury in biota including sampling across continental and oceanic components using six regional country hubs for coordinating sampling and mercury analyses. This first round of a five-year sampling period was chosen to provide a sample size that could significantly meet the need for statistical comparison while incorporating existing data. The figures have been calculated, based on previous projects of global sampling of biota (e.g., fish) and other international mercury monitoring efforts.

The estimation contemplated:

One year of preparation, followed by full sampling. Year 2, 3, and 4 would represent full field sampling years for the continental and oceanic components.

Year 5 would be used to generate a summary of findings and activities to date, as well as recommendations. Year 5 would also be used to assess capacity building for mercury analyses in the six regional country hubs.

The number of samples to be considered in the continental and oceanic components is 3,420 and 1,020 samples/year respectively for each component. Assuming the first year is a pilot year and the last year is for reporting, there would be annual sampling in years 2, 3, and 4 for a total of 10,260 and 3,060 samples.

The total estimated budget for monitoring mercury in biota at a global level for continental and oceanic purposes would be up to approximately \$10 million (USD) for an initial five-year period.



Existing fishing fleets in many countries provide a cost effective and time efficient platform for collecting samples of focal bioindicators for globally monitoring mercury.

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