Note to reader

This draft version of Chapter 7 in the Technical Background Report to the Global Mercury Assessment 2018 is made available for review by national representatives and experts. The draft version contains material that will be further refined and elaborated after the review process. Specific items where the content of this draft chapter will be further improved and modified are:

1. Quality of all graphics (Maps, Figures, Tables) will be improved prior to publication.
2. Content of all graphics (Figures, Tables) will be double-checked, updated, and refined prior to publication.
3. Table 2 and 3 will be further updated over the next couple of months.

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Chapter 7 Mercury concentrations in biota

7.1 Introduction

7.1.1 Principal sources and pathways of methylmercury availability to biota

Mercury (Hg) globally enters ecosystems through the air (e.g., emissions from coal-fired power plants and incinerators) or water (e.g., both inactive and active chlor-alkali facilities and landfills) (Pacyna et al. 2016, Kocman et al. 2017, Streets et al. 2017). Inorganic Hg emitted from natural or anthropogenic sources becomes toxic in the environment when it is converted to methylmercury (MeHg), by sulphur-reducing bacteria and other microbes (Gilmour et al. 2013). Certain ecosystem conditions (such as those found in wetlands) can encourage the production and bioavailability of MeHg in the environment. Bacteria often produce more MeHg when moderate amounts of sulphate and low oxygen (anoxic) conditions are present to provide optimal conditions for the metabolic processes of the bacteria (Hsu-Kim et al. 2013). Mercury also readily binds to dissolved organic carbon (DOC), so areas with high DOC levels may generate MeHg more readily (depending on the type of DOC) (Schartup et al. 2015), as will areas that have acidified conditions (Wyn et al. 2009).

These factors are important in assessing ecosystems sensitive to both Hg input and methylation potential. The complex chemical conversions and cycling of Hg make it particularly challenging to predict from air, water and sediment to levels of potential concern in upper trophic level fish and wildlife (Gustin et al. 2016, Sunderland et al. 2016). In other words, in areas where Hg deposition is low, effects on biota may be disproportionately high if conditions are conducive to MeHg production and biomagnification. A robust example is in southern Nova Scotia's Kejimkujik National Park of Canada, where Hg deposition levels are low, but concentrations in fish and birds tissue are above ecological health thresholds (Burgess and Hobson 2006; Burgess and Meyer 2008) and trends in fish MeHg concentrations continue to increase (Wyn et al. 2010).

Mercury is a potent neurotoxin that can cause physiological, neurologic, behavioural, reproductive, and survival harm to fish and wildlife (Scheuhammer et al. 2011). It readily biomagnifies, resulting in increasing concentrations of MeHg in the ecosystem as it moves from water and sediment, to phytoplankton and plants, aquatic insects, spiders, fish and wildlife. Once MeHg is taken up at the base of the food web it can efficiently biomagnify. As a result, top predators in a food web, such as fish, birds and mammals that prey on items that are themselves at relatively high trophic status, may have concentrations of MeHg in their tissues that are many orders of magnitude higher than the concentrations found in the water (often > 10^6 to 10^7 higher). Generally, each trophic change in the foodweb accounts for an order of magnitude of increase in MeHg concentrations, with the largest magnification occurring between water and phytoplankton in aquatic systems (Lee and Fisher, 2016).

Mercury exposure has been well documented in fish and wildlife around the world, including areas with both point sources of contamination and remote from such sources (i.e., >100 miles) across North America (Evers et al. 2005, Kamman et al. 2005, Monson et al. 2011, Evers et al. 2011, Ackerman et al. 2016, Eagles-Smith et al. 2016, Jackson et al. 2016), Europe (Nguetseng et al. 2015), Asia (Abeysinghe et al. 2017) and representing ocean basins (Carravieri et al. 2014, Drevnick et al. 2015, 2017; Lee et al. 2016, Bodin et al. 2017). Numerous studies, particularly recent ones, document adverse impacts such as reduced reproductive success, behavioural change (e.g., reduced time incubating), and neurological problems (e.g., ataxia) (Depew et al. 2012a,b; Dietz et al. 2013, Ackerman et al. 2016, Whitney and Cristol 2017, Evers 2017). Based on these and other in *situ* studies, the biomagnification and bioaccumulation of MeHg is shown to adversely affect the reproductive success of many fish and wildlife populations, representing multiple foraging guilds across many habitats and geographic areas of the world.

Building on recent and compelling evidence, wildlife species vary in their sensitivity to MeHg toxicity (potentially based on foraging guilds and phylogeny) (Heinz et al. 2009). Passeriforms (i.e., songbirds) for example, appear to be highly sensitive to the toxicity of MeHg when compared to other orders of birds. Evidence to date indicates songbirds are more sensitive to MeHg toxicity on hatching and fledging success when compared to piscivores. Understanding MeHg in foodweb pathways and the ability of MeHg to adversely impact upper trophic level wildlife is critical for developing comprehensive assessments and monitoring efforts.

In the end, identifying the proper fish and wildlife bioindicators for Hg biomonitoring are varied and complex. They differ according to the geographic area, timescale of interest, conservation concern, and whether the overall goal is for ecological or human health.

7.1.2 Existing Biotic Mercury Concentrations

There is an extensive list of published Hg data for biota and there are many biomonitoring programs in place around the world, particularly in high-income countries (e.g., U.S., Canada, across several European countries, and Japan) that generally track temporal-spatial patterns of environmental Hg (with an emphasis on fish). Existing biomonitoring programs were identified by a recent UNEP review (UNEP 2016). Existing data within the peer-reviewed literature define the many case studies that include Hg in taxa identified in Article 19 of the Minamata Convention. Those data can be summarized with an emphasis on fish (both teleosts and elasmobranchs), sea turtles, birds and marine mammals.

7.1.3 Spatiotemporal trends of methylmercury in the environment:

Based on existing data from the literature and the many well-established biomonitoring programmes, global and regional patterns are identified herein. One of the longest standing and perhaps most influential programs in connecting Hg exposure in the environment to the foods that human communities depend on is by the Arctic Monitoring and Assessment Programme (AMAP 2011). This regional program uses relatively standardized methodologies across a large geographic area, using multiple taxa (e.g., fish, birds, and marine mammals), and incorporates other variables (e.g., other contaminants). AMAP has established the bets regional template for effectively monitoring MeHg availability in the environment that can be used concurrently for ecological and human health,

7.1.4 Bioindicators useful for monitoring and assessing risk

Organisms that are at greatest risk for developing elevated MeHg body burdens are defined and grouped at relevant taxonomic resolutions. The emphasis is on biota that may pose concern for human health purposes in marine (e.g., tuna) or freshwater (e.g., bass and walleye) ecosystems, for temporal timelines of interest (e.g., short-term timeframes should use young individuals with relatively low trophic level species vs. long-term timeframes should use older individuals at high trophic levels), for spatial gradients of local to regional to global interests (e.g., for the latter, wide-ranging species such as swordfish are key), or for conservation purposes (e.g., wildlife that are rare or are well-established as at threat from Hg – such as albatrosses and loons).

7.2 Objectives

The overall goal of this chapter is to provide an overview about exposure to biota from environmental loads of Hg. The objectives of our analyses are to characterize:

1. Coverage of existing biotic Hg concentrations and biomonitoring programs;
2. Spatial gradients in Hg exposure, with an emphasis on identifying biological Hg hotspots;
3. Temporal trends of biotic Hg exposure;

4. Identification of bioindicators, with an emphasis on vulnerable taxa because of high exposures and susceptibility/sensitivity to toxic effects;
5. Linkages between Hg sources and targeted bioindicators;
6. Critical knowledge gaps.

7.3 Approach

7.3.1 Identification of existing data

A systematic literature search was used with an emphasis on long-term, standardized and broadly geographic monitoring efforts, as well as on biota identified in Article 19, with a special emphasis on (1) organisms used for human consumption and (2) species at greatest risk to adverse impacts (particularly at population levels). Only peer-reviewed publications were used and are archived in BRI's Global Biotic Mercury Synthesis (GBMS) database (Evers et al. 2016a).

This chapter aims to present data from peer-reviewed studies for which there can be reasonable confidence about the accuracy and precision of analytical results as well as about the comparability of the results over time. Studies were selected based on an adequately described study method that generally included the following parameters:

- Adequate description of the characteristics of the organism sampled, including species, size, location, date, and tissue analysed;
- Method of sample collection that met scientific standards;
- Large sample sizes (e.g., >100 for an area) or small sample sizes (<20) from areas poorly represented;
- An appropriate analytical method was used for measurement of Hg (or MeHg) in terms of limit of quantification, accuracy, and precision;
- Appropriate statistical methods were used for reporting results.

Consideration was given to selecting lower quality studies if the data were necessary to fill gaps for geographical distributions of biotic Hg exposure.

7.3.2 Explanation of preferred tissue types

This review focuses on tissues with well-established methods of measurement and interpretation and for which there is a reasonably large body of data. There are many available matrices and the choice of a tissue depends on monitoring interests and outcomes. Often the most useful tissues that can be collected in the field are non-lethal. Samples that can be analysed to assess total or MeHg exposure are commonly from the following tissues (i.e., matrix) types (Table 1).

Table 1. Major biota groupings and tissues commonly analysed for Hg.

Biota Group	**Matrix**	**% MeHg**	**Sample prep type***	**Analyses type**
Fish	Muscle fillet	>95%	ww or dw	THg
	Muscle Biopsy	>95%	dw (because greater possibility of moisture loss)	THg
	Blood	>95%	Ww	THg
Sea Turtles	Scales	>95%	Fw	THg
	Eggs	>95%	Dw	THg
Birds	Blood	>95%	Ww	THg
	Feather	>95%	Fw	THg
	Eggs	>95%	Dw	THg
	Liver/kidney	40-80%	Dw	MeHg
Marine mammals	Skin	>95%	Dw	THg
	Muscle	>95%	Dw	THg
	Liver/kidney	40-80%	Dw	MeHg
	Brain	>90%	Dw	THg

*Reported as wet weight (ww), dry weight (dw) or fresh weight (fw) analyses.

7.3.3 Identification of Hg biomonitoring programs

The identification of Hg biomonitoring programs was conducted under a formal request by the Interim Secretariat at a global level. Responses were compiled (UNEP 2016) and provide the best record of existing local, regional and global abiotic and biotic Hg monitoring programs.

7.4 Results

7.4.1 Existing biotic Hg data from peer-reviewed studies

Biotic Hg concentrations for targeted taxa (based on Article 19 of the Minamata Convention) were collected from over 700 peer-reviewed scientific publications that represent approximately 152,000 individuals at 1,675unique locations in 98 countries. It is believed that this is a relatively exhaustive literature review for field Hg concentrations in elasmobranchs, sea turtles, and marine mammals. The literature review is less exhaustive for teleost fish (both marine and freshwater) and birds.

Elasmobranchs(i.e., sharks, skates and rays) were represented in 11 Orders by 9,024 individuals at 294 distinct locations. Marine teleost fish were represented in 20 Orders by 30,483 individuals at 1785 distinct locations. A total of 73 distinct locations were found with Hg concentrations in one of three tissue types of 1,259 individual sea turtles. Marine birds were represented in 9 Orders by 9,485 individuals at 619 distinct locations, while marine mammals were placed in 4 groups and represent 6,491 individuals at 558 locations (Table 2).

Table 2. Mercury concentrations (ug/g or ppm of total Hg for selected fish, sea turtle, birds and marine mammals at the taxonomic level of Order (or other groupings for marine mammals). Biota are arranged by major group, then mean Hg concentrations from high to low.

Common Name		Order	Sites (n)	Individuals (n)	Mean	SD	Min	Max
SHARKS, SKATES, AND RAYS		***CHONDRICHTHYES***	***Muscle (ww)***					
Chimaeras		Chimaeriformes	2	161	3.13	0.27	0.73	3.14
Cow sharks		Hexanchiformes	5	37	2.56	0.85	0.92	2.99
Electric rays		Torpediniformes	6	44	1.66	1.06	0.12	2.42
Dogfishes		Squaliformes	20	647	1.48	2.16	0.09	9.66
Mackerel sharks		Lamniformes	25	308	1.43	1.15	0.01	5.42
Ground sharks		Carcharhiniformes	183	7364	1.08	0.83	0.00	18.29
Carpet sharks		Orectolobiformes	4	44	0.96	0.29	0.05	1.05
Angel Sharks		Squatiniformes	3	98	0.40	0.07	0.03	0.48
Stingrays		Myliobatiformes	29	200	0.26	0.21	0.02	0.83
Guitarfishes		Rhinobatiformes	11	59	0.22	0.28	0.03	2.05
Skates and Rays		Rajiformes	6	62	0.15	0.09	0.02	0.30
MARINE FISH		***TELEOSTEI***	***Muscle (ww)***					
Roughy		Beryciformes	16	60	0.56	0.37	0.03	1.28
Perch-like fishes		Perciformes	1217	21225	0.39	0.49	0.00	10.52
Eels		Anguilliformes	12	207	0.37	0.12	0.05	0.56
Tarpons		Elopiformes	12	268	0.36	0.22	0.03	0.72
Flatfishes, Flounders, Soles		Pleuronectiformes	84	1701	0.32	0.30	0.00	0.88
Toadfish		Batrachoidiformes	6	117	0.30	0.14	0.03	0.37
Bonefishes		Albuliformes	5	42	0.28	0.19	0.10	0.53
Catfishes		Siluriformes	50	475	0.23	0.19	0.01	0.96
Minnows, Suckers		Cypriniformes	7	96	0.13	0.07	0.01	0.19
Silversides		Atheriniformes	10	641	0.12	0.07	0.03	0.51
Scorpion fishes, Sculpins		Scorpaeniformes	49	801	0.11	0.09	0.00	0.37

Cods, Hakes, Haddocks		Gadiformes	55	1207	0.11	0.14	0.01	0.74
Anglerfishes		Lophiiformes	4	43	0.10	0.03	0.01	0.12
Puffers, Triggerfishes, Leatherjackets		Tetraodontiformes	9	52	0.09	0.06	0.02	0.15
Mullets		Mugiliformes	80	992	0.08	0.11	0.00	0.40
Needlefishes		Beloniformes	7	54	0.07	0.03	0.02	0.11
Herrings, Sardinesm Anchovies		Clupeiformes	120	1973	0.06	0.15	0.00	3.40
Aulopiforms, Lizardfishes		Aulopiformes	14	66	0.06	0.08	0.01	0.36
Salmons		Salmoniformes	20	376	0.05	0.04	0.01	0.13
Smelts		Osmeriformes	8	87	0.03	0.02	0.00	0.05
REPTILES		***REPTILIA***	***Scutes (fw)***					
Sea turtles		Testunides	13	193	0.33	0.21	0.00	0.94
			Blood (ww)					
Sea turtles		Testunides	26	780	0.02	0.03	0.00	0.20
			Muscle (ww)					
Sea turtles		Testunides	34	286	0.14	0.15	0.00	0.39
BIRDS		***AVES***	***Body Feathers (fw)***					
Hawks, Eagles, Vultures		Accipitriformes	9	122	16.77	3.74	1.05	17.80
Albatrosses, Petrels, Shearwaters		Procellariiformes	124	3191	11.87	10.34	0.25	37.80
Rails and Cranes		Gruiformes	1	126	9.04		9.04	9.04
Cormorants		Suliformes	10	71	3.78	2.26	0.25	6.48
Gulls, Terns, Other Shorebirds		Charadriiformes	82	1216	2.43	2.25	0.18	11.66
Penguins		Sphenisciformes	51	1127	1.26	1.26	0.02	5.90
Waterfowl		Anseriformes	3	42	1.16	0.51	0.83	1.69
Tropicbirds		Phaethontiformes	1	31	0.84		0.84	0.84
			Blood (ww)					
Albatrosses, Petrels, Shearwaters		Procellariiformes	102	1398	6.23	16.34	0.03	209.37
Gulls, Terns, Other Shorebirds		Charadriiformes	146	887	1.95	5.33	0.03	36.52
Cormorants		Suliformes	37	574	1.38	1.89	0.19	17.14
Loons		Gaviiformes	37	2129	1.25	0.63	0.00	3.60
Hawks, Eagles, Vultures		Accipitriformes	28	86	0.74	1.05	0.00	7.40
Waterfowl		Anseriformes	13	82	0.56	1.41	0.01	4.68
Rails and Cranes		Gruiformes	2	82	0.46	0.30	0.01	0.56
Penguins		Sphenisciformes	31	372	0.41	0.27	0.02	0.84

Tropicbirds		Phaethontiformes	2	49	0.24	0.06	0.18	0.27
			Eggs (ww)					
Loons		Gaviiformes	8	544	1.22	0.65	0.00	1.63
Albatrosses, Petrels, Shearwaters		Procellariiformes	18	269	0.47	0.29	0.12	1.18
Pelecans, Ibises, Herons		Pelecaniformes	38	315	0.40	0.24	0.03	1.90
Cormorants		Suliformes	12	244	0.30	0.10	0.13	1.07
Gulls, Terns, Other Shorebirds		Charadriiformes	200	1825	0.28	0.26	0.00	1.71
Waterfowl		Anseriformes	10	132	0.26	0.15	0.07	0.43
Hawks, Eagles, Vultures		Accipitriformes	31	190	0.08	0.03	0.02	0.15
Grebes		Podicipediformes	8	130	0.07	0.03	0.04	0.13
Penguins		Sphenisciformes	2	33	0.04	0.01	0.04	0.05
Falcons		Falconiformes	11	124	0.04	0.02	0.02	0.08
MARINE MAMMALS		***MAMMALIA***	***Muscle (ww)***					
Toothed Whales		Cetacea: Odontoceti	401	4027	2.61	4.77	0.08	93.52
Seals and Walruses		Carnivora: Odobenidae, Otariidae, Phocidae	128	1969	0.39	0.35	0.00	3.22
Baleen Whale		Cetacea: Mysticeti	28	531	0.09	0.08	0.02	0.74
Polar Bears		Carnivora: *Ursus maritimus*	5	77	0.08	0.05	0.06	0.24

7.4.2 Existing biomonitoring programs

The existing biomonitoring programs for Hg that are operated by various governments and other entities are identified within many national networks, including initiatives in the EU (Norway, Sweden, Spain, UK, Poland), Canada, United States, Japan, Republic of Korea, Colombia and Brazil, and global or regional networks (UNEP 2016). The Arctic is best monitored through AMAP (AMAP 2011) with valuable subsets from Canada's National Contaminants Program (NCP) and the ARCTOX program based in Europe for tracking Hg in seabirds. There are many programs in the temperate regions of the U.S. (e.g., the U.S. Environmental Protection Agency's seafood Hg monitoring program and NOAA's mussel Hg watch program) and Europe and Japan. In tropical countries, there are fewer national or regional long-term initiatives. Oceanic Hg monitoring efforts are many and can be found in the peer-reviewed literature and are summarized by GBMS (Figure 1; Evers et al. 2016).

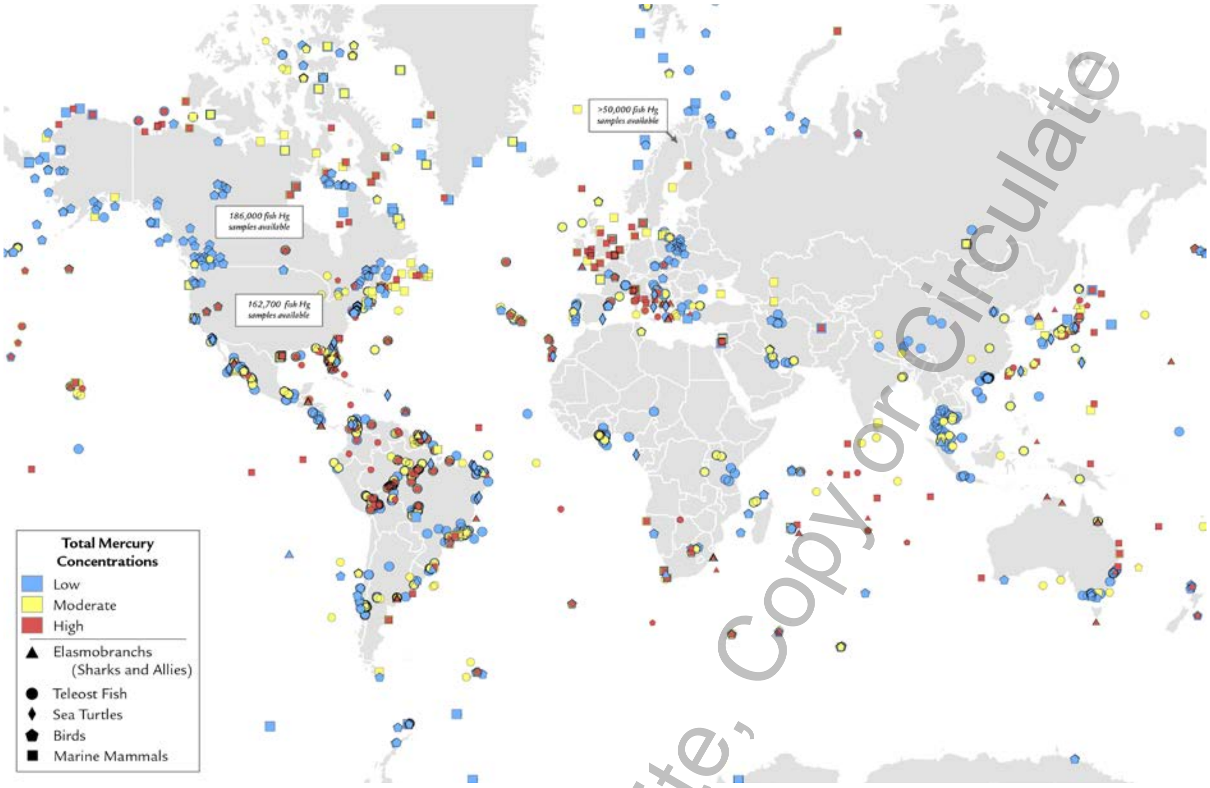

Figure 1. Distribution of four major taxa and their total Hg concentrations in three risk categories. Risk categories by major taxa and tissue type are: (1) Teleost and Elasmobranch fish muscle tissue (ppm, ww), <0.3=low, 0.3-1.0=moderate, >1.0= high; (2) Sea Turtle Blood (ppm, ww) – all tissues were deemed low exposure; (3) Bird Feathers (ppm, fw), <10=low, 10-20=moderate, >20=high; Adult Bird Blood (ppm, ww), <1.0=low, 1.0-3.0=moderate, >3.0=high; Eggs (ppm, ww), <0.5=low, 0.5-1.0=moderate, >1.0=high; Marine Mammal muscle (ppm, ww), <0.3=low, 0.3-1.0=moderate, >1.0=high.

7.5 Discussion

7.5.1 Selection of best bioindicators

The choice of target bioindicators depends on the question and circumstances. The initial choice of a human health vs. an ecological health endpoint is important and can be often combined if properly selected. Biota that have been identified to best fit these two categories are well described and should be categorized within biomes and associated aquatic ecosystems (Table 3). The taxa of greatest interest for the Minamata Convention include fish, sea turtles, birds and marine mammals – and, because of the extensive scientific published literature the exposure of Hg in biota from around the world provides confidence in properly selecting species of interest (Evers et al. 2016b).

Table 3. Potential choices of known bioindicators for ecological and human health as grouped by major terrestrial biomes and their associated aquatic ecosystems (Adapted from Evers et al. 2016b).

Target Terrestrial Biomes	**Associated Aquatic Ecosystems**	**Ecological Health Bioindicators**				**Human and Ecological Health Bioindicators**		
		Freshwater and Marine Fish	***Freshwater Birds***	***Marine Birds***	***Marine Mammals & Sea Turtles***	***Freshwater Fish***	***Marine Fish***	***Marine Mammals***
Arctic Tundra	Arctic Ocean and associated estuaries, lakes, rivers	Sticklebacks[1] (freshwater); Arctic Cod[2] Sculpin[3] (marine)	Loons[4,5]	Fulmars[6] Murres[6]	Polar Bears[7] Seals[8]	Arctic Char[9] Arctic Grayling[10]	Halibut[11] Cod[11]	Beluga[2, 12] Narwhal[2, 12] Ringed Seal[57], Hooded Seal[8]
Boreal Forest and Taiga	North Pacific and Atlantic Oceans and associated estuaries, lakes, rivers	Perch[13] (freshwater); Mummichogs[14] (marine)	Loons[15] Eagles[16] Osprey[17] Songbirds[18] (Warblers, Flycatchers, Blackbirds)	Osprey[19] Petrels[20], Albatrosses[50, 51] Herring Gulls[58]	Mink[21,22] Otter[21,22] Seals[23]	Catfish[11] Pike[10] Sauger[10] Walleye[10]	Flounder[11] Snapper[11] Tuna[11]	Pilot Whale[24]
Temperate Broadleaf and Mixed Forest	North Pacific and Atlantic Oceans, Mediterranean and Caribbean Seas, and associated estuaries, lakes rivers	Perch[13] (freshwater); Mummichogs[14] Rockfish[11] Sticklebacks[25] (marine)	Loons[4] Grebes[5,26] Egrets[27] Herons[27] Osprey[17] Terns[26] Songbirds[18] (Warblers, Flycatchers, Wrens, Blackbirds, Sparrows) Herring Gulls[59]	Cormorants[28] Osprey[5,19] Terns[26,28], skuas[49]	Otter[21,22] Sea Turtles[29, 52] Seals[23], toothed whales[53,54]	Bass[10,30,31] Bream[11] Mullet[11] Walleye[31]	Barracuda[11] Mackerel[11] Mullet[11] Scabbard-fish[11] Sharks[11,32] Swordfish[11, 45] Tuna[11,32]	
Tropical Rainforest	South Pacific and South Atlantic and Indian Oceans and associated estuaries, lakes, rivers	Catfish[23] Piranha[34] Snook[11] (freshwater); Bay Snook[11,34] (marine)	Egrets[27] Herons[27] Kingfishers[35] Songbirds[36] (Wrens, Thrushes, Flycatchers)	Albatrosses[37,38] Noddy[39, 47] Shearwaters[39] Terns[39, 47]Tropicbirds[39], Frigatebirds[4], penguins[48]	Otter[40] Sea Turtles[29] Seals[41], toothed whales[55,56]	Catfish[11] Snakehead[11]	Barracuda[11] Grouper[42] Sharks[43,44,46] Snapper[11] Swordfish[46] Tuna[46]	

[1]Kenney et al. 2014, [2]AMAP 2011, [3]Riget et al. 2007, [4]Evers et al. 2014, [5]Jackson et al. 2016, [6]Braune 2007, [7]Rush et al. 2008, [8]Dietz et al. 2013, [9]Gantner et al. 2010, [10]Eagles-Smith et al. 2016, [11]Evers et al. 2016a, [12]Wagemann, and Kozlowska 2005, [13]Wiener et al. 2012, [14]Weis and Kahn 1990, [15]Evers et al. 2011, [16]Bowerman et al. 1994, [17]Odsjo et al. 2004, [18]Jackson et al. 2015, [19]Wiemeyer et al. 1988, [20]Goodale et al. 2008, [21]Yates et al. 2005, [22]Klenavic et al. 2008, [23]Brookens et al. 2008, [24]Dam and Bloch 2000, [25]Eagles-Smith and Ackerman 2009, [26]Ackerman et al. 2016, [27]Frederick et al. 2002, [28]Braune 1987, [29]Day et al. 2005, [30]Kamman et al. 2005, [31]Monson et al. 2011, [32]Cai et al. 2007, [33]Bastos et al. 2015, [34]Mol et al. 2001, [35]Lane et al. 2011, [36]Townsend et al. 2013, [37]Finkelstein et al. 2006, [38]Burger and Gochfeld 2000, [39]Kojadinovic et al. 2007, [40]Fonseca et al. 2005, [41]Marcovecchio et al. 1994, [42]Evers et al. 2009, [43]Kiszka et al. 2015, [44]Maz-Courrau et al. 2012, [45]Storelli and Marcotrigiano 2001, [46]Bodin et al. 2017, [47]Sebastiano et al. 2017, [48]Carravieri et al. 2016, [49]Carravieri et al. 2017, [50]Bustamante et al. 2016, [51]Anderson et al. 2010, [52]Maffucci et al. 2005, 53 Correa et al. 2013, 54 Aubail et al. 2013, 55 Bustamante et al. 2003, 56 Garrigue et al. 2016, [57]Brown et al. 2016, [58]Burgess et al. 2013, [59]Weseloh et al. 2011

7.5.1.1 Human health bioindicators

There are many communities that partly depend on wild animals for subsistence, including marine fish (e.g., tuna and billfish around the world), freshwater fish (e.g., bass and pike in temperate lakes; catfish and tigerfish in tropical rivers), and marine mammals (cetaceans and pinnipeds in the Arctic). Depicting patterns of dietary MeHg uptake in humans are illustrated for marine fish at a global level (e.g., tuna, Figure 1) and in Small Island Developing States at a local level (e.g., Seychelles Study, Figure 2). Freshwater lakes and rivers have many examples of elevated fish Hg concentrations around the world, especially in temperate regions (e.g., Scandinavia) and in the tropics (e.g., South America). In the Arctic, fish and marine mammals are regularly taken by subsistence communities as important protein sources for a large portion of the population as well described by the Arctic Monitoring Assessment Program (AMAP 2011).

<u>Global Oceans – Case Study</u>: Tuna species are one of the most important global sources of marine fish. Total FAO commercial harvests are nearly 3.5 million tonnes per year – although this may not include all fisheries properly and harvests could be higher (Pauly and Zeller 2016). Muscle Hg concentrations and commercial harvest vary widely by species (Figure 2). The smallest tuna species (e.g., skipjack tuna and yellowfin tuna) have average Hg concentrations under the U.S. EPA advisory level of 0.30 ppm (ww), while the largest species (e.g., Pacific and Atlantic bluefin tunas) have the highest average Hg concentrations. Even these patterns can vary though by size class within species and ocean basis origin. For example, while yellowfin tuna tends to have lower average muscle Hg concentrations than seven of the nine tuna species with known Hg body burdens (Figure 2), individuals over 70kg are recommended to be avoided because of higher risks from Hg contamination (Bosch et al. 2016). Yellowfin and bigeye tuna Hg concentrations grouped by major ocean basin indicates that the eastern and northern areas of the Pacific Ocean have significantly higher Hg concentrations than other ocean basins (Ferriss et al. 2011, Nicklisch et al. 2017) – an area where there are increasing tuna Hg concentrations recorded over the past decade (Drevnick et al. 2015, Drevnick and Brooks 2017) and modelled for several decades thereafter (Sunderland et al. 2009). When considering the size of tuna and its origin another factor to consider is that processed tuna (e.g., canned) tends to be lower than fresh tuna in their Hg concentrations (Garcia et al. 2016).

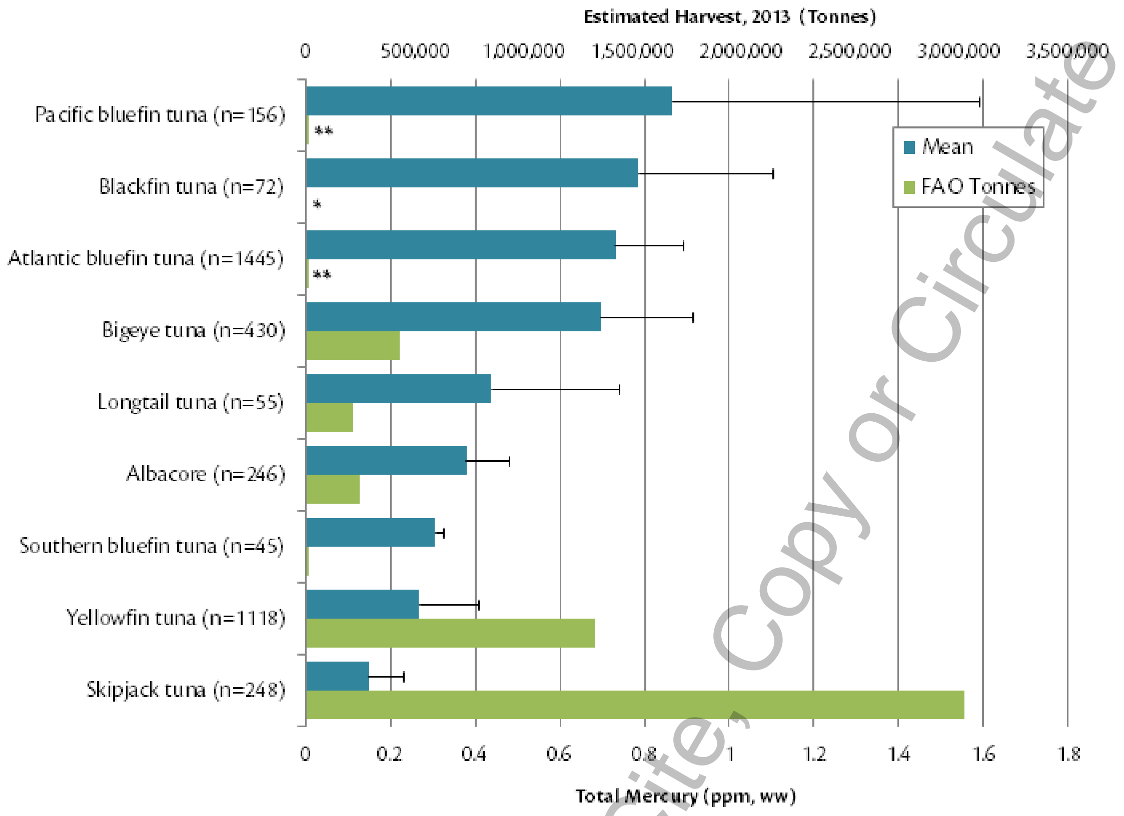

Figure 2. Average total Hg concentrations (ppm, ww) in muscle tissue of six tuna species compared with the FAO harvests estimates (in tonnes) and tuna with harvests of 10-15,000 tonnes are depicted with ** and tuna with harvest of <5,000 tonnes are depicted with *.

Small Island Developing States - Seychelles Case Study: Large pelagic species such as billfishes are one of the more appropriate bioindicators for developing and understanding broad spatial gradients of Hg contamination in the world's oceans. Mercury body burdens in billfish, such as marlin (Drevnick and Brooks 2017, Vega-Sanchez et al. 2017) and swordfish (Mendez et al. 2001, Branco et al. 2007), are some of the highest known for marine teleost fish (Table 1; Rodrigues and Amorim 2016). In swordfish, Hg body burdens vary according to major ocean basin with a tendency for the northern hemisphere having more elevated Hg concentrations than the southern hemisphere ocean basins (Figure 3; 0.83 +/- 0.42 ppm in the North and 0.38 +/- 0.34 in the South). In addition to their high trophic level and relatively long lifespan, swordfish have important commercial value and are an important income source for many Small Island Developing States (SIDS). In the Indian Ocean, 27,000 tonnes of swordfish have been harvested annually during 2006-2013 (including 270 tonnes caught by local semi-industrial fishing fleets in the Seychelles Exclusive Economic Zone-EZZ) and are mainly exported as whole fish to the

European Union (EU) (SFA 2016). The Seychelles Fisheries Authority (SFA) recently reported total Hg concentrations of 0.7±0.4 ppm (ww) measured in Seychelles swordfish edible muscle, with Hg levels increasing with fish size (Hollanda et al., in prep).

The Seychelles, as other SIDS (such as Sri Lanka; Jinadasa et al. 2014), are required to determine the muscle total Hg concentrations of swordfish and other large fish species, when exporting to the European Union (EU) – which requires fish imports to have <1.0 ppm (ww) in tissue edible for humans. Fish that are over this advisory level by the EU are not permitted (i.e., large-sized specimens with the highest commercial value) and either remain within the Seychelles or are exported to other countries for less value, which have a significant adverse economic cost on the Seychelles fishing industry and the overall country. The Seychelles semi-industrial fishing fleet is thus trying to switch from swordfish to tuna, as tuna species within the EZZ generally have Hg concentrations < 0.5 ppm (ww) (Bodin et al., 2017). This recent fishing development however may not be a long-term solution to cover the economic lost with swordfish because of the declining status of tuna populations in the Indian Ocean (e.g., yellowfin tuna: overexploited; bigeye tuna: fully exploited; IOTC 2016)

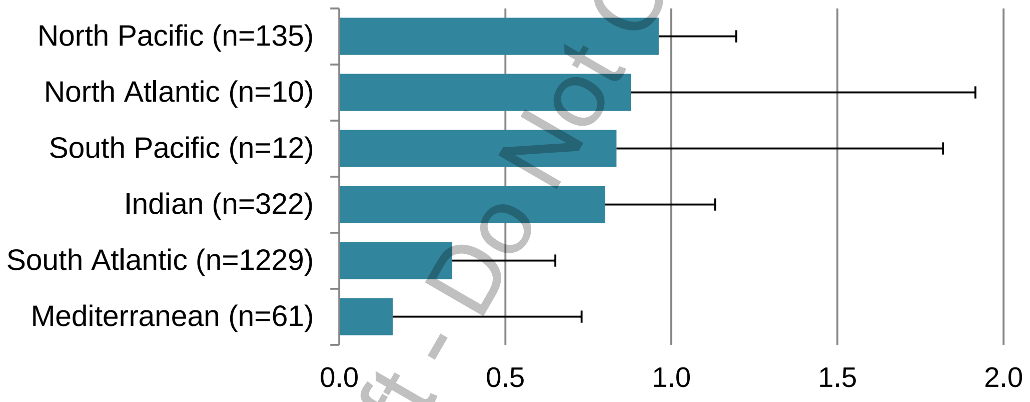

Figure 3. Average total Hg concentrations (ppm, ww) in muscle tissue of one billfish species, the swordfish, in six ocean basins.

Temperate Lakes - Scandinavian Case Study: Freshwater fish across the Fennoscandian shield have been sampled over 50 years in more than 3,000 lakes and streams. Studies on temporal trends over the recent half decade show trends of decreasing Hg concentrations in freshwater fish. Mercury levels in the southern part of the region (55°N–64°N (S)) are generally higher relative those found in the north (64°N–70°N (N)). Fennoscandian fish Hg data (ww in the muscle tissue) covers important fish species for recreational fishing with perch (*Perca fluviatilis*) (S: 0.31 ± 0.27 ppm (n=20,276), N: 0.23 ± 0.18 ppm (n=2,326)), pike (*Esox lucius*) (S: 0.69 ± 0.36 ppm (n=24,849),N: 0.56 ± 0.36 ppm (n=3,360)), and Arctic char (*Salvelinus alpinus*) (S: 0.46 ± 0.31ppm (284), N: 0.09 ± 0.04 ppm (514)) having a tendency for higher Hg body burdens in the southern vs. the northern part of Scandinavia.

Tropical rivers - South American Case Study: The major river basins of South America, including the Magdalena, Orinoco, Amazon and La Plata, support a large freshwater fishery, providing livelihoods for small-scale artisanal fisherman as well as major commercial enterprises (Barletta et al. 2010). In the interior, more remote areas of South America, *ribeirinho* communities are highly dependent on freshwater resources for their subsistence and for communities with high fish consumption, the risk of exposure to Hg and MeHg can also be high (Oliveira et al. 1010). Extensive research over several decades in the Amazon Basin has repeatedly identified the linkage between a diet high in fish consumption, particularly piscivorous and omnivorous species, with elevated concentrations of Hg in human biomarkers such as hair (Bidone et al. 1997; Lebel et al. 1997; Castillhos et al. 1998; Boischio and Henshel 2000; Bastos et al. 2006; Faial et al. 2015).

The GBMS database for South America contains over 170 peer-reviewed publications on fish Hg concentrations from more than 240 sites within 100 different waterbodies. From these published sources, more than 27,000 individual fish from more than 240 genera are represented. Mean Hg concentrations range from below detection limit to 4.4 ppm (ww). The most commonly sampled taxa include species within the *Hoplias* (tigerfishes), *Serrasalmus* (piranhas), *Pseudoplatystoma* (sorubim catfishes), *Cichla* (neotropical cichlids) and *Odontesthes* (silversides) genera. Data from the South American GBMS database highlight areas of extensive freshwater sampling (e.g., Madeira and Tapajos rivers of Brazil) as well as areas where extensive data gaps exist (e.g., the countries of Paraguay and Guyana).

From these data, biological Hg hotspots of concern for ecological and human health start to emerge (Figure 1). Much of the research on Hg in environmental and human Hg exposure has been conducted in areas impacted by ASGM. For effective long-term biomonitoring, and the establishment of regional baselines of Hg concentrations, future monitoring may also need to be conducted in areas where currently little or no information is available (e.g., Paraguay and Guyana).

Arctic – AMAP Case Study: The Arctic Monitoring Assessment Programme (AMAP) regularly fosters international collaboration and compiles measurements of Hg levels in arctic biota, including shellfish, freshwater and marine fish, seabirds, marine and terrestrial mammals and people. Temporal trends from 83 long time-series for Hg in biota monitored at 60 sites around the Arctic establish one of the best standardized, long-term biomonitoring efforts for Hg in the world (AMAP 2011). There is a need for a concerted international effort to reduce Hg levels in the Arctic environment, because of (1) long-range atmospheric transport of Hg from distance source regions including increasing emissions in east Asia that total approximately 100 tons of Hg to the Arctic, (2) changing climate of warmer and longer ice-free seasons potentially promoting the production of MeHg, (3) the release of Hg stored over the previous millennia in permafrost, soils, sediments and glaciers, and (4) the close association of native communities of people reliant on biota that are often upper trophic level species with elevated Hg body burdens (AMAP 2011, Dietz et al. 2013, Scheuhammer et al. 2015). Studies indicate that there has been a ten-fold increase in Hg levels in birds and marine mammals over the past 150 years with an average annual rate of increase of 1-4% (AMAP 2011). More recently over the last 30 years, temporal trends of MeHg bioaccumulation in Arctic fish and wildlife have been inconsistent, with Hg concentrations increasing in some cases but declining elsewhere depending on the species and location (Riget et al. 2011). Therefore, continued Hg biomonitoring is paramount to track the shifting Hg emissions and deposition and thereafter the bioavailability of MeHg in the foodweb across the Arctic region and protecting indigenous communities from contamination, especially in the eastern Canadian Arctic and Greenland (AMAP 2011) and in consideration that global climate changes are creating further uncertainty (Mckinney et al. 2015).

7.5.1.2 Ecological health bioindicators

There are many species of fish and wildlife that are at risk to the adverse impacts of Hg on their physiology, behaviour and reproductive success (Dietz et al. 2013, Scheuhammer et al. 2015, Ackerman et al. 2016, Evers 2017, Whitney and Cristol 2017). Some species are considered high profile and are listed by IUCN on their Red List, or listed as threatened or endangered by the United States.

The selection of the proper suite of bioindicators depends on the question. Taxa suitability may vary according to ecosystem interests (e.g., at habitat or biome levels of relevance), spatial gradient resolution (e.g., local, regional or global), temporal timelines (e.g., short- or long-term), human or ecological health interests, endpoints of importance (e.g., reproductive impairment), known adverse thresholds (e.g., by tissue and taxa using endpoints of interest), sampling availability (e.g., simple or challenging), and sampling outcome (e.g., non-lethal or lethal). A provisional slate of some potential bioindicators for evaluating and monitoring environmental Hg loads for ecological health purposes can be grouped in four target biomes and their associated waterbodies and by major taxa of interest (Table 3; Evers et al. 2016b).

Sharks – Case Study: Many elasmobranchs (sharks, skates and rays) are well above the human health advisory levels set by the World Health Organization (1.0 ppm, ww; Table 1). Species within the mackerel and ground sharks generally have elevated Hg body burdens (de Pinho et al. 2010, de Carvalho et al. 2014, Teffer et al. 2014, Matulik et al. 2017) and are of particular concern because of their high conservation status and that they are often used for food in some places (e.g., Central America). Although human health standards are well-established for the consumption of fish based on their Hg concentrations, the potential adverse impacts of MeHg on organisms, like sharks, are not well understood. Chronic dietary MeHg uptake of 0.2 ppm (ww) in freshwater fish had effects on reproduction and other subclinical endpoints (Depew et al. 2012). While most sharks are well over this threshold level and many shark populations are experiencing declines, it is challenging to link MeHg toxicity to significant adverse effects. Of the 14 shark genera with published muscle Hg concentrations, average levels exceed 1.0 ppm (ww) in 71% of the genera.

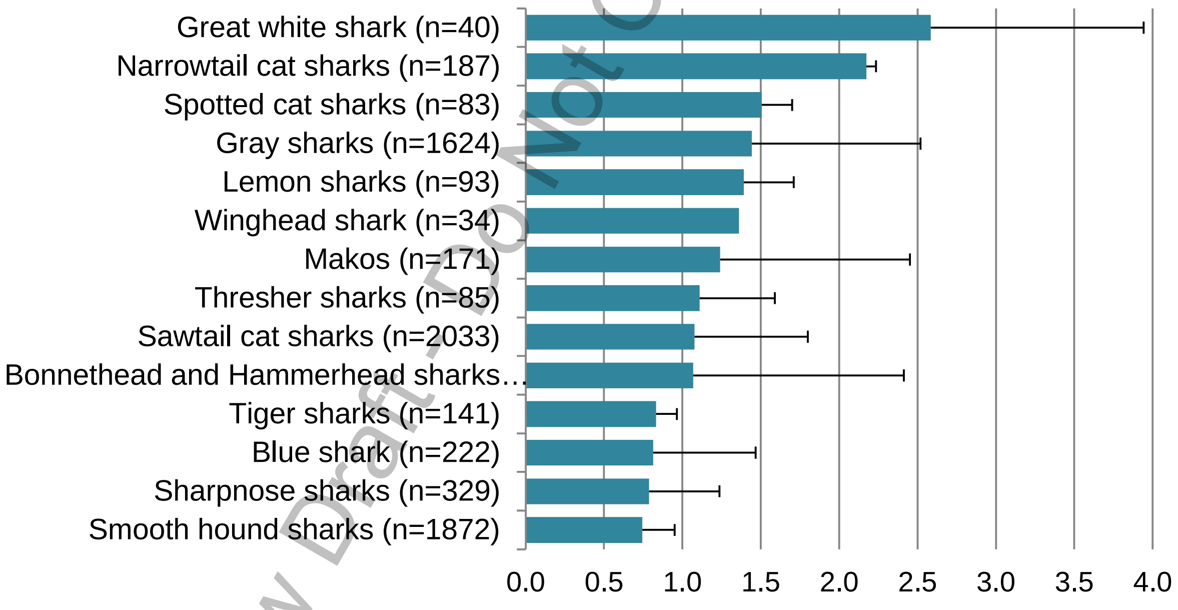

Figure 4. Average total Hg concentrations (ppm, ww) in muscle tissue of sharks by genus from the Orders of Mackerel and Ground Sharks.

Seabirds – Case Study: Marine Birds Case Study: Most seabirds are situated high in the food web, so they experience the biomagnification process and thus are highly exposed to MeHg (Monteiro and

Furness 1995). Because of their feeding ecologies and specific features (e.g., breeding sequence, molting, foraging ranges, migration patterns), seabirds generally have elevated body burden of Hg which can reduce their reproductive capacity and impact their demography (Tartu et al. 2013, Goutte et al. 2014ab). To date, a large number of studies have focused on seabirds from tropical to polar regions and from coastal to oceanic zones, covering most of the world's oceans (Table 1; Elliott and Eliott 2013). On a global scale, seabirds show a wide range of Hg concentrations regardless of the tissue examined (feathers, blood, eggs) with broad spatial differences as well as variation according to the phylogeny. For instance, penguins have the lowest Hg concentrations in eggs, blood and feathers (with the exception of tropicbirds in feathers), whereas Procellariiforms (e.g., petrels, shearwaters and albatrosses) generally had the highest ones (Table 1). Procellariiforms are the best studied group and they display a wide range of tissue Hg concentrations which reflect some phylogenetic differences. Seabirds within the family Diomedea (i.e., albatrosses) have the highest Hg concentrations among all seabirds (Muihead and Furness 1988; Stewart et al. 1999; Anderson et al. 2010).

The most important factor for predicting seabird Hg exposure, and therefore risk, is their foraging ecology. Because seabirds feed on a wide range of habitats, from the littoral zones to the oceanic environment (e.g., benthic and pelagic), they reflect Hg contamination from different parts of the ecosystems both horizontally (e.g., coastal, benthic and oceanic food webs) and vertically (i.e. epipelagic and mesopelagic food webs). Therefore, the study of a group of seabirds with contrasting ecologies from the same region allows determination of MeHg availability for multiple marine zones and therefore a more holistic view (Ochoa-Ocuña et al., 2002). As an example, crustacean-feeding seabirds have lower Hg exposure than cephalopod- and fish-feeders (Carravieri et al. 2014) and epipelagic seabirds have lower Hg exposure than those relying on mesopelagic prey (Ochoa-Ocuña et al., 2002). Therefore, seabirds of the highest trophic levels with high Hg intakes (such as albatrosses or skuas), can suffer the effects of MeHg toxicity that are associated with potential long-term declines in their populations (Goutte et al. 2014a, b).

In storm petrels from the northern hemisphere they have 10 times higher concentrations in the feathers than those from the southern hemisphere (14.1 ± 3.9 vs 1.6 ± 1.4 ppm, respectively). Such a difference is not found for albatrosses between hemispheres, but these patterns should be explored further and should be based on seabirds sharing not only close phylogeny but similar trophic ecology.

Seabirds permit Hg monitoring across large geographical scales and variations within the same species over longitudinal (e.g., brown noddy) or latitudinal scales (e.g. skuas). The differences of Hg contamination recorded in seabird tissues does reveal both differences of major ocean basin contamination and latitudinal gradients of contamination for a single basin.

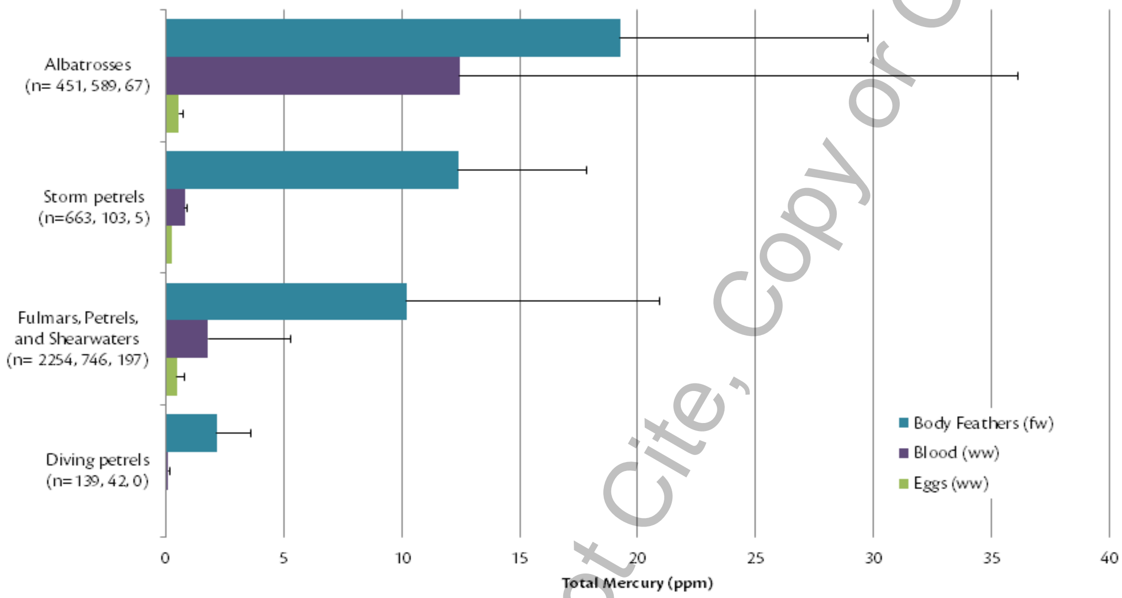

Figure 5. Average total Hg concentrations (ppm) in three tissues (fw in feathers, ww in blood and eggs) of seabird families within the Order Procellariformes.

Loons/Divers – Case Study: Species within the Order Gaviiformes (loons or divers) are piscivores that breeding on freshwater ponds and lakes in temperate and Arctic areas of the Northern Hemisphere. The larger loon species (Common Loon, *Gavia immer*, and Yellow-billed Loon, *Gavia adamsii*) are obligate piscivores and in response, have some of the highest average Hg body burdens of birds in the world (Table 2). In the winter, all loon species migrate to marine ecosystems (with parts of some populations overwintering on freshwater lakes). Loons have been used as bioindicators of MeHg availability in both their breeding and wintering areas for several decades (Evers et al. 1998, 2008, 2011a, 2014; Jackson et al. 2016). In Canada, the Common Loon and its prey are being used to evaluate the success of national regulatory standards to reduce Hg emissions to the landscape (Scheuhammer et al. 2016). The effects of Hg on loon reproductive success are now well established (Evers et al. 2011, Depew et al. 2012b) and are used as benchmarks for evaluating ecological concern.

Landbirds – Case Study: Many species of invertivorous birds (e.g., herein landbirds) are at high risk to Hg exposure. Avian invertivores often have higher body burdens of Hg within an ecosystem versus avian piscivores (Evers et al. 2005) and may have higher sensitivity to MeHg adversely impacting their rates of reproductive success (Heinz et al. 2009, Jackson et al. 2011a). There are now an increasing number of studies that have characterized Hg exposure in one group of landbirds, songbirds (Order Passeriformes); and, within the group of songbirds, certain species and breeding habitats are at higher risk than others. Generally gleaning and flycatching songbirds that breed in wetland habitats (Edmonds et al. 2010, Jackson et al. 2011b, Lane et al. 2011, Jackson et al. 2015, Ackerman et al. 2016), including rice fields (Abeysinghe et al. 2017), are at highest risk to Hg exposure, especially species that forage on predaceous arthropods such as spiders (Cristol et al. 2008). Songbird species where most of their annual life cycle is within wetland-oriented ecosystems and that migrate long-distances (e.g., neotropical migrants or palearctic migrants) may be at greatest risk to chronic Hg exposure adversely impacting reproductive success and ultimately population viability.

Marine Mammals – Case Study: Toothed whales and some pinnipeds (or seals) are the marine mammal taxa of greatest concern for human and ecological health purposes, with high concentrations of Hg recorded in brain tissue with associated signs of neurochemical effects (Table 1, Dietz et al. 2013). Many subsistence communities, mostly in the Arctic, depend on the harvest of species such as the narwhal, beluga, pilot whales, and ringed seals (Table 3). Although the effect levels in marine mammals is little understood (Desforges et al. 2016), a study on bottle-nosed dolphins found lesions were created in the liver at 61 ppm (ww) and are being used by scientists as a good benchmark for assessing ecological concern (Dietz et al. 2013). While liver tissue generally has a small percentage of MeHg and is challenging to relate to muscle tissue (which is a more relevant tissue to relate for human health purposes, Table 1), most species of toothed whales have average muscle tissue Hg concentrations well above 1.0 ppm (ww) (which generally has >95% MeHg content).

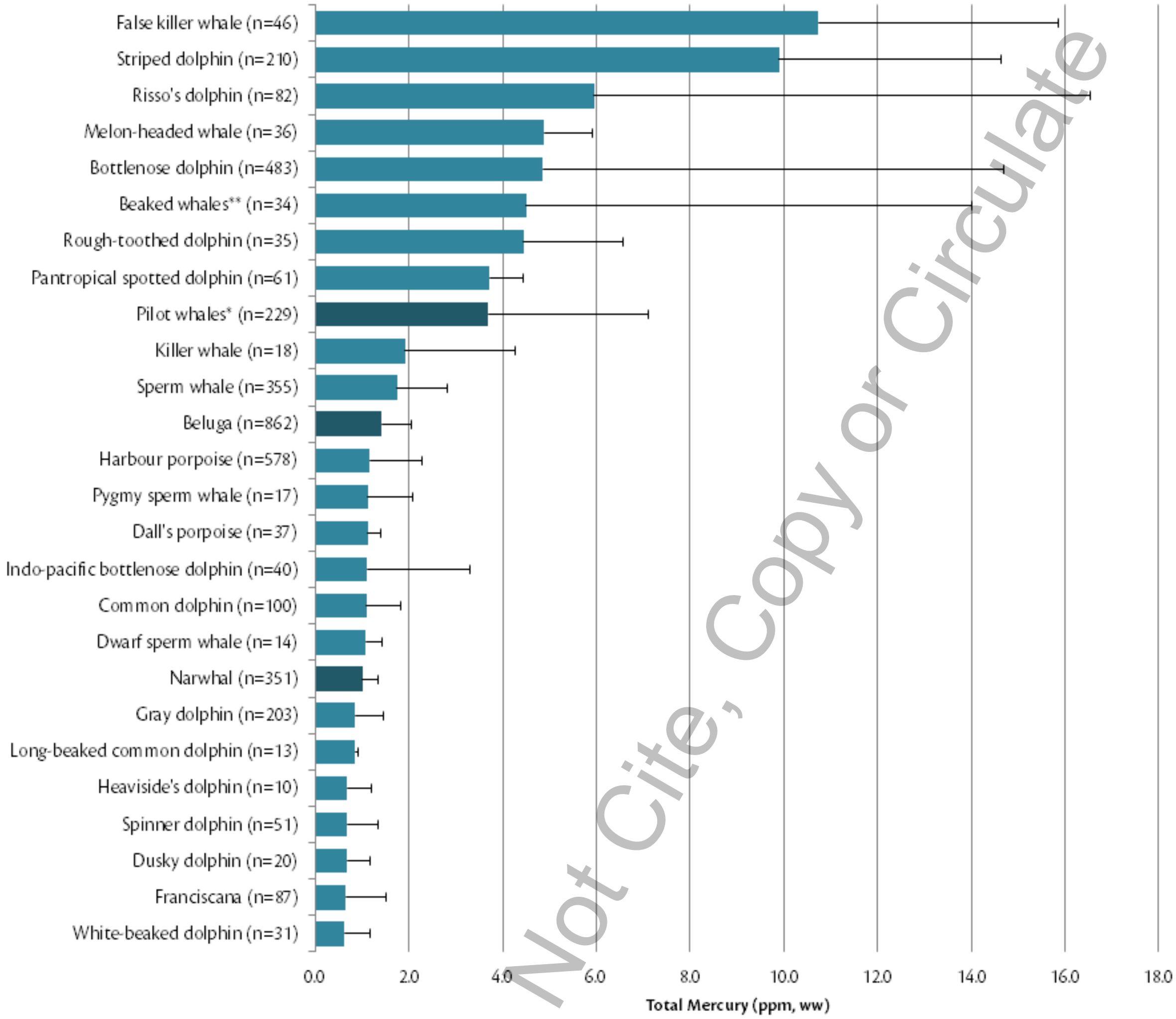

Figure 6. Average total Hg concentrations (ppm, ww) in muscle tissue of toothed whales by species (except beaked whales were combined under the family, Hyperoodontidae, and the two species of pilot whales were grouped).

Therefore, toothed whales appear to be one of the most vulnerable groups of marine mammals with mean Hg concentrations (2.61 ppm, ww; Table 1) well above the WHO human health advisory level (which is most relevant with beluga and pilot whales, because of the dependence of certain Arctic human communities on them) and several species over 4.0 ppm (ww) (Figure 6). Various species of porpoises and dolphins (Aubail et al. 2013, Correa et al. 2013), as well as beaked whales (which specialize in foraging on deep water cephalopods) generally have elevated Hg body burdens (Figure 6; Bustamante et al. 2003, Garrigue et al. 2016).

7.5.2 Overarching global patterns

The compilation of existing biotic Hg 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 modelling efforts show 55% of global Hg(II) deposition occurs over the tropical oceans (Horowitz et al., 2017). Ocean cruise observations also show high MeHg concentrations in seawater in equatorial upwelling regions of the ocean (Mason and Fitzgerald, 1993).

In freshwater ecosystems, large contaminated sites are expected to be a main driver of variability in freshwater biota concentrations. One recent effort to characterize global aquatic Hg releases to inland ecosystems is therefore especially important for understanding the spatial distribution of these locations (Kocman et al., 2017). One major driver of such spatial patterns is the location of artisanal and small-scale gold mining (ASGM) activities in developing countries (Figure 7).

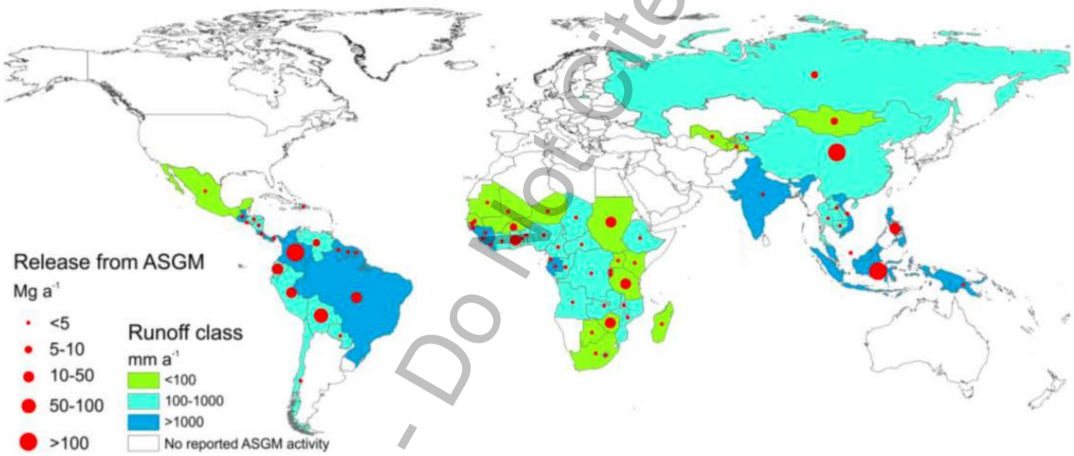

Figure 7. Global release of Hg from ASGM activities.

7.5.2.1 Spatial Gradients

The availability of MeHg to high trophic level organisms is not uniform across the world. Some ecosystems are more sensitive to Hg input than others (Driscoll et al. 2007) and it is these areas where biological Hg hotspots can form and are especially pronounced in higher trophic level organisms (Evers et al. 2007). Such areas are generally associated with wetlands and can be particularly pronounced in ecosystems with water chemistry variables such as low pH, moderate to high dissolved organic carbon concentrations, and low to moderate primary productivity. Fluctuating water levels can have a particularly important contribution in generating higher methylation rates and increases in MeHg bioavailability; and, may happen at daily (e.g., estuaries), monthly (artificial reservoirs), or ever seasonal (transition to wet season in the tropics) timeframes. Therefore, the determination of areas that may be elevated with MeHg availability does not have a linear relationship of the deposition or release of Hg into the environment. As an example, some of the lowest air Hg deposition levels in North American are in Kejimkujik National Park in Nova Scotia, Canada, yet the biotic MeHg exposure is some of the highest in North America for fish and loons (Evers et al. 1998, Wyn et al. 2010). The identification of potential biological Hg hotspots can be made through the collection of existing biotic data (Evers et al. 2011) and modelling ecosystem sensitivity.

7.5.2.2 Temporal Trends

New models simulating the deposition of Hg from anthropogenic emissions at global scales indicate a decrease of up to 50% in the Northern Hemisphere and up to 35% in the Southern Hemisphere (Pacyna et al. 2016). While tracking Hg emissions, deposition and releases are important tools for understanding patterns of environmental Hg loads, but the relationship between modelled (or measured) deposition and concentrations biota is poorly understood. Trends in Hg concentrations 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 Hg concentrations between 2004 and 2012 in the North Atlantic Ocean.

By contrast, both atmospheric emissions and freshwater discharges of Hg have been growing on the Asian continent leading to increased Hg pollution in the North Pacific Ocean (Streets et al., 2009; Sunderland et al., 2009, Zhang et al. 2015). Temporal data on fisheries in the North Pacific are more limited but some researchers have suggested there is evidence for increases in tuna Hg concentrations over the past several decades (Drevnick et al., 2015) which is further supported in an additional analyses of bigeye tuna for the same area (Drevnick and Brooks 2017).

As an example of the importance of generating baselines and how factors, such as climate change, are key can be found in Canada. Total Hg levels in aquatic birds and fish communities have been monitored across the Canadian Great Lakes by Environment and Climate Change Canada for the past 42 years (1974–2015) at 22 stations (Blukacz-Richards et al. 2017). For the first three decades, Hg 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. While strong trophic interactions among birds and fish is apparent, there also appears to be the strong likelihood of a trophic decoupling in some areas, which indicates the importance of not only long-term Hg biomonitoring efforts, but study designs that include other parameters that could be influenced by climate change (Pinkney et al. 2015).

7.5.3 Biomonitoring programs

Outside of the AMAP program (featured earlier in this chapter), an analysis of the geographical coverage of Hg biomonitoring networks reveals a general lack of national initiatives around the world. Per information gathered as part of the UNEP review of biomonitoring programs, there are no such national activities being undertaken in Africa and Australia (UNEP 2016). Most Asian countries are minimally involved with national initiatives to monitor Hg levels in biota, with notable exceptions of Japan and the Republic of Korea where more extensive programs exist.

In North America, Canada’s Northern Contaminants Program is an example of an integrated initiative for Hg monitoring throughout Canada’s vast Arctic territory (NCP 2017). Since its establishment in 1991, the program has focused on the measurement of contaminants (including Hg) in fish and wildlife that are traditional foods of northern Indigenous peoples. Monitoring and research funded by the program generates science on abiotic processes, spatial and temporal trends of MeHg bioaccumulation in biota, and human exposure to Hg from wild foods. One of the strengths of the program is the interdisciplinary approach taken to assess and monitor risks of Hg to ecological and human health through the participation of Indigenous organizations, environmental scientists, and human health professionals.

In addition to the AMAP program, there is an additional example of an international collaboration called ARCTOX, a program where seabird blood and feather samples have been collected over 54 Arctic sites and on a total of 14 seabird species (although not every species are sampled at each site). Samples are currently being collected or planned across Arctic countries, including U.S., Canada, Greenland, Scandinavia, and Russia.

Meanwhile, the hundreds of local studies, which are reflected within the GBMS database, are conducted by the global scientific community and together provide a comprehensive and geographically balanced global data platform about existing biotic Hg concentrations (Table 1). Based on the GBMS database, some of the countries with the highest fish consumption are poorly covered by biomonitoring efforts (e.g., Western and Central Africa [except Ghana] and many parts of Asia). Additional efforts are therefore needed to develop and implement projects to fill geographic and ecosystem gaps. Although national efforts can be keystones for regional biomonitoring networks, local scientific studies can make a significant and welcome contribution toward better identifying where, what and when to conducting biomonitoring.

To provide sustainable and long-term biomonitoring capacity in key regions around the world (e.g., Arctic, tropical areas associated with ASGM, and SIDS), the focus should be placed on expanding and stabilizing existing national initiatives. Moreover, it is crucial to foster international collaboration and coordination among national projects to create harmonized regional approaches, and to strive, where possible, to integrate biomonitoring activities into an interdisciplinary framework to assess ecological and human health risk that can be stitched together to represent regional and eventually global spatiotemporal patterns.

7.5.4 Linkages between Hg source types and biota

Linkages between major Hg source types and biota can now be accomplished with confidence through the use of Hg isotopes (Blum et al. 2014, Kwon et al. 2014). Mercury isotopes can separate the origin of Hg from coal burning facilities, chlor-alkali facilities, gold mining, and other source types. Separation of current major Hg source types from existing contaminated sites are of interest to identify how they may influence human and ecological health as characterized through bioindicators for purposes related to the Minamata Convention (Evers et al. 2016b).

7.6 Summary of Findings

In summary, the careful selection and use of bioindicators that closely match objectives of the interested parties can be a cost-effective and time efficient way to track human and ecological health from the anthropogenic loading of Hg onto the water and landscape at a global level (Evers et al. 2016b). The methods for biomonitoring and the interpretation of the tissues sampled are generally well-described for our target taxa. The extensive knowledge of Hg exposure in a wide range of fish and wildlife that are available in the peer-reviewed literature and now in the GBMS database provide a platform for best selecting the proper species or guild and to know what taxa can provide the upper levels of MeHg dietary uptake within a certain biome or waterbody. Biomonitoring should build from existing programs, which are generally found within developed countries at local, national and sometimes regional levels. Global pilot projects based on existing networks with local organizations and governmental agencies have been tested for fish (Buck et al. Submitted) and humans (Trasande et al. 2016) and biomonitoring approaches in temperate marine ecosystems are well described (Evers et al. 2008). Generating a more global approach that can stitch together the existing biomonitoring programs and identify the ecosystem, taxa, or geographic gaps can be completed within a structured plan. Once country needs and interests of the Minamata Convention are determined at the Conference of Parties, it is feasible to generate a biomonitoring approach that will assist in evaluating the effectiveness of parts of the treaty.

7.7 Critical Knowledge Gaps

By identifying critical knowledge gaps and adopting quantitative and replicable approaches a harmonized biomonitoring effort can be developed for all countries to use. One potential approach is to create a technical toolkit (i.e., spreadsheet of multiple data layers) that can quantify where, when, how and what to monitor for tracking environmental Hg loads, their changes over time, and potential impacts to human and ecological health. An Expert Group, compilation of existing data, and the development of a biomonitoring toolkit would provide: (1) a group of scientists and policymakers who can serve as advisors to the Conference of Parties, (2) a standardized and comprehensive database made available to Parties; (3) a peer-reviewed scientific platform of biomonitoring information (existing and new) that can be translated for policy purposes; and (4) a demonstrated model for training local field biologists and lab technicians that will ultimately build regional capacity and independence.

Iterative efforts to link realistic and applied biomonitoring efforts at local levels with science groups dedicated toward assisting the Conference of Parties of the Minamata Convention will help keep pace with the many emerging scientific findings that may fill existing information gaps that will be key for global policymaking.

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