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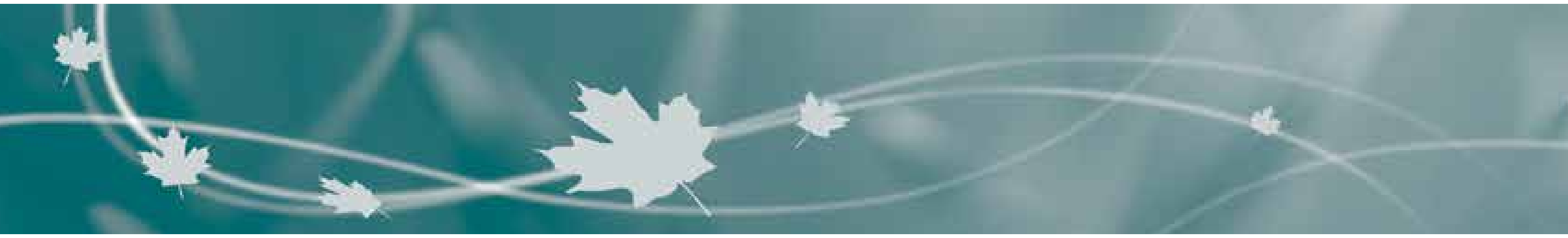

# *Canadian Mercury Science Assessment* **Summary of Key Results**

*Canadian Mercury Science Assessment*

# Summary of Key Results

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Environment and Climate Change Canada
Public Inquiries Centre
7th Floor, Fontaine Building
200 Sacré-Coeur Boulevard
Gatineau QC  K1A 0H3
Telephone: 819-997-2800
Toll Free: 1-800-668-6767 (in Canada only)
Email: ec.enviroinfo.ec@canada.ca

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# INTRODUCTION

The Mercury Science Program, part of the Clean Air Regulatory Agenda (CARA), was developed in 2007 to establish the scientific knowledge base to support regulatory decision-making for mercury. The intent of the program was (1) to determine key indicators of environmental quality and human health that are relevant to atmospheric emissions of mercury, (2) to quantify current and past levels for these indicators, and (3) to develop the capacity to predict changes in these indicators associated with changes in levels of atmospheric emissions of mercury or the receiving environment.[1] The geographic focus of the CARA Mercury Science Program was south of the Arctic Circle (60°N latitude). CARA partnered with the Canadian Arctic Northern Contaminants Program (NCP), an Aboriginal Affairs and Northern Development Canada (AANDC) program that conducts scientific research to respond to concerns about human exposure to elevated levels of contaminants, such as mercury, in fish and wildlife species important to the traditional diets of northern Aboriginal people. In 2012, NCP published *Canadian Arctic Contaminants Report III: Mercury in Canada's North* to provide a comprehensive evaluation of the environmental fate of mercury in the Canadian Arctic. The Canadian Mercury Science Assessment is a comprehensive, peer-reviewed synthesis of the state of scientific knowledge on mercury in Canada that includes information from the NCP report, covering Canada south and north of the Arctic Circle. In addition, this assessment builds on the recently published regional environmental assessments of the Great Lakes Basin[2] and northeastern North America[3] and is planned to feed into the North American Western Mercury Synthesis Report, being prepared as of 2013. The Canadian Mercury Science Assessment serves both the research and policy communities. For research, this assessment provides current information (up to 2012) about mercury in Canadian ecosystems, knowledge gaps, and predictive capabilities to inform program management. For decision-making, this Summary of Key Results provides science-based responses to several policy-related questions, and recommends directions for mercury research in Canada.

In 2010, Environment Canada and Health Canada launched its *Risk Management Strategy for Mercury*, which provided a summary of the Government of Canada's progress to date and future activities to manage mercury. This strategy outlined current federal research, monitoring and assessment activities aimed at strengthening our understanding of mercury, and summaries of expected future outcomes of regulation and science.

Preparation of this assessment began in 2008 with a series of workshops involving scientists and policy-makers from the federal, provincial, and territorial governments and from universities. These workshops led to the development of 7 science questions and sub-questions that capture the information needs of the science and policy communities in Canada. Based on these questions, the goal of this assessment is to synthesize the current state of knowledge on environmental mercury pollution in Canada. Its purpose is to inform decision-making by policy-makers and research managers through: (1) presentation of science-based information in the context of the policy-related questions; (2) establishment of a baseline against which to measure future changes in mercury levels in the environment; (3) identification of priorities for future science needs; and, (4) information to national and international scientists on the state of Hg research in Canada.

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[1] Morrison, H.A., 2011. The Canadian Clean Air Regulatory Agenda Mercury Science Program. Ecotoxicology 20, 1512-1519. 10.1007/s10646-011-0714-1.

[2] Evers, D.C., Wiener, J.G., Basu, N., Bodaly, R.A., Morrison, H.A., Williams, K.A., 2011. Mercury in the Great Lakes region: bioaccumulation, spatiotemporal patterns, ecological risks and policy. Ecotoxicology 20, 1487-1499. 10.1007/s10646-011-0784-0.

[3] Evers, D.C., 2005. Mercury Connections: The extent and effects of mercury pollution in northeastern North America. BioDiversity Research Institute., Gorham, Maine, p. 28.

**The policy-related questions are as follows:**

1. Is mercury a risk to ecosystem and human health in Canada?
    a. If so, where, how, and to what extent is mercury a risk to these assessment end points?
2. Are human activities contributing to observed mercury levels, and thus risk, in the Canadian environment?
    a. If so, what are these activities?
    b. Which activities are having the most significant impact on mercury levels in fish in Canada?
    c. What are the current and forecasted trends in mercury emissions/releases from these activities?
    d. From a long-range transport perspective, what are the major emission source regions contributing to Canada's mercury burden?
3. How are atmospheric emissions of mercury linked to methylmercury exposure and accumulation in terrestrial and aquatic biota and in humans?
    a. Are Canadian ecosystems responding to recent reductions in domestic atmospheric emissions of mercury?
    b. If so, what are the indicators of recovery, where is it occurring, and how quickly are ecosystems responding?
    c. If not, what factors are confounding/masking the expectation of recovery?
    d. Can predictions be made regarding the impact of future changes in atmospheric emissions on mercury levels in deposition and methylmercury levels in biota?
4. What are the linkages between other air pollutant emissions (e.g., acidifying emissions, greenhouse gases, etc.) and mercury accumulation in biota?
5. How might changes in other human activities (e.g., land-use practices) affect the distribution of mercury between environmental compartments, methylmercury formation, and the accumulation in biota?
6. In light of our current understanding of mercury in the Canadian environment, where, and to what extent, do we need to continue atmospheric and effects monitoring?
    a. What are the most promising environmental indicators of reductions in anthropogenic emissions of mercury?
    b. What are the most promising indicators of ecosystem recovery?
7. Where, and on what, should we focus future research efforts for mercury?

In addition to supporting Canada's domestic policy and science priorities, the assessment provides a scientific foundation to assess the effectiveness of efforts to reduce global mercury emissions resulting from the ratification and implementation of the Minamata Convention. The assessment also provides information to inform environmental decision-making outside of mercury mitigation through the assessment of the effects of land-use, eutrophication, acidification, and climate change on mercury transport and fate.

# BACKGROUND ON MERCURY

Mercury is a natural element commonly known as *quicksilver*. It is the only metal that is liquid at room temperature; it is predominantly found in the Earth's crust in the form of cinnabar (mercuric sulphide). Mercury is emitted to the environment through natural and anthropogenic (human activity-induced) sources, and may be re-emitted from previously deposited mercury of both anthropogenic and natural origin.[4] Natural sources of mercury include forest fires, volcanoes, ocean/aquatic emissions, and weathering of the Earth's surfaces. Mercury is released anthropogenically to the environment through processes such as coal burning, metals smelting, gold and silver mining, and chlor-alkali production using mercury or mercury compounds. It is also emitted from incinerators and areas flooded by dams, and through the production, breakage, and disposal of products containing mercury.

Once in the environment, mercury can be found in several forms. Each form of mercury has different chemical properties that govern how soluble, reactive, and toxic the mercury is. The most important forms of mercury with respect to environmental transport, fate, and effects are elemental mercury, divalent mercury, and methylmercury. Elemental mercury is very volatile and is stable in the air, which enables it to travel long distances once emitted. Divalent mercury forms compounds that are more soluble in water or reactive in the air. Methylmercury is the most toxic form and is the predominant form in fish, wildlife, and humans.

Animals and humans tend to absorb and retain over time most of the methylmercury in the food they consume (bioaccumulation). At each step up in the food chain, predators accumulate mercury from their prey. As a result, over their lifetime, they have much higher mercury levels in their system than their prey (biomagnification). Predatory fish and wildlife at the top of aquatic food chains can have mercury levels in their tissues 1 000 000 times greater than the levels in the freshwater where they live. Figure 1 shows simple diagrams of the bioaccumulation and biomagnification processes.

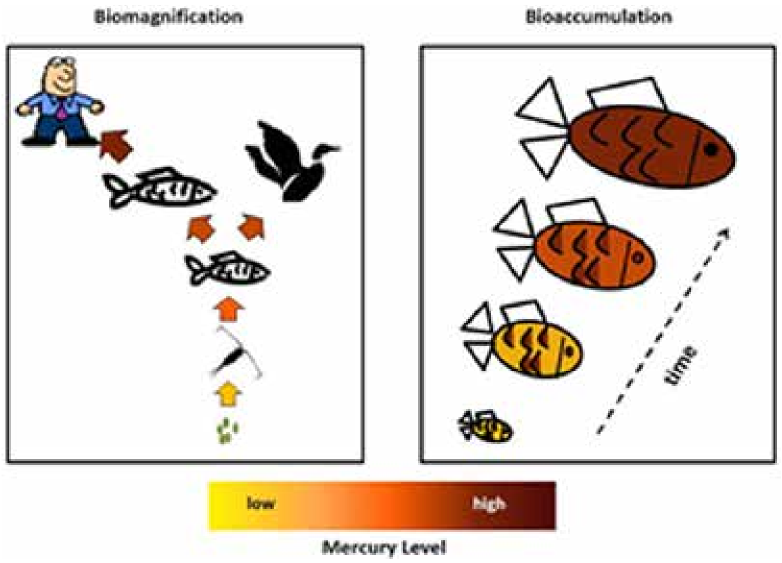

**Figure 1: Simplified schematic of biomagnification (left) and bioaccumulation (right) processes of methylmercury in the ecosystem.**

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[4] UNEP, AMAP, 2013. Technical background report for the global mercury assessment 2013. Arctic Monitoring and Assessment Programme/UNEO Chemicals Branch, Oslo/Geneva, p. 263 pp.

Environmental cycling of mercury is complex and involves many different processes and pathways. The predominant processes that mercury undergoes include emission, deposition, re-emission, transformation (methylation/ demethylation/ oxidation/ reduction), accumulation and magnification. Figure 2 is a simplified schematic showing environmental cycling of mercury in Canada. Each chapter in the assessment discusses a different contribution to the overall mercury cycle and is identified in the drawing. One chapter (9) uses the information on processes from most chapters to tie together cycling of mercury in the whole ecosystem.

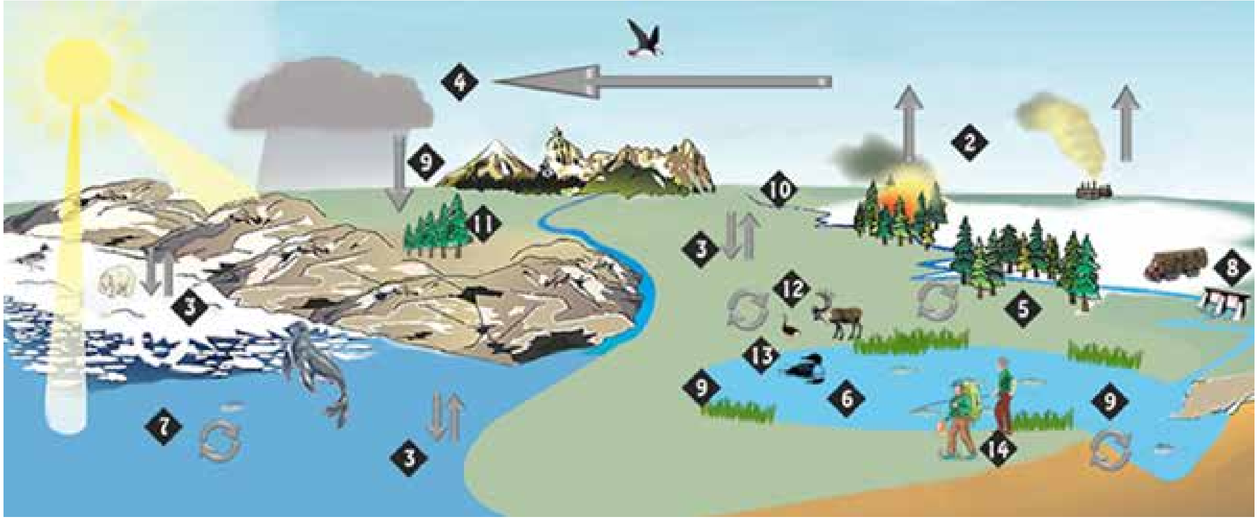

**Figure 2: The main processes that mercury undergoes in the ecosystem. The numbers indicate the chapters in which each process is discussed in the assessment report.**

**Chapter 2**: Releases of Mercury Into Air and Water From Anthropogenic Activities in Canada; **Chapter 3**: Surface Fluxes; **Chapter 4**: Atmospheric Processes, Transport, Levels, and Trends; **Chapter 5**: Mercury Fate and Methylation in Terrestrial Upland and Wetland Environments; **Chapter 6**: Mercury Fate and Methylation in Freshwater Aquatic Ecosystems; **Chapter 7** Mercury in the Marine Environment: Processes and Levels; **Chapter 8**: Influences of Anthropogenic Activities on Mercury Transport, Methylation, and Bioaccumulation; **Chapter 9**: Mercury Cycling in Ecosystems and the Response to Changes in Anthropogenic Mercury Emissions; **Chapter 10**: Mercury in Terrestrial and Aquatic Biota Across Canada: Geographic Variation; **Chapter 11**: Mercury in Terrestrial and Aquatic Biota Across Canada: Temporal Variation; **Chapter 12**: Health Effects of Mercury in Fish and Wildlife in Canada; **Chapter 13**: Assessment of Current Mercury Risks to Piscivorous Fish and Wildlife in Canada; **Chapter 14**: Mercury and Human Health

# POLICY-RELATED QUESTIONS

## Question 1:

Is mercury a risk to ecosystem and human health in Canada?

## Mercury remains a risk to Canadian ecosystems and human health.

### a. If so, where, how and to what extent is mercury posing risks?

## Ecosystem risks

In Canada, there are a substantial number of aquatic environments in which mercury levels in fish-eating (piscivorous) fish and wildlife are sufficiently high to be of concern. Methylmercury, the organic form of mercury, is of greatest concern for human and environmental health because of its high toxicity and its ability to accumulate in the tissues of living organisms and become more concentrated following transfer from prey to predators. As a result, predatory fish and wildlife at the top of aquatic food chains can have mercury concentrations in their tissues 1 000 000 times greater than the concentrations in the freshwater where they live.

The risks of mercury to piscivorous fish and wildlife across Canada have been assessed using indicator species known to have the potential for high exposure: walleye and northern pike are the indicator fish species, and common loons are the indicator bird species. Potential risks of exposure include threats to health, growth, breeding, and survival. Ecological risks of mercury increase from west to east across Canada, and mercury poses significant risks to the health and reproductive success of common loons (Figure 3) and predatory fish (Figure 4) in parts of southeastern Canada. Overall, risks of abnormal behaviour in common loons due to mercury exposure are found in 36% of the 677 Canadian lakes studied, and risks of impaired loon reproduction due to mercury, in 10% of 195 lakes studied. Similarly, mercury risks to reproduction in predatory fish are found in 82% of the 1 582 Canadian lakes studied, and mercury risks to fish health, in 73% of the 1 407 lakes studied. The higher mercury levels in eastern Canada also affect many other species of aquatic invertebrates, fish, birds, and mammals. Patterns of elevated mercury concentration levels in Arctic wildlife are different from those in wildlife in southern and central Canada. Several species of marine mammals, such as beluga whales, ringed seal, and polar bear, have higher mercury levels in the western and high Arctic (such as the Beaufort Sea) than in the eastern and southern Arctic.

In Canada, methylmercury concentrations tend to be greater in freshwater fish and wildlife in areas where the lakes and rivers are acidic. Similarly, methylmercury levels in lakes and rivers tend to be higher in areas where there are abundant wetlands in watersheds, where freshwaters are dark brown, and where there are recently flooded reservoirs. Geographic areas with bedrock and soils with poor buffering capacity (ability to neutralize additions of acid) or with high levels of acidic deposition from air pollution tendto have more acidic lakes and rivers and higher methylmercury concentrations in aquatic food webs. This combination of characteristics is more common in southeastern Canada, where methylmercury in piscivorous fish and wildlife tends to be highest.

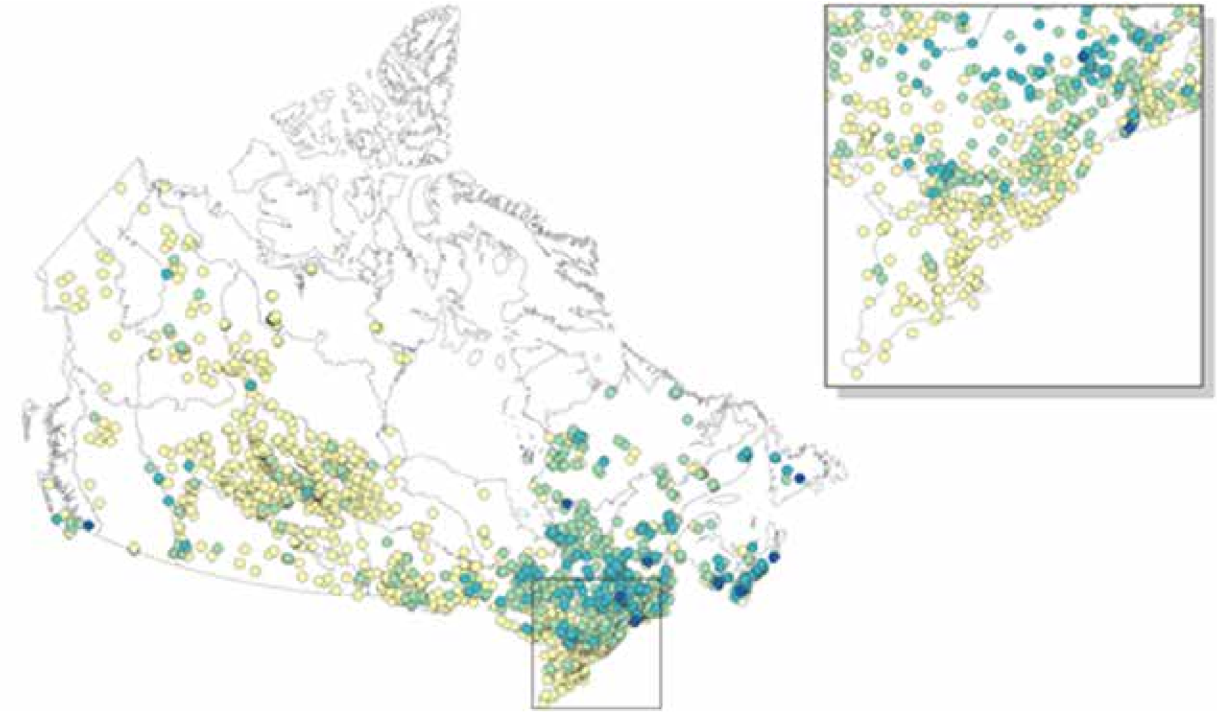

**Figure 3: Map of freshwater locations in Canada, showing mercury risks to common loons.**

**Dark blue**: Risk of failed productivity; **Teal**: Risk of impaired productivity; **Green**: Risk of impaired behaviour, and **Yellow**: Below all loon risk benchmarks

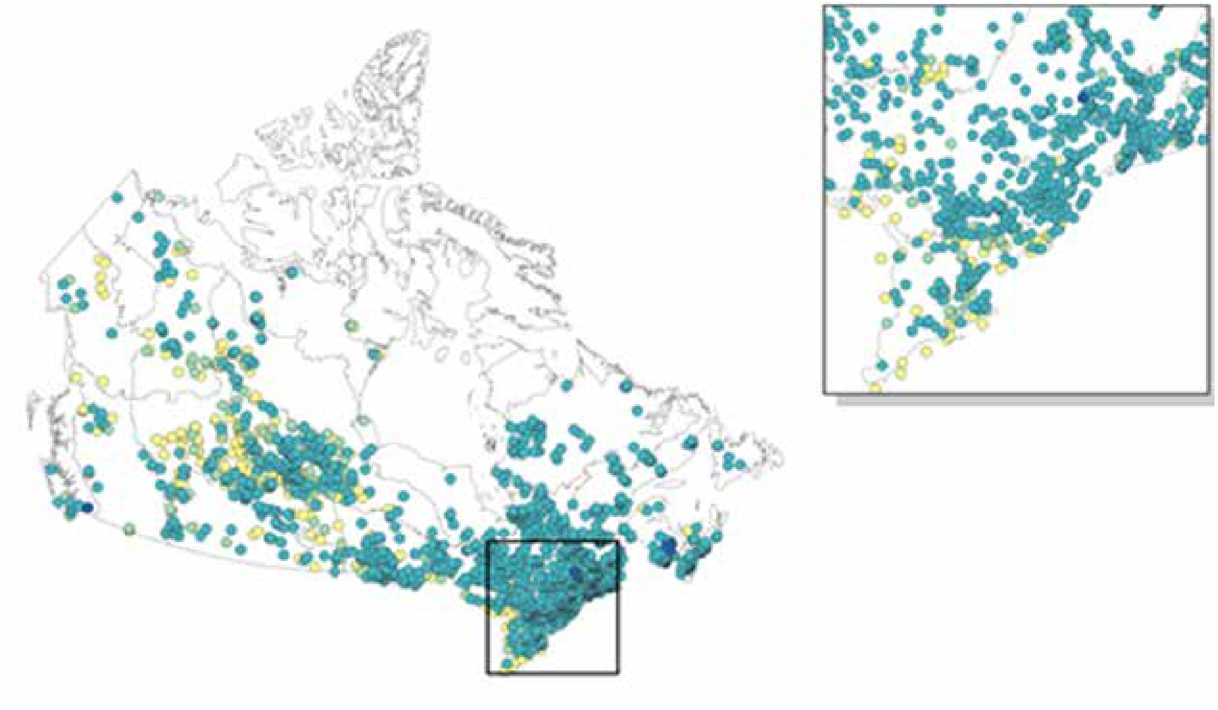

**Figure 4: Map of freshwater locations within Canada showing mercury risks to piscivorous fish.**

**Dark blue**: Risk of impaired behaviour; **Teal**: Risk of health impairment; **Green**: Risk of reproduction impairment and **Yellow**: Below all risk benchmarks

## Human health risks

In Canada, methylmercury remains a potential public health issue for populations who rely on the consumption of large predatory fish and traditional wildlife items. People are exposed to methylmercury primarily through the consumption of fish and seafood. Elemental mercury exposure from dental amalgams does not pose a health impact for the general population. In Canada, mercury blood levels of 20 µg $L^{-1}$ or lower are considered within an acceptable range. Individuals with levels between 20 and 100 µg $L^{-1}$ are considered at increasing risk, and those with levels above 100 µg $L^{-1}$ are considered at risk of health effects. However, for specific groups of people, including children (under 19 years of age), pregnant women, and women of childbearing age (younger than 50 years), a lower provisional mercury blood guidance value of 8 µg $L^{-1}$ has been proposed by Health Canada in order to account for the increased susceptibility of neurological development of young children and fetuses. Some groups, such as Aboriginal peoples, sport fishers, and Asian Canadians, may be more likely to be exposed to methylmercury in higher concentrations than the general Canadian population because of a diet high in fish and seafood.

## Biomonitoring

Several programs are in place to monitor exposure to methylmercury in biological samples (e.g., hair, urine, or blood sampling) for the general Canadian population, northern Aboriginal communities, First Nations communities, and prenatal exposure in infants and children. Other studies have evaluated methylmercury exposure in Asian Canadians and sport fishers. According to data from Cycle 1 of the Canadian Health Measures Survey (CHMS) (2007–2009), approximately 2.2% of females aged 16–49 (includes pregnant women) have blood mercury levels exceeding the guidance value of 8 µg $L^{-1}$. When children are also considered, 1.6% of Canadian children and youth and women of childbearing age combined have blood mercury levels exceeding the guidance value of 8 µg $L^{-1}$. This suggests that only a small percentage of these vulnerable populations may require follow-up testing, dietary advice, or other further action.

By contrast, Inuit in the eastern Canadian Arctic have shown the highest concentrations of mercury among northern populations, with levels exceeding 8 µg $L^{-1}$ in over 50% of mothers examined during a small study in the Baffin region of Nunavut in 1997; however, more recent data suggest that northern levels have been decreasing in the last several decades. During a follow-up study in Nunavut in 2005–2007, only 20% of mothers had levels exceeding 8 µg $L^{-1}$. Moreover, studies in the Nunavik region of northern Québec have also shown a downward trend for mercury levels in mothers from 1992 to 2007. These decreases may be due to a combination of public health interventions, dietary change, and heightened awareness among communities. Available data about mercury concentrations in people living in First Nations communities south of 60°N latitude suggest that mercury exposure is generally lower than for Arctic Inuit populations but still a concern in many isolated First Nation communities where fish is a diet staple.

## Effects

Health effects, in particular neurological impairments, are associated with exposure to high levels of methylmercury. The developing nervous system is considered to be the most susceptible to the adverse health effects of methylmercury; thus, deve=loping fetuses, infants, and young children are at a higher risk of developing adverse health effects. Recent studies suggest that neurological deficits (including decreased movement speed and dexterity, vision problems, and memory issues) in adults may also be attributable to methylmercury exposure. The level and duration of exposure to methylmercury influences the severity of adverse health outcomes. However, omega-3 fatty acids, found in high levels in some fish species, play a pivotal role in certain aspects of neurodevelopment, and may be capable of mitigating or negating some of the adverse effects of prenatal exposure to methylmercury through fish consumption. Recent studies suggest a possible link between methylmercury exposure and some adverse effects on the adult cardiovascular system, but more research is needed. Although for most populations, consuming fish carries a risk of exposure to methylmercury, the benefits of fish consumption are thought to generally outweigh these risks, depending on the levels of mercury in the fish, the frequency and amount of consumption.

## Question 2:

### Are human activities contributing to observed mercury levels, and thus risk, in the Canadian environment?

## Human activities are contributing to observed mercury levels in Canada.

### a. If so, what are these activities?

Mercury is emitted to the atmosphere through natural sources, anthropogenic emissions, and re-emission of previously deposited mercury. Anthropogenic activities such as electricity generation, smelting, cement production/ processing, waste incineration, and disposal of mercury-containing products release mercury into the environment. Canadian emissions in 2010 were 5 300 kg to air and 240 kg to water. In comparison with other major mercury-emitting countries, such as the United States and China, Canadian emissions are relatively small. Figure 5 shows the distribution of anthropogenic sources of the 2010 mercury emissions in Canada to air and water.

Until its closure in 2009, Canada's largest source of mercury to the atmosphere was the Hudson Bay Mining and Smelting operations in Flin Flon, Manitoba. Decreases in emissions from this smelter, due to decreases in the smelter operations and control technologies to reduce emissions of a variety of pollutants, accounted for the most significant Canadian decreases in Hg emissions from the early 1990s until 2010. Canadian mercury emissions have decreased over time and are expected to stabilize

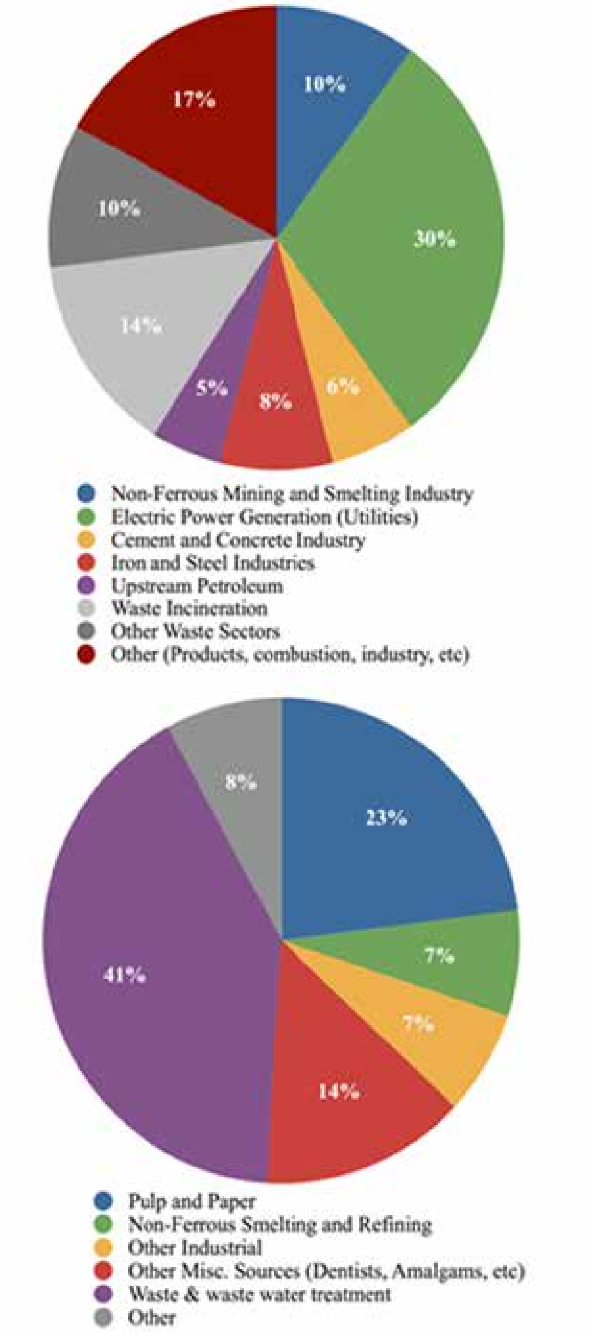

**Figure 5: Distribution of the major contributing sectors of mercury emissions to air in Canada in 2010 (left) and sector contributions of mercury releases specifically to water in 2010 (right). In the category "*other, combustion*" includes residential fuel and wood combustion and "*industry*" includes emissions from industries such as pulp and paper and iron ore mining.**

**Table 1: Provincial and territorial total mercury emissions and percentage of total national total emissions for 1990, 2000, and 2010**

| Province | 1990 | | 2000 | | 2010 | |
|---|---|---|---|---|---|---|
| | kg | % | kg | % | kg | % |
| Alberta | 1 184 | 3 | 1062 | 16 | 1 175 | 22 |
| British Columbia | 3 668 | 10 | 1 139 | 6 | 549 | 10 |
| Manitoba | 20 169 | 57 | 1 231 | 13 | 366 | 7 |
| New Brunswick | 729 | 2 | 436 | 5 | 158 | 3 |
| Newfoundland | 253 | 1 | 184 | 2 | 122 | 2 |
| Nova Scotia | 384 | 1 | 261 | 5 | 139 | 3 |
| Northwest Territories | 79 | 0 | 4 | 0 | 13 | 0 |
| Nunavut | 2 | 0 | 2 | 0 | 2 | 0 |
| Ontario | 4 426 | 13 | 2 675 | 31 | 1 191 | 22 |
| Prince Edward Island | 35 | 0 | 27 | 0 | 16 | 0 |
| Quebec | 3 667 | 10 | 1296 | 15 | 730 | 14 |
| Saskatchewan | 662 | 2 | 575 | 7 | 855 | 16 |
| Yukon | 4 | 0 | 2 | 0 | 1 | 0 |

in the future. In 2010, overall Canadian emissions of mercury were reported to have decreased by 85% in air and by about 50% in water since 1990.

Mercury emissions differ among provinces, and have decreased in most provinces between 1990 and 2010, with the exception of Alberta and Saskatchewan (Table 1). Alberta's levels have remained the same while Saskatchewan's levels have increased as a result of a doubling of emissions from coal-fired electricity generation and some small increases in the upstream and downstream petroleum sectors. In 2010, Alberta and Ontario equally shared nearly half of the national burden of mercury emissions. Saskatchewan and Quebec shared a third of the national burden, while the rest of the country made up the rest.

While many of the direct emissions have decreased, revolatilization of historically deposited mercury can contribute to the continued elevated levels of mercury in the air. For example, the highest levels of re-emitted mercury in air in Canada continue to be found in the area around the smelter in Flin Flon, although the smelter was shut down in 2009. As well, historical mine waste continues to be a significant source of mercury to the environment long after the cessation of mining and milling activities. In the case of some gold mines in Nova Scotia, mine waste continues to emit mercury 60 to 70 years later.

Other human activities contribute to high mercury levels observed in certain Canadian environments. For example, land-use changes, eutrophication[5] and acidification of aquatic ecosystems, and climate change from anthropogenic activities contribute to elevated levels of mercury. The main land-use changes that affect mercury dynamics are logging activities and reservoir[6] impoundments. As well, acidic emissions (such as sulphate and nitrate) can be subsequently deposited on land and water, where they can affect rivers and lakes. Acidification of rivers and lakes leads to transformation of elemental mercury to toxic methylmercury, which can then bioaccumulate in aquatic plants, fish, and piscivorous wildlife.

Human activities driving climate change are expected to have complex effects on mercury dynamics that are challenging to predict. Climate change impacts such as higher water temperatures and changes in the temperature layers of lakes are likely to alter methylmercury production. However,

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[5] Eutrophication is the process of enrichment of organic matter in an ecosystem. Eutrophication of waterways is caused by nitrogen and phosphorus, largely from agricultural fertilizer and manure, human sewage, and a variety of urban activities.

[6] Reservoirs are bodies of water created by humans, including flooded areas, primarily for hydroelectric power generation and, to a lesser extent, flood protection, irrigation, water supply, and recreation. The new reservoirs result in large areas of terrestrial vegetation being flooded, which creates decomposition of the vegetation and stimulation of microbial activity, including bacteria that methylate Hg.

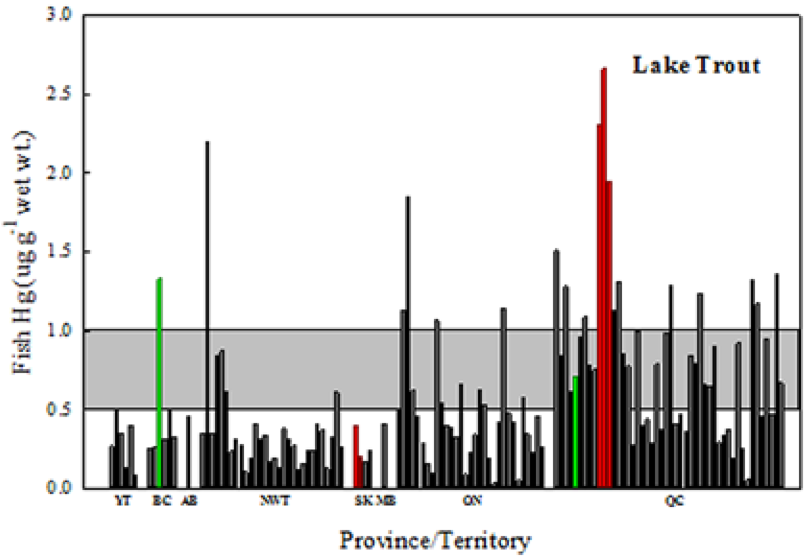

**Figure 6: Example of mercury levels in lake trout muscle from various locations (lakes or reservoirs, not including any of the Great Lakes) from west to east across Canada. The shaded area represents the range of estimated lowest observed adverse effect level for fish toxicity. Green bars = "contaminated lakes" (lakes categorized as likely receiving some level of mercury pollution from nearby sources); red bars = reservoirs.**

reduced seasonal ice cover in lakes may reduce the amount of methylmercury available. The largest changes in temperature are expected in northern Canada, where precipitation and moisture levels are expected to generally increase. Mercury cycling and bioaccumulation (especially in the Arctic) could be adversely influenced by climate change. For instance, current evidence shows that mercury levels are going up in some populations of Arctic biota but not necessarily in others, which suggests local or regional factors that may involve climate change. Mercury pollution from point sources such as smelters and mining is not currently a significant problem for marine regions in Canada; however, there have been significant local impacts on Canadian marine areas during the 20th century.

## b. Which activities are having the most significant impact on mercury levels in fish in Canada?

Anthropogenic activities such as reservoir impoundment, mining, previous chlor-alkali production using mercury cells, coal burning, municipal waste incineration, cement production, and metals smelting are generally associated with mercury contamination of local and regional ecosystems. Fish mercury levels are generally higher in eastern Canada than in central and western Canada; and Ontario, Quebec, and Nova Scotia have relatively high proportions of lakes where mean mercury concentrations in lake trout, northern pike, and walleye exceed an estimated lowest amount of mercury that causes an adverse effect[7] on these fish.[8] For example, Figure 6 shows the mercury levels in lake trout sampled from numerous lakes across Canada. Only 13% of lakes west of Ontario had trout with mean mercury concentrations that met or exceeded the lowest observed adverse effect level threshold range for fish, whereas 32% of Ontario lakes and 67% of Quebec lakes exceeded it. Furthermore, in Ontario 57% the lakes sampled for walleye and 49% of lakes sampled for northern pike reported mean mercury levels in these fish to be either within or greater than the concentration range for negative effects in fish. Some of the elevated mercury levels in fish in eastern Canada were attributable to reservoir impoundment, previous chlor-alkali emissions, and regional deposition of atmospheric emissions. However, most fish with elevated mercury concentrations were from semi-remote lakes and reservoirs characterized by nutrient-poor, low alkalinity, and low pH conditions, or by periodic flooding of wetlands.

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[7] The lowest level that produces effects on growth, health, reproduction, or behaviour, or causes death; expressed as the lowest observable adverse effect level range.

[8] The lowest observable adverse effect level is a mercury concentration of 0.5–1.0 µg g-1 wet weight of fish muscle.

Mercury levels in fish in the Great Lakes were higher in the past because of mercury deposited from industrial emissions in the region, including coal-fired power plants, metal production, waste incineration, and cement production. As these regional emissions decreased, starting in the 1970s, the mercury levels in fish in the Great Lakes declined as well. The highest mercury emissions in central Canada were from the base metal smelter in Flin Flon; however, mercury levels in fish (yellow perch) near Flin Flon were no higher than those in more distant reference lakes, and were not sufficiently high to affect the health of fish or of fish-eating wildlife. Similarly, lakes close to Alberta coal-fired power plants did not have fish with elevated mercury levels, compared with more distant lakes. By contrast, lakes contaminated by mercury mining activities, such as Pinchi Lake in central British Columbia, had high mercury levels in fish (trout).

Why are levels of mercury often high in fish, even in lakes far from point sources such as smelters, coal-fired power plants, and mines? To link anthropogenic inputs of mercury to fish mercury levels in lakes, key factors such as the chemical and physical properties of the lake and surrounding watershed must be considered. It has been shown that the acidity of the lake water is one of the most significant factors affecting mercury levels in fish. Thus, while there may be a significant mercury input to the lake from a given industry, if the pH/alkalinity of the lake is high, there may be relatively little mercury methylation and hence little accumulation of mercury by fish. For example, most of the lakes where Hg concentrations in yellow perch exceeded estimated toxicity thresholds for breeding common loons, that use these fish as a food source, were from lakes with higher acidity (pH<6.5). Conversely, lakes near the base metal smelter at Flin Flon (pH 7-8.5) showed the greatest inputs of Hg, yet corresponding fish Hg levels were low.

Other activities such as changes in land use, eutrophication, and climate change likely affect levels of mercury in the Canadian environment, although the relative magnitude of ecosystem responses (including fish mercury concentrations) is not precisely known. These long-term environmental changes influence mercury methylation processes, which affect the transfer and accumulation of mercury in biota.

### c. What are the current and forecasted trends in mercury emissions/releases from these activities?

Overall, atmospheric mercury emissions in Canada have declined 85% between 1990 and 2010, from approximately 35 to 5 tonnes (t) per year (Table 2). This large decline is primarily due to process changes in the non-ferrous metal mining and smelting sector (where emissions have declined

**Table 2: Sectors emitting mercury to air in Canada**

| Sector | Total emissions yr$^{-1}$, t | | | | |
|---|---|---|---|---|---|
| | 1990 | 1995 | 2000 | 2005 | 2010 |
| Non-ferrous metal mining and smelting | 24.9 | 4.7 | 1.9 | 1.7 | 0.5 |
| Electric power generation | 2.3 | 2.0 | 4.0 | 2.1 | 1.6 |
| Cement and concrete industry | 0.5 | 0.4 | 0.4 | 0.2 | 0.3 |
| Iron and steel industries | 0.9 | 1.0 | 1.0 | 0.7 | 0.4 |
| Waste sectors | 3.8 | 4.3 | 2.1 | 1.4 | 1.3 |
| Other | 2.9 | 2.4 | 1.7 | 1.2 | 1.2 |
| Total emissions | 35.3 | 14.7 | 11.2 | 7.3 | 5.3 |
| % per year decrease (over previous 5 years) | | 11.7 | 14.6 | 10.7 | 6.0 |

98%) as well as economic and regulatory impacts on the sector. The second largest decline in emissions is from waste sectors (where emissions have declined 76% over the same period of time). The smallest decline in the reported mercury emissions is from the electric power generation sector (30%). Currently, fossil fuel combustion for electric power generation is the largest single source of mercury emissions in Canada, accounting for 30% of the total emissions.

Canadian mercury emissions are forecasted to remain relatively constant in the future (Figure 7). After 2010, significant anticipated reductions in emissions from non-ferrous smelting and refining, pulp and paper, and electric power generation sectors are offset by anticipated increases from other miscellaneous sources and the waste sector. It is difficult to estimate any changes in releases of mercury from products and from changes in recycling, since regulations governing disposal of products have not yet been enforced and there is uncertainty associated with the current information (up to 50% for legacy emissions). The contributions of other minor sectors are expected to increase due to population growth and increased demand for materials.

## d. From a long-range transport perspective, what are the major emission source regions contributing to Canada's mercury burden?

Based on results from Environment Canada's Global/Regional Atmospheric Heavy Metals (GRAHM) model, an estimated 95% of the anthropogenic mercury deposited in Canada comes from sources outside of the country. These contributions are approximately 40% from East Asia, 17% from the United States, 8% from Europe, and 6% from South Asia.

Mercury can remain in the air for a long time (6–12 months) and can be transported long distances from its source, termed long-range transport. Thus, it is important to identify primary source regions outside of the country that contribute to deposition in Canada to understand the full mercury burden within Canada.

Global mercury emissions are currently dominated by East Asia, followed by emissions from sub-Saharan Africa, South America, South Asia, Europe, and the United States. The relative contributions of emissions to net deposition in Canada from various source regions have been assessed for the year 2005 using the GRAHM model. As an example, the relative size of emission source contributions from 9 continental regions to deposition in 4 selected sub-regions in Canada is shown in Figure 8. In 2005, approximately 115 t of mercury was deposited to Canada; approximately 40% of the mercury deposited was from current global anthropogenic emissions and approximately 60% from other global terrestrial (approximately 35%) and oceanic (approximately 25%) emissions. These other emissions include both natural emissions and re-emissions of mercury deposited in the past.

East Asia and the United States are the predominant areas contributing to Canada's mercury burden. Europe, South Asia, Africa, South America, and Australia all contribute at similar levels to mercury deposition in Canada. Approximately two-thirds of all mercury deposited from East and Central Asian to all regions in Canada is of anthropogenic origin. Anthropogenic and terrestrial emissions from sources in Europe and South Asia contribute equally to deposition across Canada. In contrast, the relative contributions of anthropogenic and terrestrial emissions from the United States and Canadian sources to mercury deposition vary depending on the region of Canada receiving mercury. In northern and western Canada, the total contribution of anthropogenic and terrestrial emissions to annual deposition from East Asian (24 to 26%) is twice as high as the total contribution from the United States (7 to 12%). In comparison, in eastern Canada the total contribution of the same emissions from East Asia (20 to 23%) is comparable to the total contribution from the US (15 to 22%). European contributions to northern, western, and eastern regions in Canada are all comparable (5 to 7%).

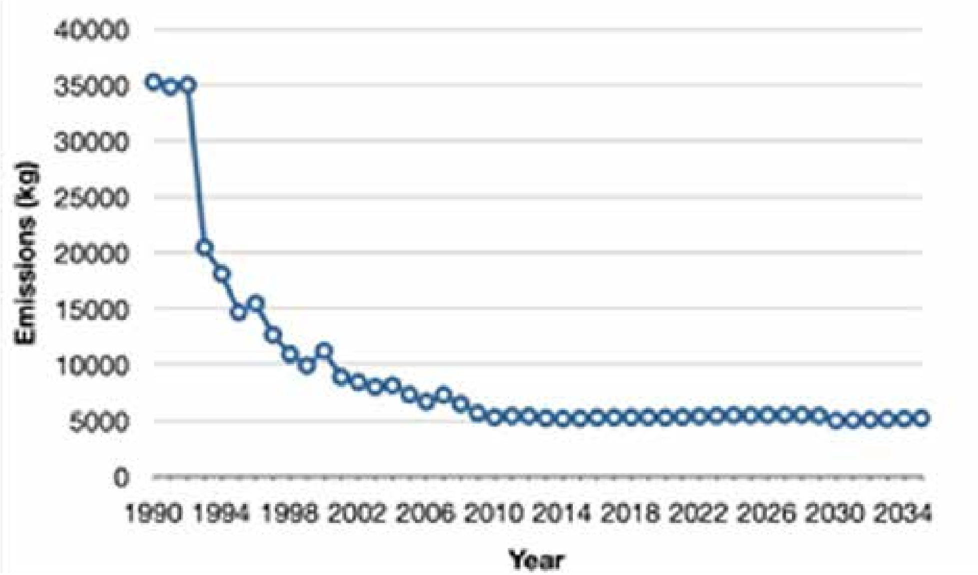

**Figure 7: Historical and projected Canadian mercury emissions trends in air using the Energy, Emissions, and Economic Model for Canada (E3MC) model.**

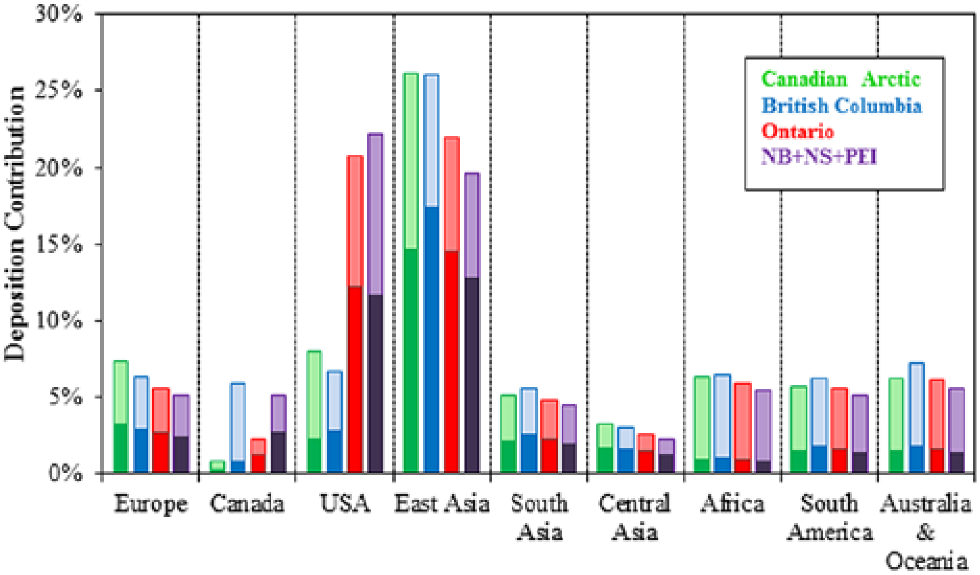

**Figure 8: Relative contributions from emissions from individual source regions to net mercury deposition for the Canadian Arctic, British Columbia, Ontario and New Brunswick, Nova Scotia and Prince Edward Island combined for the year 2005 (as estimated by the Global/Regional Atmospheric Heavy Metals model). Contributions from each source region are divided into contributions from "anthropogenic" sources (shown as dark colours) and "other terrestrial" (including both natural and re-emission) sources (shown as light colours).**

## Question 3:

### How are atmospheric emissions of mercury linked to methylmercury production, exposure, and bioaccumulation in terrestrial and aquatic biota and humans?

## Atmospheric mercury emissions are linked to methylmercury exposure through a series of biogeochemical processes in the environment.

### a. Are Canadian ecosystems responding to recent reductions in domestic atmospheric emissions of mercury?

The responses of Canadian ecosystems to decreases in domestic emissions vary among ecosystem compartments. In the past 15 years, the atmosphere has shown varying declines in mercury levels, likely in response to reductions in emissions. However, the response in fish and wildlife in Canada differs more significantly among regions and among species. Of the fish and wildlife populations studied, mercury levels had increased in 31%, decreased in 21%, and remained stable in 48%. Of all the populations that report increases, 83% are from the Arctic and the greatest increases have been seen in seabirds. Mercury levels in fish populations also vary: 50% of the populations that showed a decline were fish and seabirds from known areas of emission reductions (Great Lakes and Atlantic regions).

Whether ecosystems have responded to changing emissions is challenging to determine because mercury is transported through several compartments in the ecosystem between emissions and exposure; thus, it cannot be assessed as a simple cause-and-effect relationship. Further, the response depends on many factors affecting the ecosystem, which adds challenges to scaling information from specific ecosystems to all of Canada. Research into understanding ecosystem responses to emissions, both experimentally and through modelling, is discussed in this assessment.

## Response in the atmosphere

In recent decades, inventories have reported a decline in mercury emissions domestically and, until most recently, globally, but not in all geographical regions. While measured total gaseous mercury levels have declined in Canada, there has been no significant decline in wet deposition of mercury (mercury reaching the ground through rain) reported. Canadian atmospheric mercury emissions have declined 85% from 1990 to 2010 (Table 2). Levels of mercury measured in ambient air have ranged between no decline and 26% total decline over various time periods and locations between 1995 and 2011. From 1995 to 2011 the total decline in the high Arctic was 15%; however, this is less than declines reported in temperate regions over the same time period (15-23% ±1-2 years). In the Great Lakes region declines are reported to range from 10 to 21% and are likely as a result of reductions in North American emissions. Interestingly, at a site close to a power plant in Genesee, Alberta there have been neither declining nor increasing trends reported in mercury levels over 7 years. Many point sources have reduced emissions over time, including the smelter in Flin Flon, Manitoba (which reduced emissions until its closure in 2009). While local mercury levels in the air near the smelter have declined 20% since the closure, they still remain approximately twice as high as those at any other monitoring site in Canada. This is likely a result of re-emissions of locally deposited mercury. As well, elevated levels of mercury in the sediments around Flin Flon have been attributed to atmospheric deposition from the smelter.

Overall, decreases in ambient mercury levels have not decreased by the same amount as Canadian mercury emissions over the past 2 decades.

This is likely because of incoming emissions from outside of Canada, as shown by model results, as well as naturally occurring and re-emitted mercury. Although Canadian, North American, and European anthropogenic emissions have declined in the past decades, recent inventories (2010) suggest that global emissions remained the same or were slightly higher than in 2005, reflecting greater emissions abroad, particularly from Asia.

In the northern hemisphere, ambient mercury levels peaked in the 1980s and then decreased to a plateau between 1996 and 2001. These trends were confirmed through simulations using the GRAHM model and primarily result from the decreases in global and regional emissions of mercury. However, more recent measurements up to 2010 show that the global mercury concentration levels have decreased more significantly than can be explained by changes in emissions alone, suggesting a shift in the biogeochemical cycling of mercury. In addition, mercury concentrations in precipitation have declined at most sites in Canada since the mid-1990s. However, the amount of wet deposition of mercury has not changed significantly, and this is influenced by trends in precipitation. Finally, mercury levels in the air are not entirely controlled by emission reductions, as they are also affected by natural emissions as well as re-emissions of anthropogenically released mercury.

## Response in biota

Mercury levels in monitored fish, birds, and mammals in Canada have shown varying trends, with differences among species and geographical regions. In this report, the regions in Canada that have been most influenced by domestic emission changes are the Great Lakes and Atlantic Canada. The Great Lakes region has shown both the largest and most numerous declines in mercury levels in individual populations (40% of fish and seabird populations reported). However, more recently, studies show that some of these decreases are reversing in some species. In Lakes Superior, Huron, and Ontario, mercury levels in fish have declined an average 60% (in lake trout) and 67% (in walleye) from the 1970s to 2007. The same fish species from Lake Erie showed a similar decrease in mercury levels until the mid-1990s, when levels started to increase again. Levels of mercury in some wildlife around the Flin Flon area show no influences of local emissions. In Atlantic Canada, 63% of populations show no change, 12% have decreasing mercury levels, and 25% have increasing levels. Some of these populations are considered to be at risk from mercury exposure (Figures 3 and 4). Over the 40 years in Canada, mercury levels in wildlife and

**Figure 9: Overall trends in mercury concentrations in Canadian terrestrial mammals, fish, polar bears, beluga whales, seals, seabirds, and mussels (1967–2012).**

fish have shown increasing, stable, or decreasing trends, with variation among monitored species and regions (Figure 9). Overall, mercury levels have increased in 31% of the populations investigated in this report, decreased in 21%, and remained stable in 48% (note: over 50% of the populations reported on are from the Arctic region). Of all the populations that show an increasing trend, 83% are from the Arctic. While marine mammals and fish are similarly represented in this group, the greatest increases are seen in seabirds. The only Arctic population showing decreasing trends is fish, based on short-term data.

## Other factors affecting mercury levels in ecosystems

The observed variation in mercury levels and trends in biota across Canada is partly due to many factors, aside from emissions, that affect mercury behaviour. These factors include physical, chemical, and biological conditions in the atmosphere, land, and aquatic systems. Mercury levels in the environment vary naturally and may change in response to multiple factors such as emissions, climate change, and acidification. Ultimately, the amount of methylmercury available for uptake drives mercury levels in biota. Land vegetation (terrestrial) systems receive mercury from the air and export a portion to rivers and lakes. In fact, mercury levels in terrestrial and aquatic systems may still be changing in response to emissions from the past century because of delayed response in the ecosystem. This delay complicates efforts to determine the response of ecosystems to changes in recent domestic mercury emissions. These effects have been investigated as part of a unique long-term mercury study, Mercury Experiment to Assess Atmospheric Loadings in Canada and the United States (METAALICUS), conducted at the Experimental Lakes Area[9] (ELA) in Ontario. METAALICUS studied the response of a whole ecosystem when mercury loads were increased experimentally. Results confirm that reductions in mercury deposition from the air result in reductions in mercury in the fish. However, METAALICUS and other projects have also shown these reductions may be delayed because drainage basins around lakes are sinks for mercury that is deposited from the air. These basins respond slowly to changes in mercury levels (over decades to centuries).

## Modelling the impact of emissions on mercury in ecosystems

For this assessment, an integrated air/land/water computer model was developed to address the complexities of the relationship between mercury emissions, deposition, and, ultimately, levels in fish. The model looks at the impact on fish of changes in global and domestic mercury emissions. Changes in mercury levels in lakes are controlled by 5 factors: (1) how important the input of mercury to the lake from stream inflow is when compared with direct atmospheric deposition; (2) how long it takes for deposited mercury to go from the surrounding area into the lake; (3) how much mercury emissions have declined; (4) how close the surrounding lake area is to the changing emission sources; and (5) how important is the production of methylmercury in water column when compared to its production in sediments in the lake. Combinations of these factors dictate how fish mercury levels change over time in response to changes in emissions. Ecosystems closer to major domestic sources are more likely to show reductions in fish mercury levels in response to the reductions in domestic mercury emissions because of the greater influence of these emissions on deposition in these ecosystems.

### b. If so, what are the indicators of recovery, where is it occurring, and how quickly are ecosystems responding?

Indicators such as the concentration of mercury, or other chemical elements, in teeth of Arctic marine mammals have been used to show historical changes in the environment from the onset of the industrial revolution. Analysis of teeth has shown that mercury levels in marine biota increased after the late 19th century, with the most substantial increases occurring in the mid-20th century. This is an indicator of an impact on the Arctic marine ecosystem of the several-fold increase in anthropogenic mercury emissions over that time.

Currently, the indicators that can be used to show declines in mercury levels include changes in

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[9] In April 2014, the Experimental Lakes Area was reopened under the name "International Institute for Sustainable Development - Experimental Lakes Area (IISD-ELA)". The work conducted for this assessment was undertaken prior to April 2014 and thus this research site is referred to as ELA in this report; future work will refer to IISD-ELA.

mercury levels in the air, aquatic, and terrestrial systems. These indicators can also show ecosystem recovery from exposure and uptake. In addition, mercury levels in species such as piscivorous fish, seabirds, and marine mammals can also be used as indicators of ecosystem recovery. How quickly fish mercury levels respond completely to changes in the ecosystem depends on terrestrial and direct atmospheric loads to the lake where the fish live, as well as on whether and where mercury concentrations in the aquatic system are transformed into methylmercury. Overall, lakes where mercury input is primarily from the air will take less time for fish mercury concentrations to respond than lakes where mercury loads from terrestrial sources are important.

In the air, mercury levels across Canada have declined as emissions have decreased, although this recovery varies among regions. Modelling results show that most of the atmospheric response to changes in domestic and global emissions takes place within 6 to 18 months, but it can take approximately 5 years for the atmosphere to equilibrate to these changes. The strongest recovery in the air is in areas close to emission sources such as in Flin Flon (Manitoba), Bratts Lake (Saskatchewan), Reifel Island (British Columbia), Point Petre (Ontario), and St. Andrews (New Brunswick), where mercury levels have declined up to 3.3%[10] per year. At these sites, declines in mercury levels have occurred more quickly than at sites that are impacted mainly by regional and global emissions. For example, in the Canadian high Arctic, the rate of decrease is significantly slower (approximately half as fast) than in temperate regions. Another source of mercury in air is re-emission of mercury previously deposited on the land and oceans. Reductions in these re-emissions are expected over various time scales, depending on the surface.

One way to assess the recovery of aquatic systems is to measure changes of mercury levels in piscivorous fish and wildlife species. In particular, fish, seabirds, and common loons have been used as indicator species in Canadian ecosystems. Mercury levels in fish living in water systems that have historically received direct inputs of mercury from industrial activity have declined since the implementation of mercury emissions controls. For instance, mercury levels of fish and wildlife in the Great Lakes region in Canada have largely declined over the last 4 decades, reflecting decreased air emissions in the region. For fish not directly impacted by nearby anthropogenic inputs, the estimated rate of change in mercury levels in fish, including standard-length lake trout, walleye, and northern pike, vary considerably, ranging between -1.5 and +1.5% yr$^{-1}$.

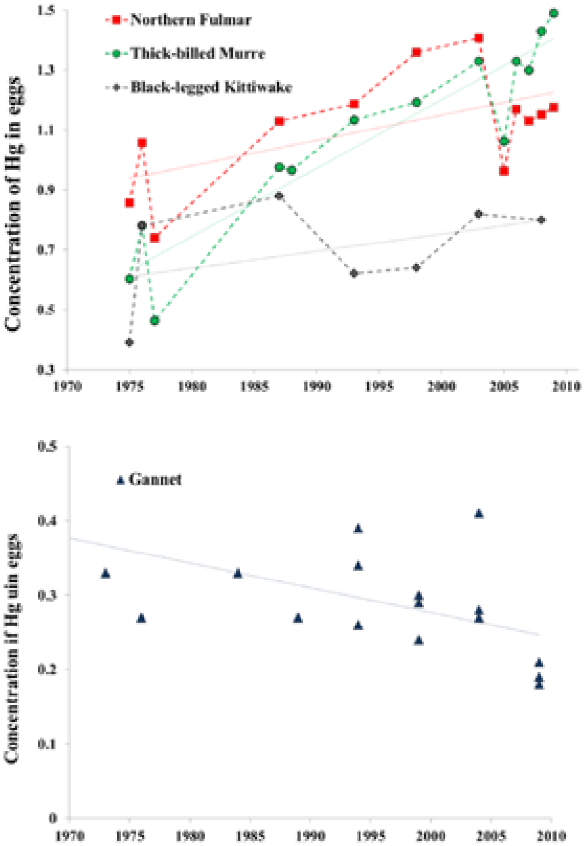

**Figure 10: Change in mercury levels in eggs of 3 seabird species from Prince Leopold Island, Nunavut (left: concentration μg g$^{-1}$ (dry weight)), and in seabird eggs from the Gulf of St. Lawrence (right: concentration μg g$^{-1}$ (wet weight)). Solid lines are linear trends.**

Mercury concentrations in indicator species such as seabirds in the Arctic suggest that levels are continuing to increase in the Arctic marine ecosystem; however, seabirds from other areas show decreases or stable levels, suggesting that those ecosystems are now less impacted by mercury. Dietary shifts in seabirds make the interpretation of trends more challenging. Figure 10 shows that mercury levels in Arctic seabirds have increased overall by 54% to 119% in the eggs of

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[10] Flin Flon was not included in this result.

black-legged kittiwakes, northern fulmars, and the thick-billed murres over 35 years. By contrast, it shows the decline in mercury levels in northern gannet eggs from the Gulf of St. Lawrence over 30 years.

In marine mammals, only beluga whales from the western Arctic show increases in mercury levels up to 2002 and declines since that time. Thus, this indicator species shows some signs of the recovery of this ecosystem over the past 10 years. However, for the most part, other marine mammal populations studied showed no signs of changes in mercury.

The integrated model developed for this assessment investigated the response time of fish mercury levels as an indicator of ecosystem recovery from changes in mercury emissions. Recovery depends on the response rates of many atmospheric, terrestrial, and aquatic processes. At the ELA, aquatic systems responded to decreases in mercury deposition by a decline in mercury levels over a long time scale. For terrestrial systems, there are no long-term records for observed mercury levels in streams, which are required to estimate their recovery time scale. The overall response time of an ecosystem is limited by those processes that respond most slowly, and the terrestrial system is the slowest step in the overall response of freshwater fish mercury levels to changes in mercury emissions. As noted, in lakes where mercury loading is primarily from the air, fish mercury concentrations will fully balance back to lower levels more quickly than in lakes where terrestrial mercury loading is important. For example, the Great Lakes primarily receive mercury from direct deposition from the atmosphere; therefore, observed declines in mercury levels in Great Lakes biota in recent decades are likely a result of decline in mercury emissions in the region. Lakes with a mix of terrestrial and atmospheric mercury input exhibit multiphase responses, with a quick response on a scale of years and a slow second phase on a scale of decades and possibly centuries. In addition to mercury loading to a lake, mercury concentrations within the lake take time to respond. Inorganic mercury concentrations in sediments may require decades to fully equilibrate, whereas the water column can respond within months.

## **c.** If not, what factors are confounding/ masking the expectation of recovery?

Mercury levels in Canada are not driven solely by domestic emission of mercury. The mercury cycle is multifaceted; thus, there are many factors complicating our ability to directly link reductions in Canadian emissions of mercury to levels in the ecosystem and biota. The main factors are emission sources, acidification, land-use changes, urbanization, eutrophication, and climate change.

Global and US emissions are larger than Canadian emissions, which make distinguishing between domestic and foreign impacts a challenge. Input from external mercury emissions can mask the recovery of an ecosystem from changes in domestic emissions. Further, anthropogenic emissions other than mercury can cause acidification of terrestrial and aquatic systems. The resulting acidic deposition from these other emissions enhances methylation of mercury and may mask (or hide) the impact of mercury emission reduction efforts. Changes in land use also impact the amount of mercury available within the ecosystem. For instance, newly formed reservoirs release mercury from the flooded area and enable it to enter the new aquatic system, where it is methylated. As well, eutrophication driven by agriculture and aquaculture can cause nutrient enrichment and increase the methylation potential of a given ecosystem. By contrast, urbanization removes the natural landscapes that enable methylation processes.

The largest unknown is the impact of climate change on the cycling and methylation of mercury. A warming climate, as well as changes in sunlight, in the amount of organic matter, in precipitation patterns, and in the frequency and intensity of forest fires will change the dynamics of the ecosystem and food webs. These changes may have serious impacts on how mercury is methylated within the system and how it is taken up by biota. Some areas are projected to experience increased precipitation, runoff, and soil moisture levels, which would likely change the production rates and mercury loads to the system. Increased watershed nutrient loads and primary productivity in aquatic systems under warmer and wetter conditions could partially offset other factors that increase fish mercury levels. In regions such as the Arctic, changes in climate affect sea ice cover, which impacts how much mercury is transformed, deposited, and retained. Currently, it is very difficult to make accurate statements about future national trends in mercury processes and levels in biota resulting from climate change.

## **d.** Can predictions be made regarding the impact of future changes in atmospheric emissions on mercury levels in deposition and methylmercury levels in biota?

The impacts of changes in mercury emissions on deposition and methylmercury levels in fish are generally predicted through models. Using the GRAHM model, future changes in mercury levels in the air and in deposition have been predicted using various emission reduction scenarios from different regions such as Canada, the United States, Asia, and Europe, separately and in combination. The "best case scenario"[11] of worldwide controls on anthropogenic emissions resulted in predicted reductions in mercury deposition of 20%–50% among modelled ecosystems. Model scenarios involving reductions in Canadian anthropogenic emissions[12] resulted in minimal (1%) reduction in atmospheric deposition (mercury deposited from the air) in remote ecosystems, but up to 70% reductions for ecosystems close to major Canadian mercury emission sources.

A suite of process-based atmospheric, terrestrial, aquatic, and bioaccumulation models was integrated into a single framework for this assessment

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[11] The "best case scenario" is the Maximum Feasible Technological Reduction (MFTR), which assumes that all available technological methods of reducing anthropogenic Hg emissions are implemented globally in all sectors.

[12] 90% capture rate of emissions from coal-fired facilities or 50% emission reduction for all sectors.

to simulate the effects of different emission reduction scenarios on fish mercury levels in lakes. The integrated ecosystem model simulated the relationships among mercury emissions, atmospheric cycling and deposition, export to lakes from land, mercury cycling within lakes, and bioaccumulation in fish. The integrated model was applied to 5 lake ecosystems in different regions of Canada. Figure 11 shows an example of the application of the model to 2 lakes: Wabamun Lake, Alberta (a lake close to local mercury emissions from coal-fired facilities), and Lake 240, in the ELA in Ontario (a remote lake), using 2 emission scenarios: (1) the “best case” scenario of emission reductions and (2) “no additional emissions controls” scenario. The model predicted that, in the absence of additional emissions controls above current levels, in the future fish mercury concentrations will rise above current levels in all the lakes modelled. Implementing any of the emissions controls scenarios resulted in lower future fish mercury levels compared to the “no additional emissions controls” scenario (up to 30% for the lakes investigated after 150 years for the “best case” scenario). While the models showed that emissions controls are beneficial compared with no action, even the best case mercury emissions controls would not lower fish mercury concentrations in all watersheds below current levels. If mercury deposition decreased modestly, fish mercury levels would decline in some ecosystems systems, remain stable in some ecosystems, or continue to rise and stabilize at higher levels in others. Therefore,

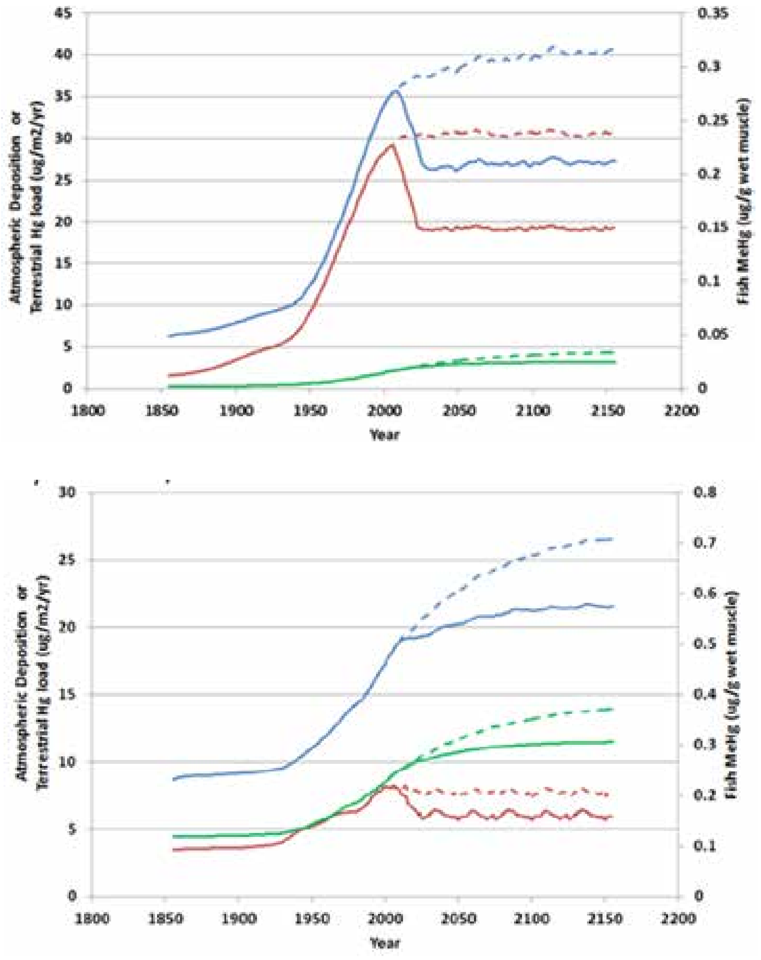


**Figure 11: Predicted atmospheric mercury deposition (red), mercury levels in lake inflow streams (green), and fish mercury levels (blue) from the year 1840 to 2156 in 2 lakes investigated. Solid lines are associated with the “best case scenario” for emissions controls, applied starting in 2007, and the dashed lines are associated with the scenario in which no additional emissions controls are implemented. Top: Wabamun Lake, Alberta (close to mercury emissions from coal-fired power plants); bottom: Lake 240, Experimental Lakes Area, Ontario (remote lake).**

significant global-scale reductions in mercury emissions would be required to broadly reduce fish mercury concentrations below current levels across Canada.

The ecosystem modelling conducted in this study and the results presented here consider only the impact of changes in anthropogenic emissions on mercury levels in the ecosystems. Other environmental changes, such as land use, climate, other air pollutant emissions and environmental chemistry or biology, can alter the biogeochemical transformations of mercury in the ecosystems and, therefore, influence mercury levels in Canadian ecosystems.

### Question 4:

### What are the linkages between other air pollutant emissions (*e.g.*, acidifying emissions, greenhouse gases, etc.) and mercury accumulation in biota?

**Atmospheric emissions of greenhouse gases and acid precursors can be linked, under some circumstances, to enhancement of methylmercury in aquatic ecosystems and subsequent accumulation of mercury in biota.**

Mercury goes through a complex cycle in the ecosystem from emission to accumulation in biota. Many factors affect the multiple processes throughout the cycle. The main driver of Hg accumulation in biota is the formation and availability of methylmercury in the ecosystem. The main environmental factors that affect methylation of mercury include temperature, pH, and sulphur, nitrate, and oxygen conditions, all of which are affected by industrial emissions.

Increases in greenhouse gas emissions have resulted in changes in the global climate, with temperatures predicted to increase across Canada in the 21st century. Climate change could act to either increase or decrease fish mercury levels, depending on the conditions of the ecosystem. Hence, it is impossible to make simple overarching statements about expected national trends in fish mercury levels as the climate changes. Regions that are projected to be warmer and experience increased precipitation, runoff, and soil moisture levels would likely experience increased mercury loading from the atmosphere and terrestrial systems. In turn, this may increase microbial activity and the rate of production of methylmercury. On the other hand, under warmer and wetter conditions, other factors (increased watershed nutrient loads, primary productivity, and faster growth rates of fish in aquatic systems) may offset the increases in fish mercury levels. Sensitive areas such as northern Canada are already witnessing effects of a warming climate, predominantly through changes in sea ice patterns, which may affect the deposition of mercury in the spring. Changes in temperature are expected to accelerate in the future, and precipitation and moisture levels are expected to increase. Hence, mercury cycling and bioaccumulation (especially in the Arctic) could be affected by increases in greenhouse gases and the resulting changes in global and regional climate.

Acidification of Canadian waters has contributed to the current high concentrations of mercury found in fish and other biota in some regions of the country. More acidic (lower pH) aquatic conditions generally lead to higher methylmercury levels in biota. Refining fossil fuels, burning coal, and metal smelting emit mercury and associated acid precursors, such as sulphur dioxide and nitrous oxides, to the air. Acid deposition from these sources leaches mercury from soils to aquatic systems and can cause an overall decrease in water pH. The lower pH and higher concentrations of metals found in acidic waters increase the uptake of toxic metals in biota, affecting the growth, survival, and reproduction of fish, invertebrates, and primary producers and pose a major threat to aquatic biodiversity. Further, bacteria in lake sediments produce methylmercury when little to no oxygen is present (for example, because of eutrophication of lakes). Therefore, measures aiming to control acid precursor emissions will indirectly contribute to reducing mercury bioaccumulation in aquatic biota. The acidification of aquatic systems that lack properties to buffer acid is long-lasting and may continue for decades after acid emissions controls have been implemented. It is unclear how much of the recent decreases in mercury concentrations in fish in Canadian lakes can be attributed to decreased acid emissions or to other environmental factors. However, controlling acid emissions in Canada will limit atmospheric mercury emissions, which will ultimately lead to reduced mercury methylation in these aquatic systems.

## Question 5:

How might changes in other human activities (*e.g.*, land-use practices) affect the distribution of mercury between environmental compartments, methylmercury formation, and the accumulation in biota?

**Human activities such as logging, reservoir impoundment, mining activities, and activities causing eutrophication can affect the transport of mercury, increase the methylation of mercury, and enhance mercury bioaccumulation in biota.**

Human activities unrelated to mercury emissions can induce long-term environmental changes influencing mercury transport, methylation, and bioaccumulation in aquatic organisms. These activities include logging, mining, reservoir creation, agriculture, and urbanization (including sewage). These human factors may alter not only the bioavailability of recently released anthropogenic mercury but also that of natural mercury already present in the environment, which would otherwise be unreactive if left undisturbed.

Logging activities have important consequences for mercury input to nearby small lakes, where increased levels of mercury in biota have been reported. Smaller lakes are more impacted than larger lakes by soil disturbance resulting from logging activities. In larger lakes, other environmental activities tend to offset these disturbances. Mining activities have been responsible for long-lasting mercury contamination of aquatic organisms in productive lakes. Mercury from mining is generally released in an insoluble inorganic form, and certain aquatic conditions are required for the mercury to be methylated. However, the combination of mining, eutrophication resulting from urbanization, and extensive logging on the watershed of small lakes may result in optimum conditions for methylating large amounts of mercury in surface sediments, and these conditions may last for several decades. Thus, while mining may not be a direct source of methylmercury, mine wastes with elevated levels of mercury should not be placed near lakes with a high potential for mercury methylation. Particular attention should be placed on lakes and rivers located near towns with a history of gold and mercury mining where local residents often fish.

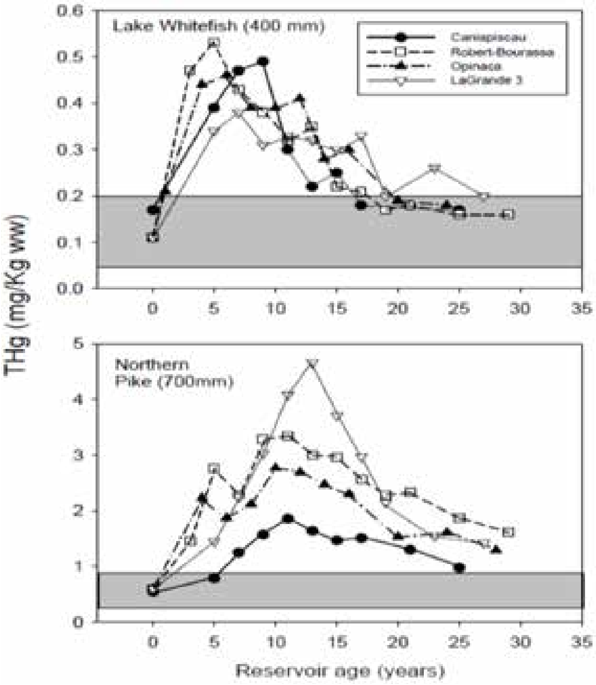


**Figure 12: Mercury levels in fish from newly created reservoirs in northern Quebec.**

The creation of reservoirs often increases concentrations of methylmercury in fish and other biota. New reservoirs result in large areas of terrestrial vegetation being flooded, leading to decomposition of the vegetation and stimulation of microbial activity, including bacteria that methylate mercury. The establishment of reservoir impoundments creates a sharp increase in methylmercury levels in predatory fish, which continues for several decades (20–30 yr), before levels start to decline to normal levels (Figure 12 as an example). Concentrations of methylmercury in fish populations within reservoirs often exceed consumption guidelines, and human exposure to this contaminant through fishing has caused concern in Canada, especially in northern communities. As well, levels of mercury in fish are frequently elevated in rivers and lakes downstream of new reservoirs. In whole-ecosystem experiments conducted at the ELA, the creation of small experimental reservoirs resulted in large increases in methylmercury.

Eutrophication is caused by inputs of nitrogen and phosphorus to waterways, largely from agricultural fertilizer and manure, human sewage, and a variety of urban activities. Eutrophication can stimulate productivity in aquatic systems, which leads to the enhancement of mercury methylation. The levels in organisms living in most highly eutrophic systems are low, but moderate eutrophic conditions are responsible for higher rates of mercury methylation and uptake by aquatic organisms that can last for several decades.

Overall, several land-use activities affect mercury bioaccumulation in aquatic organisms. Human vulnerability to the presence of mercury in Canadian aquatic systems is a real concern. In planning land uses that can increase mercury levels in waterways, special emphasis should be placed on the lakes and rivers most frequently used for fishing and hunting, including even occasional sport fishing, food sources for native communities, and subsistence hunting.

## Question 6:

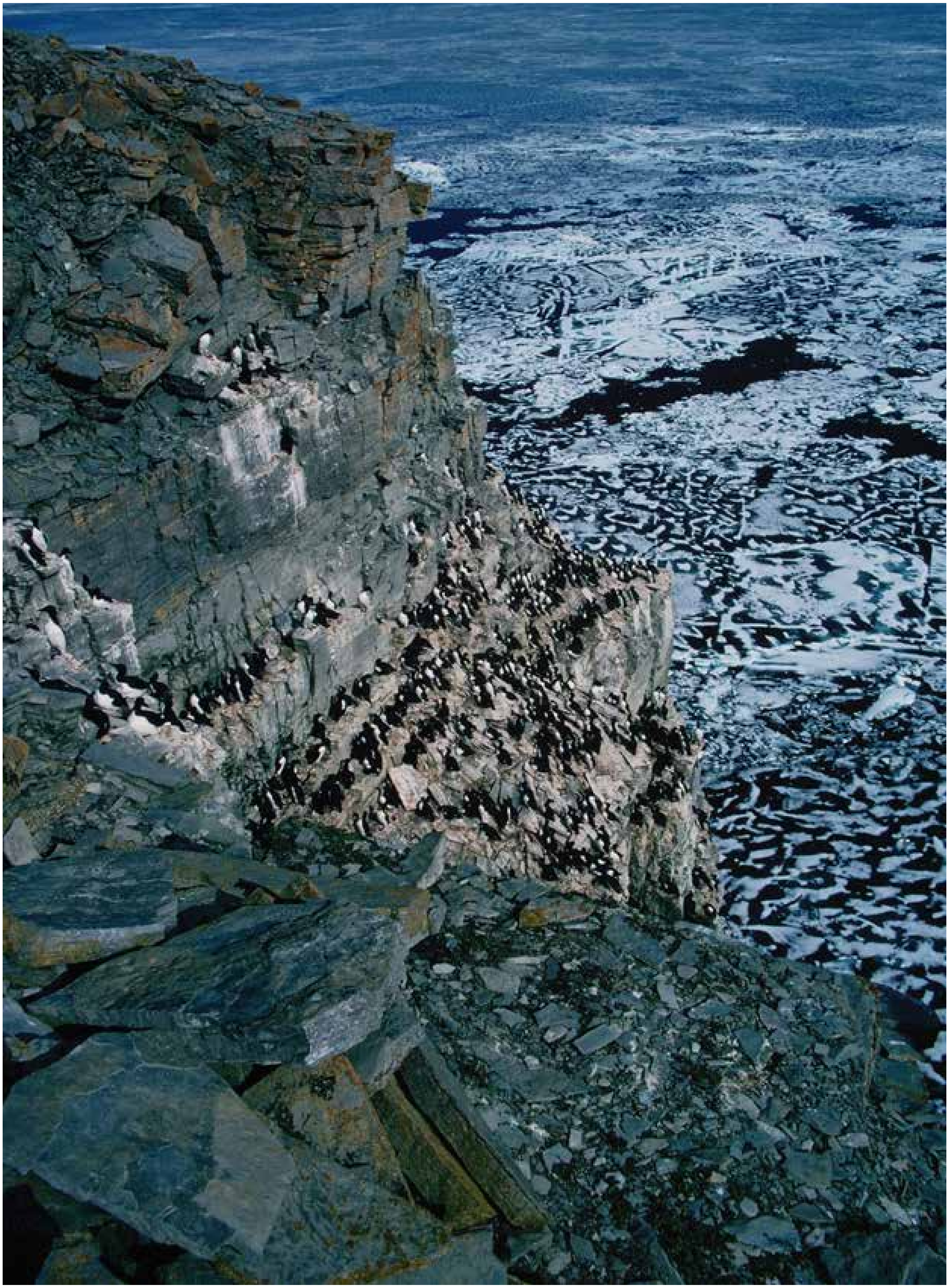
In light of our current understanding of mercury in the Canadian environment, where, and to what extent, do we need to continue atmospheric and effects monitoring?

**Monitoring of mercury should continue in Canada.**

**Monitoring of air levels and astmospheric deposition needs to be increased.**

**Long-term monitoring of predatory fish and birds, as well as some terrestrial and marine mammals, needs to be increased.**

Long-term monitoring is necessary to know whether changes in mercury emissions are having an impact on the mercury levels in Canadian ecosystems. To adequately respond to long-term impacts on the Canadian environment, it is recommended that: 1) current efforts to monitor mercury in the atmosphere, in deposition, in lake/marine environments, and in biota continue or increase; 2) selected research efforts for mercury in abiotic (non-living) and biotic (living) systems be initiated or increased to target areas and species that have been identified to be at risk and 3) new technologies for monitoring must be developed to increase spatial coverage and minimize, when possible, costs of monitoring. It should be taken into consideration that multidisciplinary research efforts and monitoring of trends and effects should be combined and undertaken at the same locations, where possible.



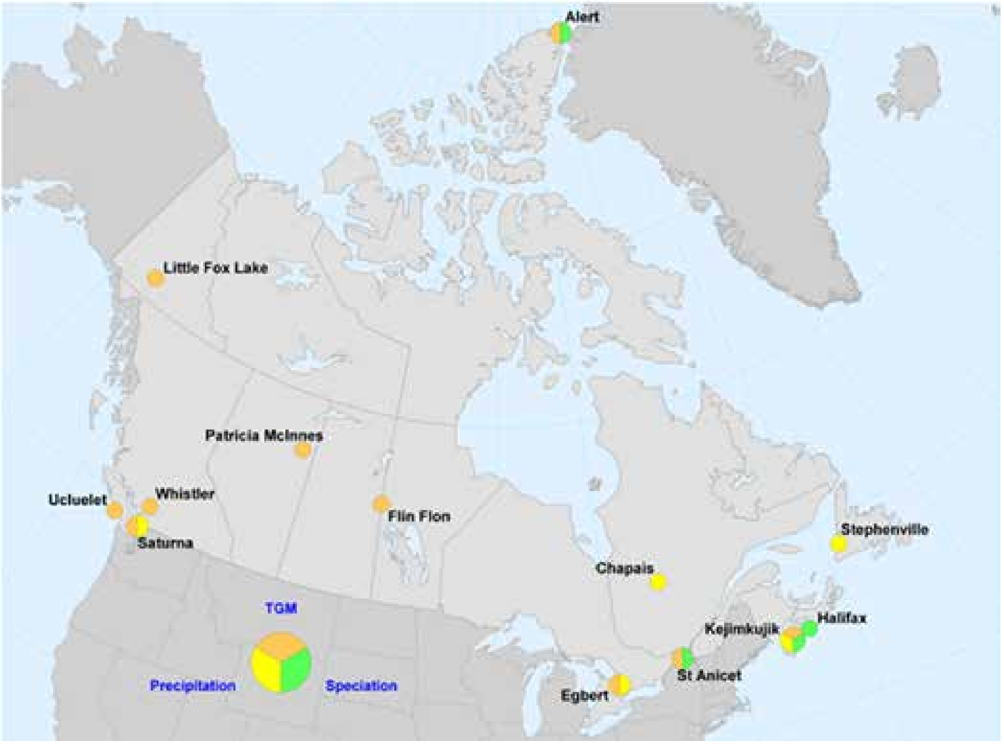


Figure 13a: Map of the 2014 atmospheric mercury monitoring and wet deposition (precipitation) sites in Canada.

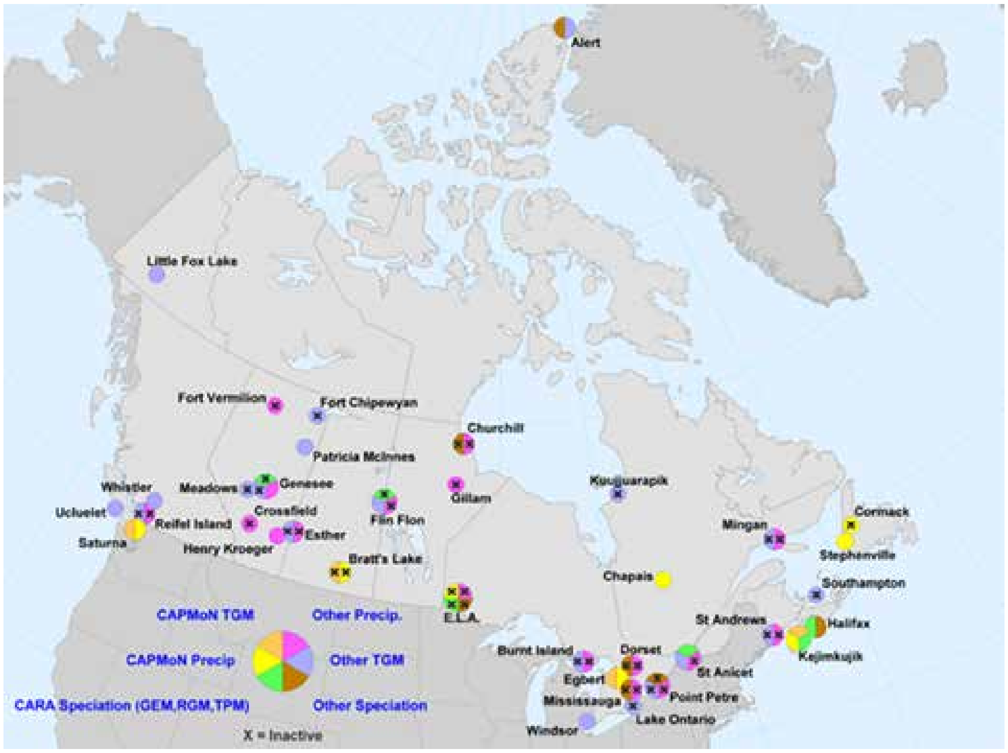


Figure 13b: All sites of atmospheric mercury monitoring in Canada from 1995 to 2014. A full list of the time coverage for each site can be found in the full science assessment Chapter 4: Section 4.3.

### a. What are the most promising environmental indicators of reductions in anthropogenic emissions of mercury?

Environmental indicators that have been used to monitor anthropogenic mercury reductions in Canada include levels in air; wet deposition; lakes, rivers, and oceans; surface emissions; sediments; wetlands; mammals, piscivorous fish and birds; and insectivores. Each of these indicators provides a different aspect of understanding mercury issues in the Canadian environment.

## Atmospheric mercury

The air is the first place to identify changes in emissions of mercury. Currently[13], measurements are in operation by Environment Canada at the following 10 sites: Alert (Nunavut), Whistler (British Columbia), Little Fox Lake (Yukon), Saturna (British Columbia), Ucluelet (British Columbia), Patricia McInnes (Alberta), Flin Flon (Manitoba), Egbert (Ontario), St Anicet (Quebec), Kejimkujik (Nova Scotia); these sites and type of measurements made are shown in Figure 13a. A map of all atmospheric mercury measurements that have been collected in Canada over various time periods between 1995 and 2014 is shown in Figure 13b.

Atmospheric monitoring is undertaken to address several different goals including: (1) to measure the input levels of mercury to ecosystems; (2) to measure ambient levels resulting from domestic and regional emission sources; and (3) to assess transboundary transport of mercury into Canada.

1) To measure atmospheric input/deposition into vulnerable Canadian ecosystems atmospheric monitoring should be continued or enhanced at Kejimkujik, Flin Flon, Ucluelet, International Institute for Sustainable Development - Experimental Lakes Area (IISD-ELA), the Great Lakes region, the Arctic region, resource development areas, and areas close to emission sources.
2) To measure ambient levels resulting from domestic and regional emission sources monitoring should be continued or enhanced at Kejimkujik, Flin Flon, Windsor, St.Anicet, Saturna, the Great Lakes region, the Arctic region, resource development areas, and areas close to emission sources.
3) To assess transboundary transport of mercury monitoring should be continued or enhanced at Kejimkujik, Whistler, the Arctic region, and the Great Lakes region.

Mercury is neither created nor destroyed but is only transformed in the environment; thus, several forms of mercury (termed *speciated mercury*[14]) must be investigated. Current measurements of speciated atmospheric mercury provide some indication of the transformation and deposition of mercury. At this time (2014), 4 sites in Canada collect these measurements: Alert, St. Anicet, Kejimkujik, Halifax, and the oil sands region (see Figure 13a). More monitoring and research to identify these species is required to entirely understand atmospheric transformation and deposition of mercury. Atmospheric deposition is the main pathway for the introduction of mercury to watersheds, and thus air levels need to be understood to follow the pathways through the environmental compartments. Wet deposition of mercury is a good indicator of changes in the mercury load from the atmosphere to the environment. Currently, Environment Canada operates 5 wet-deposition monitoring sites: Stephenville, Kejimkujik, Chapais, Egbert, and Saturna (see Figure 13a). Additional monitoring

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[13] September 2014

[14] Currently, there is uncertainty in identifying which Hg compounds make up the various atmospheric Hg species; thus, they are defined operationally. There are also limitations in the current measurement methods.

is recommended in areas where modelled trends indicate recent increases in wet deposition, notably in the Arctic, the west coast of Canada, and areas of increased resource development. Dry deposition measurements are not yet routine but are included as part of recommended activities.

New technologies are emerging to aid with monitoring and evaluating declines in mercury emissions. Passive samplers (samplers requiring no power) are being developed to increase spatial coverage in Canada to better assess mercury levels across the country. As well, new techniques employing the isotopic fractionation of mercury are being developed to assess source regions of atmospheric mercury. The research and development for these potential monitoring tools should be encouraged for future implementation.

## Terrestrial and aquatic mercury

Mercury found in lake sediments, ice cores, forests, and peat bogs is a good indicator of changes over time. However, the information gathered from these samples does not allow differentiation between mercury that is produced through deposition or biogeochemical processes. Lichen and mosses are the only terrestrial vegetation that absorb and accumulate appreciable amounts of mercury, although their use as a good indicator for mercury is uncertain. Currently, there is a lack of programs, outside of the METAALICUS program, investigating terrestrial system mercury deposition indicators in Canada. Further, there are few long-term measurements of mercury in lakes, rivers, and oceans in order to ascertain changes in deposition or inputs from watersheds. It is recommended that terrestrial and aquatic monitoring be initiated in conjunction with other measurements to allow integration of information from all systems.

## Biota

Monitoring mercury in biota in Canada should reflect the following overall objectives: (1) monitoring the species that are most likely to show adverse health effects due to mercury exposure; (2) monitoring mercury in species that would reflect changes in atmospheric mercury deposition, and (3) monitoring mercury trends that are important in consumption

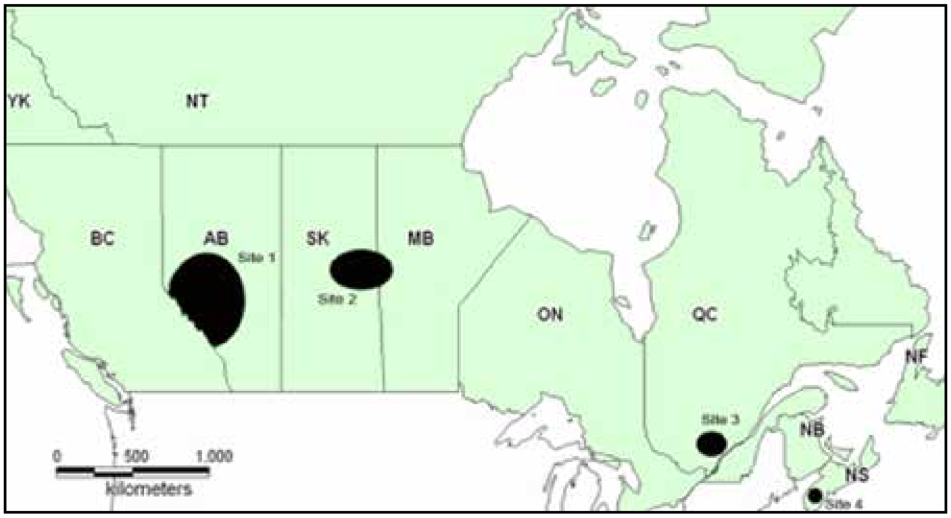

Figure 14: Locations of CARA fish and wildlife mercury study sites.

and exposure. Further, the key species chosen for long-term monitoring should meet the following criteria: (1) be resident in Canada, (2) accumulate measurable concentrations of mercury, (3) be easily sampled, and (4) have a reasonably stable or small home range.

Bearing these considerations in mind, several animal species are recommended for long-term mercury monitoring in Canada, specifically for freshwater (mink, common loon, walleye, northern pike, lake trout, Arctic char), marine (seabirds, mussels, marine fish, seals, beluga whales, polar bears), and terrestrial (caribou, little brown bat) environments.

Piscivorous fish are good indicators of methylmercury exposure, in particular predatory fish such as lake trout, northern pike, and walleye. The common loon is perhaps the most studied avian species with respect to methylmercury toxicology in Canada. New mechanisms need to be developed throughout Canada to encourage monitoring of mercury concentrations using consistent methods in fish and wildlife. Such mechanisms should be coordinated among federal, provincial, territorial, and Aboriginal government agencies, universities, and non-governmental organizations.

For monitoring of aquatic ecosystems, multidisciplinary work at recommended sites should be undertaken. The first CARA Mercury Science Program conducted research on biota at the 4 sites shown in Figure 14. We recommend that enhanced measurements be undertaken at Flin Flon, IISD-ELA, Kejimkujik, sites in Ontario/Quebec and at the ELA.

### b. What are the most promising indicators of ecosystem recovery?

Whole-system monitoring of mercury over time is a valuable method to assess the changes in ecosystems and their recovery from mercury exposure. Mammals, predatory fish and sea birds are good indicators of biotic exposure to mercury in aquatic environments. For example, sea birds are currently being monitored on a regular basis by Environment Canada in the Pacific, Atlantic and Arctic marine regions. Comprehensive studies such as the Great Lakes Basin Mercury Assessment and the Canadian Arctic Contaminants Assessment Report are excellent tools to assess overall ecosystem recovery that can be used to improve integrated models including air, earth, and water, as well as biology, geology, and chemistry. National-scale investigations, such as a Canada-wide fish survey for mercury are a valuable indicator of recovery.

An effective national mercury monitoring program could make use of existing programs for mercury monitoring and for sampling biota for other purposes (other contaminants, biological indices, and health monitoring). This type of national coordination would include only a few changes to existing protocols and could operate at minimal extra cost. Local hunters, trappers, fishers and provincial monitoring programs of sport fish also provide a valuable and cost-effective resource for sample collection; working with them has the added benefit of involving stakeholders in these monitoring programs. A strong, coordinated, national leadership that engages partners from all aspects of wildlife management, research, and use will be the key to the success of this initiative.

## Question 7:

### Where, and on what, should we focus future research efforts for mercury?

**Future research efforts for mercury in Canada should build on currently successful programs and should emphasize the development of nationally led integrated programs that address priority gaps of knowledge.**

Canada has been successful at conducting research and monitoring on the environmental and health processes of mercury over the past decades; however, many unknowns remain. This scientific assessment on mercury in Canada has led to the recognition of several detailed priority gaps of knowledge and has provided scientific recommendations for focus areas and future research. Some of these gaps are as follows:

- Overall impacts of climate change and land-use changes on the mercury cycle remain uncertain

- There remains a lack of adequate, long term, coordinated, integrated and dedicated monitoring of mercury in Canada for air, water and biota
- An increase in detailed information on reported emissions to the National Pollutant Release Inventory is required
- There is a shortage of knowledge on emissions of mercury from surfaces and the impact of these emissions and re-emissions on Canadian inventories
- There is a lack of understanding of the factors affecting methyl mercury production and promotion into aquatic food webs in Canadian ecosystems
- Mercury dynamics in the terrestrial ecosystem represent the highest uncertainty in Canadian ecosystems
- Characterization of atmospheric mercury species and their deposition remains unknown; this continues to limit predictive capabilities of current models
- The number of exposure studies of mercury needs to be increased in infants and children less than 6 years of age, particularly for First Nations infants
- There is a lack of information on the relationship between methyl mercury exposure and cardiovascular and renal diseases, and immunologic and carcinogenic effects

Several recommendations from this assessment report are as follows:

- An effective nationally coordinated mercury monitoring program for sampling key indicators should be initiated
- Integrated ecosystem research on mercury needs to be coordinated and conducted
- A more detailed evaluation of the impacts of climate and land-use changes on the cycling and uptake of mercury is required
- Detailed process research on deposition, terrestrial and ocean cycling, methylation and surface emissions should be prioritized
- A comprehensive evaluation of the mercury emissions reported to the NPRI is required
- Continued biomonitoring and follow-up studies to monitor trends of methyl mercury exposure is recommended, especially for vulnerable populations
- Emphasis on proper communication of the risks of mercury exposure and the nutritional and socioeconomic benefits of fish and traditional wildlife food consumption should be made

A detailed summary of the gaps of knowledge and recommendations for future research can be found in Chapter 15.

# ASSESSING MERCURY IN CANADA

The Science Assessment is structured to follow mercury through the ecosystem from source to sink. It begins with anthropogenic emissions of mercury, followed by a discussion of the many processes that mercury undergoes, including surface exchange, atmospheric, aquatic, terrestrial, and marine processes. A discussion of how human activities impact mercury dynamics is followed by a description of the modelling work that depicts the ecosystems response to mercury inputs. Spatial and temporal trends of mercury levels in biota are presented and are followed by an analysis of the biological effects of mercury and the ecological risk of mercury to select species. The assessment concludes with an analysis of the human exposure to mercury, health effects and risk management measures in Canada.

## Highlights of individual chapters

### Chapter 2: Releases of Mercury Into Air and Water From Anthropogenic Activities in Canada

Coordinating author: Gregor Kos

In 2010, Canadian mercury emissions were reported to be 5 300 kg to air and 240 kg to water. Canadian air emissions are small in comparison with those from other major mercury-emitting countries (for example, approximately 35% of US levels in 2008 and 1% of levels in China in 2010). Releases to air and water in Canada have decreased from 1990 to 2010 by 85% for air and about 50% for water. While these numbers reflect significant decreases, there remains considerable uncertainty in these estimates (up to 50% uncertainty for legacy emissions). Control technologies that have been implemented in Canada to reduce emissions for a variety of pollutants have resulted in the lowering of mercury emissions. Canadian mercury emissions are expected to stabilize in the future.

## Chapter 3: Surface Fluxes

### 3a: Factors Affecting Mercury Emissions from Canadian Soils

Coordinating author: Nelson J. O'Driscoll

Mercury is emitted naturally from soils to the air. These emissions are an important part of the global mercury cycle, contributing an estimated 700–2 000 Mg $yr^{-1}$ to the global atmosphere. Mercury emissions from Canadian soils depend on the make-up and mercury content of the underlying geology. Emissions range from -0.3 to 91.8 ng $m^{-2}$ $h^{-1}$. Currently, accurate national estimates of mercury emissions and re-emissions from soils to the air cannot be made because of a lack of empirical data; thus, estimates are based on mercury cycling models. Of the few soils studied in Canada, those in certain areas of Ontario and British Columbia have much higher emissions of mercury than study locations in the United States, Brazil, and Sweden. In fact, some mineralized soils and shale rock from Ontario and cinnabar from British Columbia have the highest mercury emissions measured from any soils in the world. By contrast, background and agricultural soils in Ontario and Nova Scotia have the lowest mercury emissions of soils that have been studied to date. Factors that affect the emission of mercury from soils include soil moisture and temperature, solar radiation, organic matter content, and microbes in the soil.

### 3b: Total Mercury Concentrations in Stream and Lake Sediments Across Canada

Coordinating author: Paul A. Arp

Mercury levels in stream and lake sediments vary across Canada by region and from one location to another. Mercury concentrations in sediments decrease from south to north, are low in barren and ice-covered landscapes, and are somewhat correlated with the modelled atmospheric mercury deposition patterns. Levels tend be high in areas where substantial deposits of natural mercury erode into the surfaces and stream banks. Sediment mercury levels are highest downstream from current and past mining and smelting activities and lowest in the Arctic and high alpine areas. Mercury accumulations differ from stream to lake sediments, with the latter containing more organic matter, thus enabling Hg methylization and thereby stimulating MeHg uptake by biota.

### 3c: Mercury in Forest Soils and Vegetation, Including Mosses and Mushrooms – A Case Study

Coordinating author: Paul A. Arp

This chapter summarizes how mercury deposited from the air accumulates in undisturbed forested areas, using a recent case study. The accumulation of mercury gradually increases to areas such as canopy foliage, mosses, fungal mycelia, or soil substrates with increasing exposure time. While some fungi (such as boletes) are mercury hyper-accumulators, others (such as chanterelles) are not; the difference is due to increased mycelial longevity and extent. Mercury concentrations increase sharply within the accumulating forest litter, and mercury generally remains within the mineral soil for 1 000 or more. Local mercury sources from geological processes further add to the mercury loads in forest soils and vegetation. However, root uptake of mercury by forest vegetation and transfer of this mercury into wood is low. As a result, most of the mercury in forested catchments remains in the forest soil and litter.

## Chapter 4: Atmospheric Processes, Transport, Levels, and Trends

Coordinating author: Alexandra Steffen

Considerable research, monitoring, and modelling have been conducted to understand atmospheric processes affecting mercury in Canada. Mercury undergoes several chemical and physical transformations in the air that lead to enhanced deposition. The Arctic is especially vulnerable to mercury deposition because of its unique chemistry, which results in precipitation of mercury from the air to the snow and ice during the spring. While measured levels of mercury have decreased since 1995 across Canada, the decreases are not the same in all regions. Greater decreases are found in regions that have experienced large decreases in anthropogenic emissions such as urban areas, Flin Flon, Manitoba, and the Great Lakes region. Levels of mercury in precipitation have also declined at most sites in Canada since the mid-1990s. Wet deposition amounts across Canada were simulated for 2006 and were fairly uniform across the country except for localized areas of high mercury deposition along the west coast and in coastal areas in the western Arctic and sub-Arctic. Using modelling, it is estimated that 40% of the deposition in Canada comes from worldwide anthropogenic emissions and 60% from other terrestrial and oceanic emissions (including geogenic emissions/re-emissions of previously deposited mercury). From the model, it is estimated that over 95% of the anthropogenic mercury deposited in Canada comes from sources outside of the country (40% from East Asia, 17% from the United States, 8% from Europe, and 6% from South Asia). In northern and western Canada, the total contribution to annual deposition from anthropogenic and other terrestrial emissions from East Asia (24 to 26%) is twice as high as the total contribution from the United States (7 to 12%). In comparison, in eastern Canada the total contribution from anthropogenic and other terrestrial emissions from East Asia (20 to 23%) is comparable to the total contribution from the US (15 to 22%).

## Chapter 5: Mercury Fate and Methylation in Terrestrial Upland and Wetland Environments

Coordinating Author: Vincent St. Louis

This chapter describes the current state of knowledge about the transport, transformation, and fate of mercury in undisturbed terrestrial ecosystems in Canada. The chapter highlights the complex array of factors that ultimately control methylmercury production and transport to water bodies. Mercury deposited from the air remains in vegetation until it enters upland and wetland soil pools, where it may be stored for long periods of time or methylated and transported downstream. This chapter also highlights the uniquely Canadian processes controlling mercury accumulation and release from snowpacks, as well as changes in soil mercury storage due to wildfire.

## Chapter 6: Mercury Fate and Methylation in Freshwater Aquatic Ecosystems

Coordinating Author: Vincent St. Louis

In Canada, ponds, wetlands, and small shallow lakes tend to have higher methylmercury concentrations than larger, deeper lakes. Methylation (methylmercury production) is carried out primarily by micro-organisms such as sulphate-reducing bacteria, iron-reducing bacteria, and methanogenic archea. Demethylation (methylmercury destruction) can be caused by photochemical or microbial processes and is important for reducing methylmercury available to aquatic organisms. Methylation of mercury is determined by how much mercury is available to methylating micro-organisms and how efficiently the micro-organisms can convert mercury to methylmercury. Production of methylmercury in bottom sediments and the water column, as well as inputs of methylmercury from wetlands, are the primary sources of methylmercury in lakes. Inputs of methylmercury from upland terrestrial catchments and the atmosphere are less important. Photochemical destruction in lake waters and loss through outflows are the primary mechanisms for removing methylmercury from lakes, which helps to decrease exposure of aquatic organisms and foodwebs.

## Chapter 7: Mercury in the Marine Environment: Processes and Levels

Coordinating author: John Chételat

Marine animals are important dietary items that expose many Canadians who rely on them as a major food source to methylmercury. Mercury from anthropogenic emissions and natural sources enters Canada's marine environments by long-range atmospheric transport, ocean currents, coastal erosion, and rivers. The relative importance of these pathways of mercury transport differs among marine ecosystems in Canada. Methylmercury production in the marine water column is likely important, and, in coastal regions, sediments are also production sites. Methylmercury is found in seawater at ultra-low levels; however, its biomagnification through long food chains in the marine environment can result in elevated concentrations in predatory fish, mammals, and seabirds.

## Chapter 8: Influences of Anthropogenic Activities on Mercury Transport, Methylation, and Bioaccumulation

Coordinating author: Marc Lucotte

In addition to point-source releases of mercury and atmospheric deposition, several anthropogenic activities may also influence its transport, methylation, and bioaccumulation in aquatic organisms. These activities therefore contribute to mercury levels in terrestrial and aquatic environments in Canada. This chapter describes the effects of anthropogenic activities such as land use and land-use changes, eutrophication, acidification, and climate change. These may affect the dynamics of recently released anthropogenic mercury and of natural mercury in the environment. Reservoir impoundments will continue to contribute to enhanced mercury levels in predatory fish for several decades. Mining activities are responsible for long-lasting mercury contamination of aquatic organisms, especially in nutrient-poor lakes). Eutrophication leads to enhanced growth rates in fish and higher mercury biodilution. It therefore does not lead to increased methylmercury levels in aquatic organisms except in newly, impounded reservoirs. Acid emissions and deposition can lead to acidification of lakes, which leads to increased methylmercury levels in aquatic systems and biota. The predicted influences of climate change on the mercury cycle could increase or decrease mercury levels in fish, depending on ecosystem conditions. The areas in Canada most vulnerable to the impact of climate change on mercury processes are the sub-Arctic and the Arctic.

## Chapter 9: Mercury Cycling in Ecosystems and the Response to Changes in Anthropogenic Mercury Emissions

Coordinating author: Ashu Dastoor

A suite of computer models for atmospheric, terrestrial, aquatic, and bioaccumulation processes was integrated into a single framework and used to simulate the effect of different emission reduction scenarios on fish mercury levels in Canadian lakes. The size of change and the time required for fish mercury concentrations to fully respond to emission reductions varied among ecosystems. The model predicts that, without additional emissions controls, fish mercury levels will rise above current levels in all lakes investigated. Emissions controls will result in lower future fish mercury levels compared with no emissions controls in the lakes investigated. However, lakes will take years to centuries to fully respond to emissions reductions, depending on the characteristics of the catchment. The “best case scenario” of worldwide anthropogenic emissions controls (all available methods of mercury emission reduction) result in a 20–50% reduction in mercury deposition to ecosystems and will lower fish mercury levels up to 30% after 150 years when compared with the “no emission reductions” scenario. However while beneficial, the “best case scenario” would not decrease fish mercury concentrations in all watersheds below current levels. Mercury levels will decline in some ecosystems systems, remain stable in some systems, and continue to rise and stabilize at higher levels in others. Greater global-scale reductions in mercury emissions are required to broadly reduce fish mercury concentrations below current levels across Canada.

## Chapter 10: Mercury in Terrestrial and Aquatic Biota Across Canada: Geographic Variation

Coordinating author: Neil Burgess

Data on mercury concentrations in Canadian plants and animals have been collected for decades. More mercury data exists for animals than plants, and more data for aquatic animals than terrestrial animals. Predatory fish and wildlife at the top of freshwater and marine food webs generally have the highest mercury concentrations due to biomagnification. In the southern portion of Canada, mercury concentrations generally increase from west to east across the country. Mercury concentrations in common loon, bald eagle, great blue heron, osprey, lake trout, walleye, northern pike, whitefish, and yellow perch all tended to be highest in southeastern Canada. A different geographic pattern was observed in the Arctic. Mercury concentrations tended to be higher in the western and high Arctic for ringed seal, polar bear, and beluga whales (with a few exceptions).

## Chapter 11: Mercury in Terrestrial and Aquatic Biota Across Canada: Temporal Variation

Coordinating Author: Mary Gamberg

This chapter presents the current knowledge of changes over time in mercury concentrations in biota in Canada. No overall consistent trends were seen, geographically or by trophic position. For example, mercury concentrations are increasing in seabirds in the high Arctic but not in marine mammals or predatory fish in that area, while mercury concentrations remain relatively constant in all but one colony of seabirds on the Atlantic coast. Mercury concentrations in wildlife may be affected by small-scale, local drivers (such as the introduction of zebra mussels into the Great Lakes), large-scale climatic drivers (perhaps related to the Pacific Decadal, Atlantic or Arctic Oscillations) or complex interactions of both. Increasing mercury concentrations, seen in some populations, may be cause for concern (seabirds from Prince Leopold and Coats Island, burbot from Fort Good Hope, and burbot and lake trout from Great Slave Lake). Other populations that have shown decreasing or generally stable trends in mercury concentrations in the past have exhibited an increasing trend in recent years (such as porcupine caribou, lake trout from 2 lakes in Yukon, sea-run char from Cambridge Bay and Nain, beluga whales from Hudson Bay and the western Arctic, ringed seals from Arviat, and mussels from the Gulf of St. Lawrence).

## Chapter 12: Health Effects of Mercury in Fish and Wildlife in Canada

Coordinating author: Anton M. Scheuhammer

In many aquatic environments in Canada, the average mercury levels in biota are high enough to be of concern. The species at greatest risk for elevated mercury exposure are large predatory fish and fish-eating mammalian and avian wildlife. Elevated mercury exposure in breeding common loons and the fish that they feed on is found mainly in semi-remote lakes and reservoirs in eastern Canada, including Ontario, Quebec, and Nova Scotia, with nutrient-poor, low alkalinity, low pH conditions, or periodic flooding of wetlands. Fish and wildlife populations that are at risk would likely benefit from further reductions in industrial mercury emissions, which would decrease the deposition of new mercury available for methylation and bioaccumulation. Reduction in environmental methylmercury production would eventually lower mercury exposure and accumulation in high-trophic-level fish and wildlife species associated with mercury-sensitive aquatic food webs.

## Chapter 13: Assessment of Current Mercury Risks to Piscivorous Fish and Wildlife in Canada

Coordinating author: Neil Burgess

Risk of mercury exposure for common loons and predatory fish was calculated based on estimated mercury concentrations in the prey fish they consume in over 1 900 lakes across Canada. The results indicated potential risk to common loon behaviour in 36% of the study lakes and to reproduction in 10%. Similarly, the findings indicated potential risks from mercury exposure to reproduction in predatory fish in 82% of the study lakes and to health in 73%. For both loons and fish, the risks were greatest in southeastern Canada in areas of extensive forest cover, elevated deposition of atmospheric mercury, and poorly buffered soils. There was greater uncertainty associated with the assessment of mercury risks to fish than to loons, because there are fewer high-quality research studies on the impacts of dietary mercury on the health and reproduction of wild fish species, compared with research in common loons.

## Chapter 14: Mercury and Human Health

Coordinating author: Tara Leech

This chapter presents knowledge of mercury exposure of Canadians, studies of human health effects, and measures for risk management. In Canada, methylmercury remains a public health issue for populations who consume significant amounts of predatory fish and certain traditional wildlife food items (*country food*). Exposure to mercury varies depending on regional, social, and occupational differences. Some groups, such as Aboriginal peoples, sport fishers, and Asian Canadians, are more likely to be exposed to mercury than the general Canadian population because their diet tends to be rich in fish and seafood. Biomonitoring of pregnant women and women of childbearing age show that approximately 2% of these women in the general Canadian population exceed the proposed guidance value (8 $\mu g\ L^{-1}$), and therefore require follow-up testing, dietary advice, and/or other intervention. Inuit mothers in the eastern Arctic have some of the highest concentrations of mercury among northern populations, with 20% of mothers from a small study in 2005-2007 exceeding the 8 $\mu g\ L^{-1}$ guideline (down from 53% in 1997). Health effects such as neurological impairments have been associated with exposure to high levels of methylmercury. The developing nervous system (in fetuses, infants, and young children) is considered to be the most susceptible to the adverse health effects of methylmercury. In addition, methylmercury exposure has been linked to adverse effects on the adult cardiovascular system as well as neurobehavioural outcomes in children, but more research is needed.

# REGULATING MERCURY IN CANADA

Because mercury contamination is considered a national and global environmental and health issue, steps to mitigate emissions and exposure have been taken by the Government of Canada and the United Nations.

Mercury and its compounds are identified as a toxic substance under the *Canadian Environmental Protection Act, 1999*. In 2010, Environment Canada and Health Canada developed a *Risk Management Strategy for Mercury* that provides a comprehensive and consolidated description of the Government of Canada's actions to manage risks associated with mercury. Annex A of the strategy tabulates numerous existing risk management initiatives for mercury including regulatory action, environmental codes of practice/guidelines, pollution prevention plans, and Canada-wide standards, which cover areas such as emissions from industrial sources, mercury-containing products, and total mercury in fish for consumption.

Further, the strategy recommended undertaking science in support of policy initiatives on mercury. The strategy recommended the following actions: (1) monitor mercury levels in the environment; (2) improve our understanding of processes that govern mercury transformation; (3) increase our ability to predict the fate and transport of mercury; and (4) assess and communicate the accumulated scientific knowledge in Canada to inform domestic and global policy initiatives on the reduction of mercury emissions.

In October 2013, the Minamata Convention on Mercury (led by the United Nations Environment Programme) was opened for signature and has since been signed by 100 governments, including Canada, with the primary goal to protect the human health and the environment from anthropogenic emissions and releases of mercury and mercury compounds. The provisions within the Convention address all aspects of the mercury lifecycle, and of particular interest to Canada, aims to control and reduce atmospheric emissions of mercury from listed industrial sources. The preamble of the Convention, which sets out the context in which the Convention's obligations should be interpreted, includes several statements that directly affect Canadians, including (but not limited to):

> "*Recognizing* that mercury is a chemical of global concern owing to its long-range atmospheric transport, its persistence in the environment once anthropogenically introduced, its ability to bioaccumulate in ecosystems and its significant negative effects on human health and the environment…
>
> *Noting* the particular vulnerabilities of Arctic ecosystems and indigenous communities because of the biomagnification of mercury and contamination of traditional foods, and concerned about indigenous communities more generally with respect to the effects of mercury…"

This national assessment can serve to inform scientists, science managers, and policy-makers on the current status and baseline information of mercury in Canada. Further, this assessment provides recommendations for future research and monitoring needs on mercury both nationally and internationally.

# CONTRIBUTORS

## Summary of Key Results

Author/Editor:
Alexandra Steffen
Air Quality Research Division
Environment Canada
4905 Dufferin Street
Toronto ON M3H 5T4
Canada

## Canadian Mercury Science Assessment

Editor:
Alexandra Steffen
Air Quality Research Division
Environment Canada
4905 Dufferin Street
Toronto ON M3H 5T4
Canada

CARA Mercury Science Program coordinator:
Heather Morrison
Science Assessment and Integration Branch
Environment Canada
4905 Dufferin Street
Toronto ON M3H 5T4
Canada

## Chapter 1

Coordinating author: Alexandra Steffen
Lead authors: Heather Morrison, Alexandra Steffen

## Chapter 2

Coordinating author: Gregor Kos
Lead authors: Gregor Kos, Yi-Fan Li, David Niemi
Co-Authors: Martha King, Shirley Anne Smyth, Christian Zdanowicz, Jiancheng Zheng
Contributors: Cathy Banic, Ashu Dastoor

## Chapter 3a

Coordinating Author: Nelson J. O'Driscoll
Lead authors: Nelson J. O'Driscoll, Ravinder Pannu, Steven D. Siciliano

## Chapter 3b

Coordinating Author: Paul A. Arp
Lead Authors: Paul A. Arp, Mina Nasr

## Chapter 3c

Coordinating Author: Paul A. Arp
Co-authors: Paul A. Arp, Mary-France Jutras, Mina Nasr

## Chapter 4

Coordinating Author: Alexandra Steffen
Lead authors: Amanda Cole, Alexandra Steffen
Co-Authors: Parisa Ariya, Cathy Banic, Ashu Dastoor, Dorothy Durnford, Chris Eckley, Jenny Graydon, Rachel Mintz, Martin Pilote, Rob Tordon, Andrei Ryzhkov, Leiming Zhang.
Contributors: Pierrette Blanchard, John Dalziel, Julie Narayan, David Neimi, Laurier Poissant, Vince St. Louis

## Chapter 5

Coordinating Author: Vincent St. Louis
Lead Author: Jennifer Graydon
Co-Authors: Carl Mitchell, Claire Oswald, Vincent St. Louis
Contributers: Paul Arp, Brian Branfireun, John Chételat, Amanda Cole, Ashu Dastoor, Dorothy Durnford, Craig Emmerton, Sarah Ghorpade, Catherine Girard, Britt Hall, Andrew Heyes, Jane Kirk, Linnea Mowat, Mina Nasr, Murray Richardson, Alexandra Steffen, Merritt Turetsky

## Chapter 6

Coordinating Author: Vincent St. Louis
Lead Authors: Jennifer Graydon, Igor Lehnherr, Vincent St. Louis
Contributers: Mark Amyot, Mary-Luyza Avramescu, John Chételat, William F. Donahue, Chris S. Eckley, Catherine Girard, Jennifer A. Graydon, Britt D. Hall, Stéphanie Hamelin, Reed Harris, Andrew Heyes, Carol A. Kelly, David Lean, Igor Lehnherr, Nelson O'Driscoll, Claire J. Oswald, Alexandre Poulain, John W. M. Rudd, Vincent L. St. Louis

## Chapter 7

Coordinating author: John Chételat
Co-authors: Jane Kirk, Linda Campbell, Gareth Harding, Lisa Loseto
Contributors: Steve Beauchamp, Birgit Braune, Dorothy Durnford, Marlene Evans, Aaron Fisk, Bailey McMeans

## Chapter 8

Lead coordinator: Marc Lucotte
Co-authors: Linda Campbell, Meredith Clayden, Chris Eckley, Reed Harris, Mark Kelly, Karen Kidd, David Lean, Matthieu Moingt, Serge Paquet, Ravinder Pannu, Michael Parsons, Mike Paterson

## Chapter 9

Coordinating Author: Ashu Dastoor
Lead Authors: Ashu Dastoor, Dorothy Durnford, Reed Harris
Co-Authors: Peter Dillon, Adrienne Ethier, Amanda Poste, Andrei Ryzhkov
Contributors: Karl Abraham, Parisa Ariya, Paul Arp, Cathy Banic, Don Beals, Cody Beals, Satyendra Bhavsar, Kristin Bielefeld, Paul Blanchfield, Neil Burgess, Tom Clair, Amanda Cole, Ian Dennis, Chris Eckley, Marlene Evans, Martyn Futter, Jennifer Graydon, Karen Kidd, Jane Kirk, Marc Lucotte, Rachel Mintz, Heather Morrison, Derek Muir, Julie Narayan, Mina Nasr, David Niemi, Nelson O'Driscoll, Michael Paterson, Martin Pilote,Rick Robinson, Alexandra Steffen, Vincent St. Louis, Rob Tordon, Leiming Zhang

## Chapter 10

Coordinating Author: Neil Burgess
Co-authors: David Depew, Mary Gamberg, John Chetelat
Contributors: Tanya Brown, Linda Campbell, Meredith Clayden, Marlene Evans, Michel Leboeuf, Robert Letcher, Lisa Loseto, Derek Muir, Michael Power, Ken Reimer, Gary Stern, Shannon van der Velden

## Chapter 11

Coordinating Author: Mary Gamberg
Lead authors: Mary Gamberg, David Depew, Marlene Evans
Co-authors: Birgit Braune, Louise Champoux, David Depew, Marlene Evans, Ashley Gaden, Mary Gamberg, Nikolaus Gantner, Rob Letcher, Lisa Loseto, Derek Muir, Peter Outridge, Gary Stern

## Chapter 12

Coordinating Author: Anton M. Scheuhammer
Lead authors: N. Basu, David Depew, Anton M. Scheuhammer
Contributors: Satyendra Bhavsar, Birgit Braune, Neil Burgess, Louise Champoux, John Elliott, Mary Gamberg, Laurie Hing Man Chan, S. Lord, M. Wayland,

## Chapter 13

Coordinating Author: Neil Burgess
Co-Authors: David Depew, Neil Burgess, Linda Campbell

## Chapter 14

Coordinating Author: Tara Leech
Lead authors: Meredith Curren, Shawn Donaldson, Jennifer Gibson, Tara Leech, Ellen Lye
Co-authors: Bryan Adlard, Mary Albert, Nathalie Arnich, Roni Bronson, ChemRisk Consulting, Elizabeth Elliott, Mark Feeley, Mike Inskip, Angela Li-Muller, Stephen MacDonald, Maria Ooi, Harold Schwartz, Constantine Tikhonov, Jay Van Oostdam
Contributors: Karelyn Davis

## Chapter 15

Coordinating Author: Alexandra Steffen
Lead author: Alexandra Steffen
Co-authors: Paul Arp, Neil Burgess, John Chételat, Ashu Dastoor, David Depew, Mary Gamberg, Jennifer Gibson, Jenny Graydon, Gregor Kos, Tara Leech, Igor Lehnherr, Marc Lucotte, David Neimi, Nelson O'Driscoll, Claire Oswald, Vincent St. Louis, Anton Scheuhammer

# PEER REVIEWERS

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In alphabetical order: Christopher Babiarz, Steve Balogh, Tamar Barkay, Kevin Bishop, Satyendra Bhavsar, Laurie Chan, Heleen deWit, Aurelien Dommergue, David Gay, Eric Dewailly, John Elliott, David Evers Xinbin Feng, Heather Golden, Michael Goodsite, Jane Kirk, Chris Knightes, Tom Kosatsky, Marco Lemes, Lisa Loseto, Mark Mallory, John Munthe, Bruce Monson, Christine Moore, Diane Nacci, Daniel Obrist, Jozef Pacyna, Michael Parsons, Alexandre Poulain, Jeroen Sonke, David Streets, Elsie Sunderland, Oleg Travnikov, Bill Van Heyst, and James Wiener.

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Additional information can be obtained at:

Environment and Climate Change Canada
Public Inquiries Centre
7th Floor, Fontaine Building
200 Sacré-Coeur Boulevard
Gatineau QC  K1A 0H3
Telephone: 1-800-668-6767 (in Canada only) or 819-997-2800
Email: ec.enviroinfo.ec@canada.ca