

MERCURY MATTERS

*Linking Mercury Science
with Public Policy
in the Northeastern United States*



A Science Links Publication of the Hubbard Brook Research Foundation



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The mission of the **Hubbard Brook Research Foundation** (HBRF) is to promote the understanding and stewardship of ecosystems through scientific research, long-term monitoring, and education. HBRF was established to support the work of the Hubbard Brook Ecosystem Study. Since 1963, ecosystem experiments and continuous ecological monitoring have been conducted at the Hubbard Brook Experimental Forest, a 7,800-acre tract of land in central New Hampshire managed by the USDA Forest Service. The site is part of the National Science Foundation's Long Term Ecological Research (LTER) Network. Scientists participating in the world-renowned Hubbard Brook Ecosystem Study have made discoveries regarding the ecology of forested watersheds and the effects of timber harvesting, climate change, acid rain, and other natural and human-caused disturbances. HBRF is a nonprofit 501(c)(3) organization, supporting ecosystem science at Hubbard Brook by operating housing and other facilities and by conducting educational programs.

Through its Science Links Program, HBRF develops strategies to leverage science for sound public policy by building bridges between research scientists, policymakers, land managers, government officials, environmental leaders, and members of the public. Previous Science Links publications have addressed acid rain and nitrogen pollution.



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HBRF Science Links participants

Project Leader: Charles Driscoll, PhD, Syracuse University
Research Fellow: Young-Ji Han, PhD, Hubbard Brook Research Foundation
Tom Butler, Institute of Ecosystem Studies/Cornell University
Celia Chen, PhD, Dartmouth College
Tom Clair, PhD, Environment Canada
David Evers, PhD, BioDiversity Research Institute
Wing Goodale, BioDiversity Research Institute
Tom Holsen, PhD, Clarkson University
Neil Kamman, Vermont Agency of Natural Resources
Kathy Fallon Lambert, Ecologic: Analysis & Communications
Ron Munson, PhD, Tetra Tech

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Executive Summary

Mercury pollution is a vexing environmental problem that leads to the contamination of forests, soils, lakes, streams, and oceans around the world. Today every part of the globe has been touched by mercury pollution. Even the remote Arctic, with no known sources of mercury, harbors polluted waters and contaminated fish. While mercury has been widely recognized as a global pollutant, new insights into emissions, deposition, and ecological effects also underscore its importance as a regional and local pollutant.

Historically mercury occurred at only trace levels in the environment, but mercury concentrations in fish and other animals in the northeastern United States (the Northeast) now routinely exceed human and wildlife health thresholds. State and federal fish consumption advisories blanket the nation, demonstrating that mercury pollution is widespread. Solutions to this complex problem have been hampered by conflicting information on the sources, transport, and accumulation of mercury in the environment. The Hubbard Brook Research Foundation (HBRF) convened a team of scientists to analyze mercury data in the region and address key questions facing decision-makers.

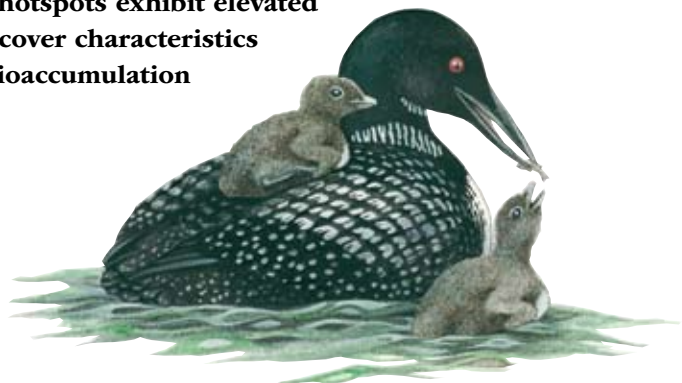
Key Findings

Mercury emissions to the atmosphere are the largest source of mercury pollution globally and in most areas of the Northeast. Watersheds throughout the nation receive mercury that is emitted from the smokestacks of coal-fired power plants and other sources and then deposited to the Earth. Some of the mercury eventually runs off into nearby rivers and lakes where, under the right conditions, it can bioaccumulate up to 1 million times as it passes from water to fish, wildlife, and people.

The HBRF team completed a **new assessment of mercury in fish, birds, and mammals and identified five confirmed and nine suspected biological mercury hotspots in the northeastern United States and southeastern Canada**. The primary causes of these biological mercury hotspots are airborne mercury emissions and deposition, which can be amplified by heightened watershed sensitivity, water-level fluctuations in reservoirs, or large local emission sources.

Scientists have long known that some watersheds are particularly sensitive to mercury pollution. Acidic waters draining forests and wetlands produce fish that are most likely to exceed the U.S. Environmental Protection Agency (EPA) human health criterion for mercury of 0.3 parts per million. **The HBRF team established chemical indicators of mercury sensitivity and determined that several of the confirmed and suspected biological mercury hotspots exhibit elevated mercury because their water chemistry and land-cover characteristics are particularly conducive to the transport and bioaccumulation of mercury.**

The HBRF team completed a new assessment of mercury in fish, birds, and mammals and identified five confirmed and nine suspected biological mercury hotspots in the northeastern United States and southeastern Canada.



New data show that several of the biological mercury hotspots are linked to water level manipulation within reservoirs in the Northeast. Mercury deposited from the atmosphere can bioaccumulate to high levels in reservoirs with large draw downs that expose extensive shore land. Mercury levels in fish and loons are elevated in several Northeast reservoirs that fluctuate 10.5 feet or more annually.



The HBRF team evaluated mercury deposition patterns in southern New Hampshire and northeastern Massachusetts and estimated that mercury deposition is 10 to 20 times higher than pre-industrial conditions, and four to five times higher than current EPA estimates. Local emission sources contribute approximately 65 percent of the mercury deposition in the study area, and nearby coal-fired power plants produce 40 percent of this locally derived mercury deposition. The results from this case study suggest that 1) EPA computer models can underestimate mercury deposition near large emission sources, and 2) the mercury cap-and-trade approach in the current U.S. Clean Air Mercury Rule (CAMR) could perpetuate or even exacerbate areas of high deposition and associated biological mercury hotspots if emissions continue unabated at coal-fired power plants.

The HBRF team also analyzed historical emissions and biological data to assess the prospects for recovery in the lower Merrimack River watershed of southern New Hampshire and northeastern Massachusetts. **Between 1999 and 2002, mercury levels in fish and common loon blood declined 32 and 64 percent respectively, following a 45 percent reduction in mercury emissions from local sources. These results suggest that fish and wildlife can respond rapidly and proportionally to further reductions in mercury emissions from large local sources in the Northeast.**

The continued widespread mercury contamination of fish and wildlife across the Northeast demonstrates that current mercury deposition is still too high to achieve recovery, despite recent control measures. Furthermore, the data presented in this report and the supporting peer-reviewed articles highlight the connection between airborne mercury emissions from United States sources and the existence of highly contaminated biological mercury hotspots. In addition to further reducing mercury emissions to the atmosphere, the United States and Canada must substantially improve mercury monitoring across the continent in order to track mercury pollution levels, further identify biological mercury hotspots, and assess the impact of policy decisions on mercury pollution.

The continued widespread mercury contamination of fish and wildlife across the Northeast demonstrates that current mercury deposition levels are still too high to achieve recovery, despite recent control measures.

Quicksilver Clouds: How Mercury Enters, Cycles, and

Emissions & Deposition

Watershed

Bioaccumulation

Mercury is emitted to the atmosphere

Mercury is deposited in rain and snow and as gases and particles

Mercury is transported through watersheds and converted to methyl mercury

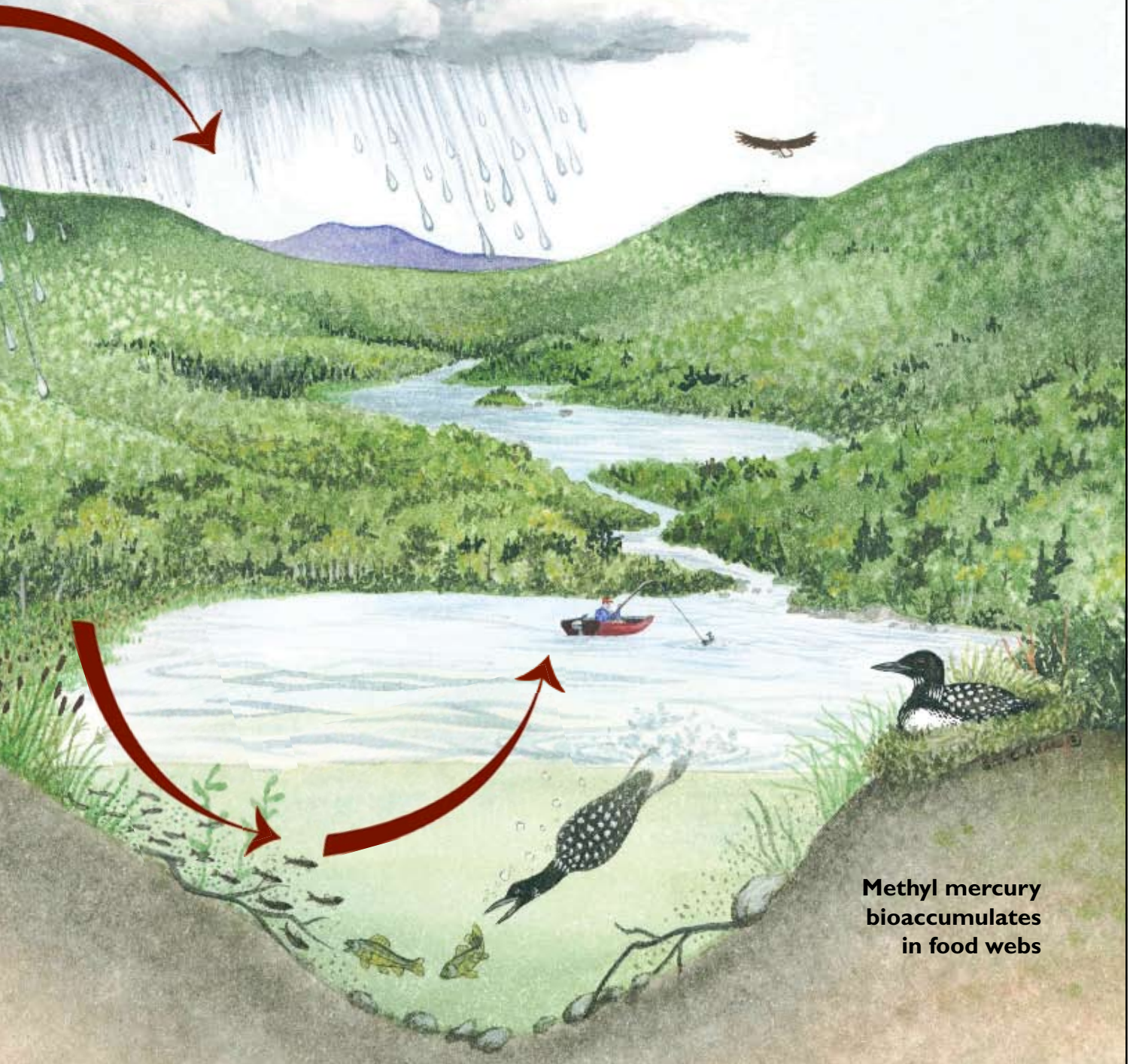
Impacts Ecosystems

Cycling

in forests

Lake Cycling

Bioaccumulation in lakes and reservoirs



What Is Mercury and Why Is It a Problem?

Mercury is a natural element existing in trace amounts in the Earth's crust. Through natural processes and human activities it can be mobilized into the environment and transformed into a toxic pollutant.

Mercury (Hg) is released naturally to the environment by volcanoes, the breakdown of rocks known as “weathering,” and other processes (UNEP 2003). Human beings have extracted mercury for thousands of years for use in products such as paints and thermometers and processes such as gold mining. Prior to industrialization most of these uses released only small amounts of mercury into the environment. However, human activities in recent decades are responsible for a three-fold increase in global mercury deposition (UNEP 2003). That increase reaches four- to six-fold in the northeastern United States (the Northeast) as reflected in the increase in mercury deposited to sediments of lakes (Perry et al. 2005).

As a fundamental chemical element, mercury is persistent in the environment and does not break down or degrade. After mercury is released from ores or mineral deposits and emitted to the atmosphere, it is deposited to the Earth's surface, and some eventually flows into rivers and streams. Within watersheds and lakes, mercury is processed by specialized bacteria that convert it to methyl mercury – a form that is more readily absorbed in the digestive system of animals and magnified to high levels in the food web. Methyl mercury binds to proteins and can bioaccumulate through the food web in fish, birds, and other wildlife.

Most people and wildlife are exposed to methyl mercury by eating fish, an important source of animal protein. In human populations, the most at-risk and sensitive individuals include women of childbearing age who may become pregnant, nursing mothers, and children under 12 years of age. The most highly exposed people, due to fish-

consumption habits, include: recreational fishers and their families, some Native American populations, Asians and Pacific Islanders, and individuals who fish to meet their or their families' nutritional needs (subsistence fishers).

A United States Environmental Protection Agency (EPA) scientist estimates that between 200,000 and 400,000 children are born each year in the United States with pre-natal exposure to methyl mercury sufficient to put them at risk for neurologic impairment due to fish consumption by the mother (Mahaffey 2005). These children can experience decreased ability to perform in school, declines in visual and spatial functions, deficits in ability to recall and process information, and a general decrease in intelligence (NAS 2000).

Several studies also point to a connection between mercury exposure through dietary consumption and cardiovascular disease in men. Dietary intake of fish and mercury were associated with a significantly increased risk of acute heart disease and death in men living in Eastern Finland (Salonen et al. 2000). Another study of men in Europe and Israel noted similar findings (Gaullar et al. 2002).

The impacts of mercury on fish and wildlife have been documented in numerous studies (see Evers 2005 and Chan et al. 2003 for comprehensive summaries and references). Research has linked elevated mercury in fish to decreased spawning success, increased embryo mortality in lake trout eggs, altered schooling movements, and at extreme levels, acute toxicity. In fish-eating birds, mercury exposure is

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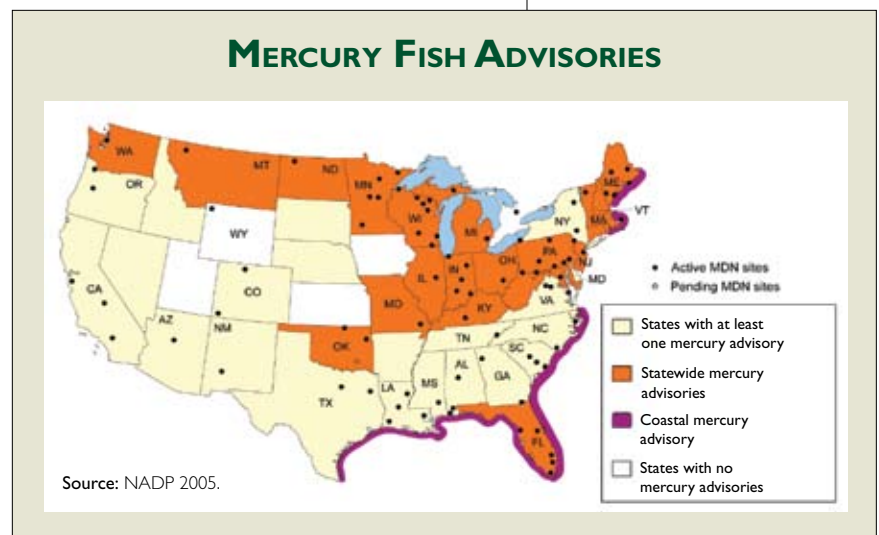


FIGURE I:
In 2004, 44 states had one or more fish-consumption advisories warning consumers about the risk of eating fish that may be high in mercury.

associated with reduced reproductive success, decreased chick survival, spinal cord degeneration, disrupted hormone levels, and difficulty flying, walking, and standing. Mammals have been studied to a lesser degree, but research shows that high mercury levels in mink and otter can cause impaired motor skills, weight loss, and acute toxicity.

To address growing concerns over fish contamination and human exposure to elevated mercury, the EPA and the U.S. Food and Drug Administration (FDA) established a human health criterion for methyl mercury in fish tissue of 0.3 parts per million (ppm), as measured in wet weight of fish fillets. The criterion represents the maximum advisable concentration of methyl mercury in freshwater and estuarine fish that protects the average consumer of fish and shellfish among the general population. Canada and the states of Maine and Minnesota have elected to set a stricter standard of 0.2 ppm to protect human health. Efforts are under way to address the impact of mercury on wildlife, including the development of wildlife criteria values for the protection of common loons, mink, and river otter in Maine (Evers et al. 2004).

In 2004, as shown in Figure 1, 44 states issued fish-consumption advisories for mercury, including 21 statewide advisories for fresh waters and 12 statewide advisories for coastal waters (EPA 2004). Through these advisories the FDA and EPA advise women who may become pregnant, pregnant women, nursing mothers, and young children to avoid some types of fish, and to eat fish and shellfish that are lower in mercury. The agencies further suggest that some types of fish should be avoided entirely (see complete details at www.epa.gov/mercury/advisories.htm).

Where Does Mercury Pollution Originate?

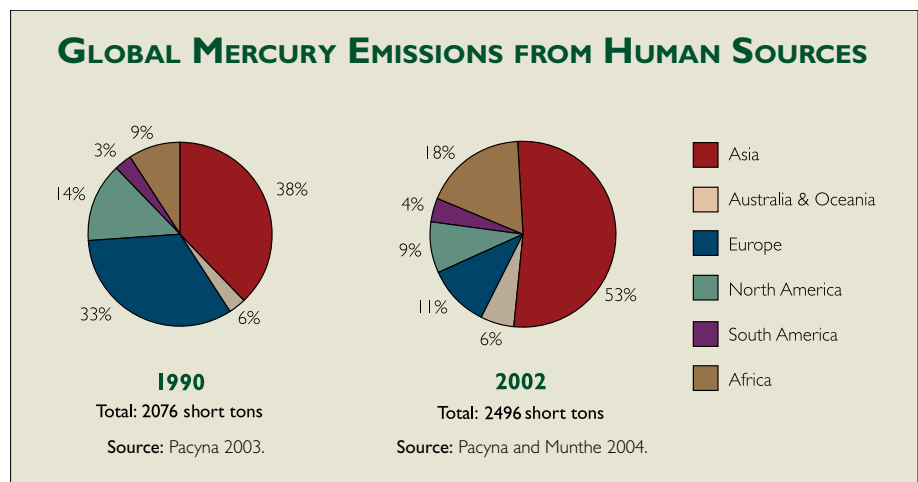
Emissions from coal-fired power plants located within the United States are the largest source of human-caused mercury emissions in many areas of the Northeast.

Mercury is released to the global environment in several ways, but the dominant pathway is airborne emissions and deposition (UNEP 2003). Fossil-fuel combustion and waste incineration rank first and second among anthropogenic mercury emission sources worldwide (UNEP 2003). Coal-fired power plants are the largest single source of anthropogenic mercury emissions in the United States, followed by industrial boilers and electric arc furnaces (NEI 2002). Mercury is also released to lakes and streams from point and nonpoint sources. In the United States, direct discharges by wastewater treatment plants and chlorine production facilities top the list of waterborne point sources. Diffuse nonpoint sources include the leaching of mercury from contaminated soils associated with industrial facilities and landfills, as well as runoff from urban landscapes. Given the prevalence and impact of airborne emissions, the balance of this report will focus on atmospheric emissions and deposition of mercury.

The total amount of mercury released to the atmosphere worldwide is approximately 7,000 short tons, of which two-thirds originate from current and past human sources. The remaining third is emitted from volcanoes, mid-ocean ridges, and other natural sources. Global emissions associated with current human activities increased roughly 15 percent from 1990 to 2002, with a growing share contributed by Asia and Africa (Figure 2).

Coal-fired power plants are the largest single source of anthropogenic mercury emissions in the United States, followed by industrial boilers and electric arc furnaces.

FIGURE 2: Global mercury emissions from human sources increased 15 percent between 1990 and 2002. Large increases in Asia and Africa were responsible for this increase.



U.S. Mercury Emissions by Source

Source Category	US 1990 (ton/yr) ¹	US 1996 (ton/yr)	US 1999 (ton/yr)	US 2002 (ton/yr)	Northeast 2002 (ton/yr)
Coal-fired power plants	58.8	51	47.9	50.3	0.82
Medical waste incinerators	51	40.5	2.8	0.3	0.017
Municipal waste combustors	57.2	31.8	5.1	4.2	1.2
Industrial/commercial/institutional boilers and process heaters	14.4	12	12	11	0.36
Chlorine production	10	7.8	6.5	5.4	0
Electric arc furnaces	7.5	No Data	No Data	10.7	No Data
Hazardous waste incineration	6.6	4.5	6.5	4.6	0.001
Total (all categories)	245	185	120.3	113.8	5.2

Source: NEI 1999, NEI 2002. ¹ Measurements are in short tons.

Mercury emissions in the United States have declined from 245 short tons in 1990 to 114 short tons in 2002, due largely to controls on municipal and medical waste incinerators. As shown in Table 1, emissions from coal-fired power plants did not change appreciably from 1990 to 2002 (NEI 1999; NEI 2002).

Regional studies show that mercury emission sources in the United States can play a disproportionately important role in mercury pollution, as demonstrated by studies in Ohio (Keeler et al. 2006), the Adirondack and Catskill Mountains of New York (Figure 3), and southern New Hampshire and northeastern Massachusetts (see case study on page 16). The substantial contribution by domestic emission sources to mercury pollution in the United States is corroborated by evidence from mercury accumulation in the sediments of lakes. Lake sediments tell the story of how mercury pollution has changed over time and where it may originate. A data set representing 39 lakes across the Northeast demonstrates that mercury deposition to lake sediments has been declining for the past two decades. The sediment pattern contradicts the global pattern of increasing global emissions, but closely tracks United States emissions trends, suggesting that mercury deposition in the Northeast is responsive to mercury emissions from within the United States.

TABLE 1:

Mercury emissions from some sources have declined substantially since 1990. Emissions from coal-fired power plants remain largely unchanged. Note that the individual source categories do not sum to the total because area sources and minor point source categories are not shown. (1 short ton equals 0.907 metric ton.)

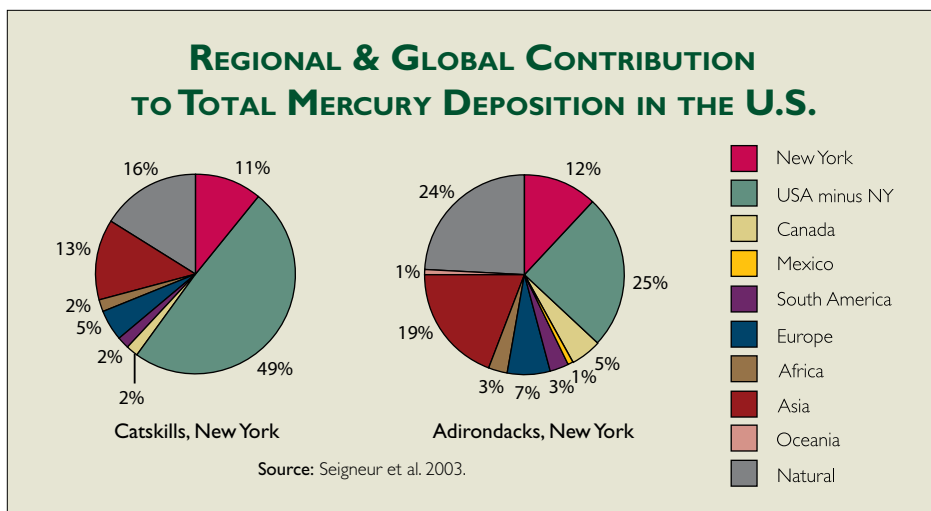


FIGURE 3:

Studies show that U.S. mercury emission sources play an important role in mercury pollution in the Catskill and Adirondack regions.

Where Does Mercury Go?

Emerging science suggests that mercury is not only transported globally, but is deposited regionally and locally to a greater extent than once thought.

Mercury was once considered a pollutant that, when emitted to the atmosphere, travels far from its source. For that reason, mercury has been considered a “global pollutant” with far-reaching impacts but minimal local effects. Emerging science has changed the dominant view of mercury from a strictly global pollutant to a global *and* regional and local pollutant.

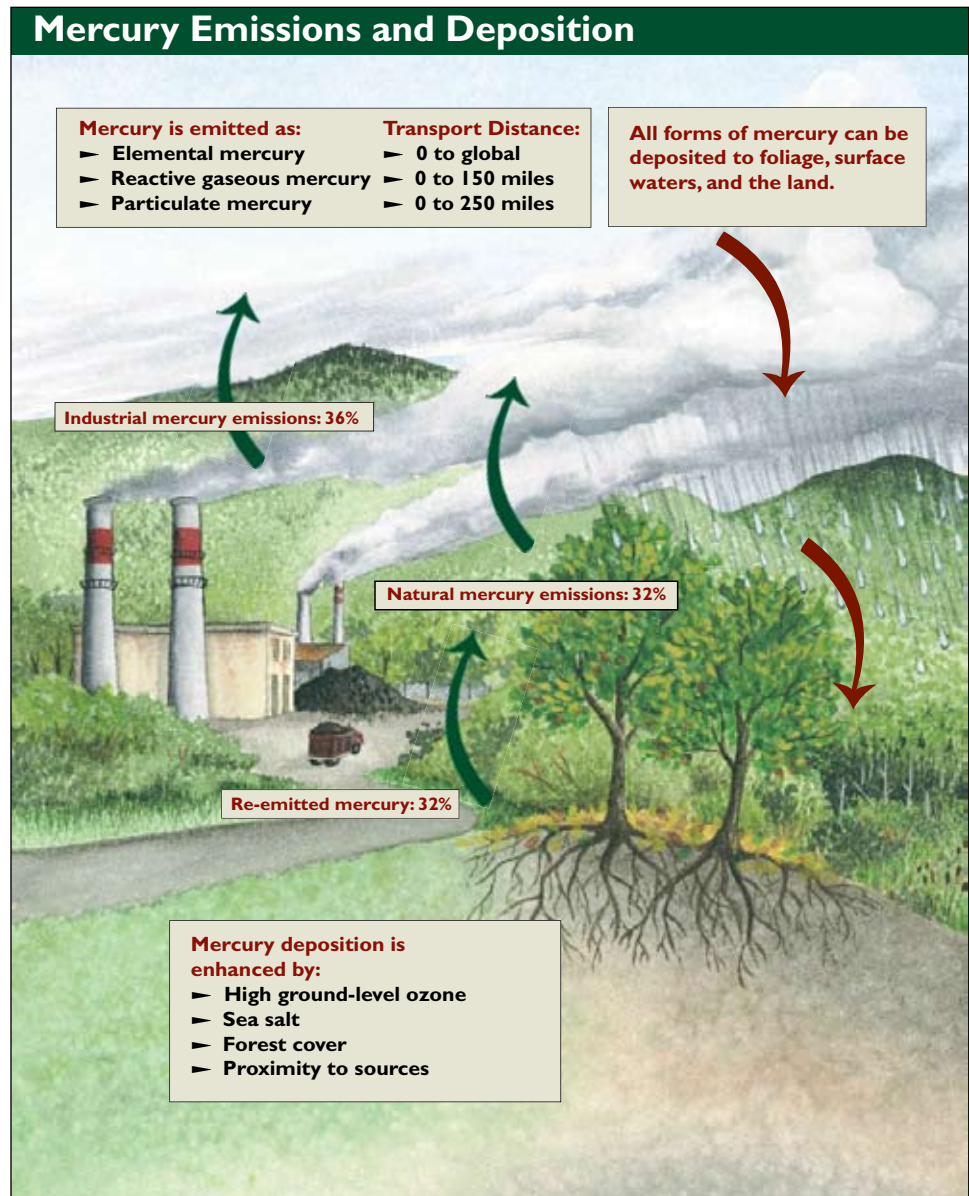
The ultimate fate of mercury emissions is controlled in large part by the transport distances of different mercury “species” or forms. The three major forms of mercury in the atmosphere are gaseous elemental mercury, reactive gaseous mercury, and particulate mercury. Each form of mercury has specific physical and chemical characteristics that determine how far it travels in the atmosphere before depositing back to Earth (Figure 4).

Elemental mercury in the atmosphere is relatively inert and not easily dissolved in water. This form can be transported a considerable distance. Reactive gaseous mercury (also referred to as “oxidized mercury”) is more chemically reactive and soluble than elemental mercury, and therefore deposits more rapidly and closer to the emissions source in precipitation (wet deposition) or on contact (dry deposition). Particulate mercury can travel short to moderate distances. The proportion of each mercury form emitted by specific sources in the United States is summarized in Table 2.

Scientists have identified two processes that enhance local and regional deposition of elemental mercury. The first is the conversion of elemental mercury to more reactive forms. This transformation occurs in the atmosphere and has been observed in areas where ground-level ozone is high and sea salt is prevalent in the air (such as coastal zones). Both of these situations are common in the Northeast. The second process is the direct deposition of elemental mercury to the foliage of trees and the subsequent transfer of this mercury to the land surface with leaf fall.

FIGURE 4:

Different forms of mercury can travel varying distances before depositing to foliage, surface waters, and the land. Also, certain conditions enhance mercury deposition.



Mercury Species by Source

Source Category	Elemental Mercury Average %	Reactive Gaseous Mercury Average %	Particulate Mercury Average %
Coal-fired electric utilities – U.S. average	50	40	10
Coal-fired electric utilities – the Northeast	30	68	2
Utility oil boilers	50	30	20
Municipal waste combustors	22	58	20
Pulp & paper production	50	30	20
Chlorine production	95	5	0
Hazardous waste incinerators	58	20	22
Municipal landfills	80	10	10

Sources: NEI 1999, Pacyna et al. 2003, NESCAUM 2005.

Mercury emission and deposition are just two steps in a series of complex processes that convert mercury from an inert element in the Earth's crust to a pollutant harmful to fish, wildlife, and people. Most mercury deposited from the atmosphere occurs as inorganic mercury that generally exists at very low concentrations that pose no direct health risk. However, as this form of mercury is transported through the watershed, it can be processed by bacteria in soils, wetlands, and lake or river sediments and converted to a form known as methyl mercury. Methyl mercury occurs at low concentrations in water (less than 1 part per trillion), but then bioaccumulates through the aquatic food web and reaches toxic levels in fish (Figure 5). A compilation of data from across the Northeast illustrates that total mercury increases approximately 1 million times and methyl mercury can increase in concentration as much as 10 million times in the aquatic food chain, depending on the chemistry and ecosystem characteristics of a particular lake or river.

How Much Airborne Mercury Pollution Does the Northeast Receive?

Some areas in the Northeast receive mercury deposition 10 to 20 times higher than historical levels, with particularly high amounts in forests and areas near large emission sources.

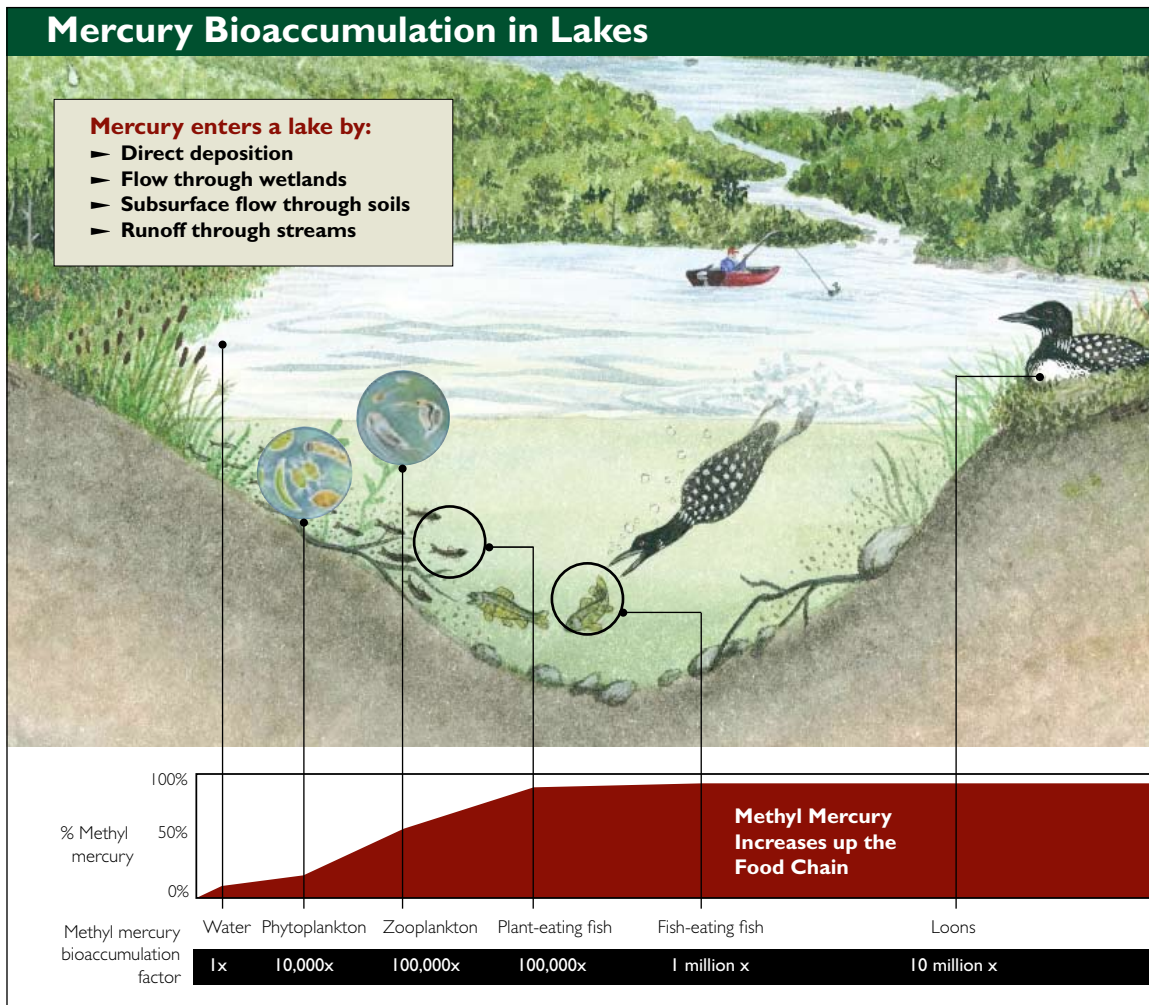
Scientists use several methods to estimate how much mercury is deposited from the atmosphere to the Earth's surface. Wet and dry deposition together constitute total mercury deposition. Wet deposition in rain or snow is measured at a network of 92 mostly rural stations in North America known as the Mercury Deposition Network (MDN). The MDN is part of the National Atmospheric Deposition Program (NADP), which measures background mercury concentrations in areas generally distant from large sources, and is operated as a public-private collaborative, coordinated primarily by the federal government.

According to MDN measurements, the average wet deposition in the United States ranges from 2.0 to 20 micrograms per square meter per year ($\mu\text{g}/\text{m}^2\text{-yr}$). Wet deposition tends to be somewhat higher in the eastern portion of the nation, with the highest levels recorded in the Southeast. Wet deposition ranges from 6 to 10 $\mu\text{g}/\text{m}^2\text{-yr}$ in the Northeast.

Dry deposition includes the deposition of mercury associated with gases and particles. It is not systematically measured in the United States due to technical challenges, but has been estimated at some research sites. In the Northeast, scientists

TABLE 2:
Different sources of airborne mercury emissions have varying percentages of the three main forms of mercury.

Mercury Bioaccumulation in Lakes



predict that dry deposition contributes 50 to 70 percent of total deposition in some forested areas.

Air quality models are useful tools for examining the impacts of air quality regulations or policies. There are many types of air quality models and each type has advantages and disadvantages for assessing air quality impacts from emission sources. There are three common types of models: plume models, trajectory models, and grid models. The EPA's large grid model, the Community Multi-Scale Air Quality model, predicts that total mercury deposition ranges from 5.0 to 40 $\mu\text{g}/\text{m}^2\text{-yr}$ across the United States (EPA 2005a).

While large-scale models provide a picture of average mercury deposition across the United States, they often do not accurately depict local or regional variation. A regional model of total deposition in the Northeast which incorporates elevation and land cover, provides greater spatial resolution and generally predicts higher deposition in high-elevation forests and in southern New England (Miller et al. 2005).

Detailed local models demonstrate that total mercury deposition near large emission sources can be even greater than the levels predicted by national or regional models. The southern New Hampshire and northeastern Massachusetts case study on pages 16 and 17 shows that total mercury deposition near a coal-fired power plant can reach upwards of 70 $\mu\text{g}/\text{m}^2\text{-yr}$. Scientists and policymakers are only just beginning to understand and account for the wide variation in total mercury deposition, its linkage to biological mercury hotspots, and its implications for public policy.

FIGURE 5:

Methyl mercury occurs at low concentrations in water, eventually bioaccumulating through the food chain, often reaching harmful levels in fish-eating fish and loons.

What Are Biological Mercury Hotspots?

A biological mercury hotspot is a location on the landscape where mercury concentrations in fish, birds, or mammals exceed established thresholds for human or ecological health in a high number of samples compared to the surrounding landscape.

The definition above of a biological mercury hotspot is based on mercury concentrations in several biological indicators and is thus independent of the source of the mercury pollution. Areas of high mercury deposition have also been referred to as hotspots, but should more accurately be called “mercury deposition hotspots.” In contrast, the EPA limits its focus to “utility hot spots” which it defines as a water body that is a source of consumable fish with methyl mercury tissue concentrations, attributable solely to utilities, greater than the EPA’s human health criterion of 0.3 ppm (EPA 2005b).

There are three important considerations in defining biological mercury hotspots. First, many scientists agree that the definition of a biological mercury hotspot should not be constrained to one single mercury source, since ecosystems respond to the combined effects of mercury pollution from multiple sources.

Second, it is important to consider the possibility that given the range in sensitivity to mercury pollution, biological mercury hotspots can occur in diverse locations across the landscape, not only in areas of elevated mercury deposition.

Finally, the Clean Water Act has established national goals for water quality that appear to be at odds with the EPA’s definition of what constitutes a mercury hotspot. Specifically, the Clean Water Act stipulates that states should strive to maintain or restore water quality in order to provide for “the protection and propagation of fish, shellfish, and wildlife” (CWA 1996). Therefore, a definition of mercury hotspots strictly limited to surface waters with *consumable* fish containing mercury levels exceeding the EPA human health criterion of 0.3 ppm from a single source would not appear to support the goals of the Clean Water Act.

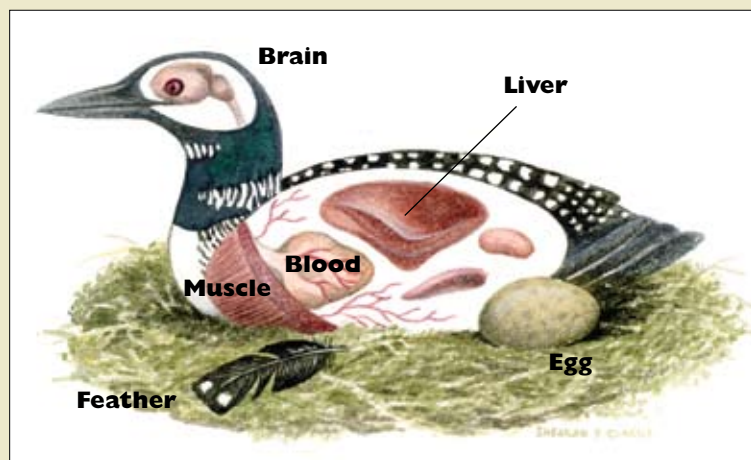
Many scientists agree that the definition of a biological mercury hotspot should not be constrained to one single mercury source since ecosystems respond to the combined effects of mercury pollution from multiple sources.

Mercury Effects on the Common Loon

Field and laboratory research show that common loons experience significant neurological, physiological, behavioral, and reproductive impacts from elevated mercury exposure. When loons ingest mercury by eating fish, the mercury is transported via the bloodstream to the birds’ vital organs, including the brain.

Loons can naturally eliminate a portion of the ingested mercury from their bodies by transferring it to their feathers and eggs. They also attempt to reduce the toxicity of mercury by binding it as a nontoxic mercury compound and storing it in the liver, kidney, and spleen.

Despite these complex mechanisms, mercury still accumulates to high levels in loons, leading to adverse impacts such as brain lesions, spinal cord degeneration, difficulty flying and swimming, production of fewer and smaller eggs, lowered reproductive success, and higher body burdens of mercury over time (Evers et al. 2003, 2005). Comprehensive studies show that these effects are much more pronounced in “high risk” loons with mercury concentrations in blood above 3.0 ppm.



Mercury accumulates in the bodies of common loons and has adverse physiological, reproductive, and behavioral effects.

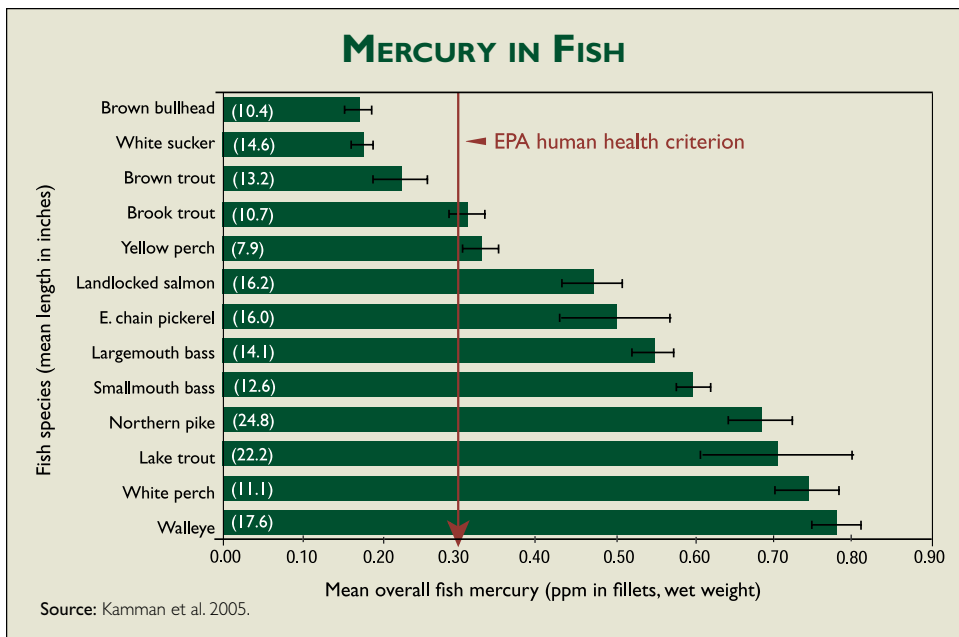


FIGURE 6: Mercury measurements show that yellow perch tend to be low in mercury compared to species higher on the food chain. Ten of thirteen species exceed the EPA human health criterion of 0.3 ppm.

The HBRF team analyzed a data base with more than 6,800 observations for seven wildlife species to identify confirmed and suspected biological mercury hotspots. Several indicator species were chosen to reflect human and ecological health risks associated with mercury pollution. For each indicator species, an *adverse effects threshold* has been defined based on federal criteria and existing scientific research.

Yellow perch and common loon served as the primary indicator species in the biological hotspot analysis. Yellow perch was chosen as the primary indicator species for human health, using the EPA’s recommended criterion of 0.3 ppm of mercury as the adverse effects threshold. Yellow perch are abundant in the region, have been widely sampled for mercury, and are regularly consumed by recreational fishermen. It is important to note, however, that yellow perch occupy a position in the middle of the aquatic food chain and are likely to have lower mercury concentrations compared to fish that are higher on the food chain such as pike, lake trout, and walleye (Figure 6).

TABLE 3: The HBRF team used two primary indicator species to identify biological mercury hotspots and five secondary species to indicate “suspected” hotspots.

Biological Mercury Hotspot Indicators and Thresholds		
Indicator Species	Threshold (ppm)	Tissue Type
Primary		
Common loon	3.0	Blood
Yellow perch	0.3 ¹	Fillet
	0.16 ²	Whole body
Secondary		
Largemouth bass	0.3	Fillet
Brook trout	0.16	Whole body
Bald eagle	1.0	Blood
Mink	30.0	Fur
River otter	30.0	Fur

¹Threshold based on EPA human health criterion.
²Threshold based on ecological impacts.

Source: Evers et al. 2007.

The common loon was chosen as the primary indicator for ecological health, using the population effect level of 3.0 ppm of mercury in blood as the adverse effects threshold. The common loon is a large, fish-eating bird, positioned high on the aquatic food chain, and it accumulates considerable mercury over its long lifetime. Common loons are ubiquitous in the Northeast and mercury exposure and effects are well characterized by a large regional data base of mercury in loon blood, eggs, and feathers. Consistent with its life history and position on the food chain, loons typically have high mercury levels compared to other aquatic and terrestrial birds.

The adverse effects threshold for loons is based on existing scientific research, which indicates that loon pairs with blood mercury levels of 3.0 ppm fledged up to 40 percent fewer young than pairs with blood mercury less than 1.0 ppm. The study further determined that when 25 percent or more of the loons in a given area exceed this blood mercury threshold, population levels are likely to decline.

Despite the extensive yellow perch and common loon data sets in the region, insufficient information exists to quantify mercury contamination levels in some areas. To address these gaps, the HBRF team used a set of secondary indicators to identify suspected biological mercury hotspots. The secondary indicator species include: brook trout, largemouth bass, bald eagle, mink, and river otter (see Table 3 for corresponding adverse effect thresholds).

Where Do Biological Mercury Hotspots Occur?

Five confirmed and nine suspected biological mercury hotspots have been identified in the northeastern United States and southeastern Canada.

The HBRF team produced a map of the five confirmed and nine suspected biological mercury hotspots (Figure 7), which builds on a preliminary mercury hotspot analysis published by D.C. Evers (Evers 2005). The map pinpoints areas of especially high risk that emerge against the backdrop of fish consumption advisories in the region.

The five confirmed biological mercury hotspots span the region from Kejimikujik National Park in Nova Scotia to the Adirondacks of New York. Information on mercury concentrations in each hotspot is summarized in the table in Figure 7, shown on page 15. Nine suspected biological mercury hotspots were also identified in the region. Strong evidence of elevated mercury levels in fish and wildlife exists at these sites, but there is insufficient data at the present time to classify them as confirmed biological mercury hotspots. Additional sampling at these locations is needed to make a final determination as to their status.

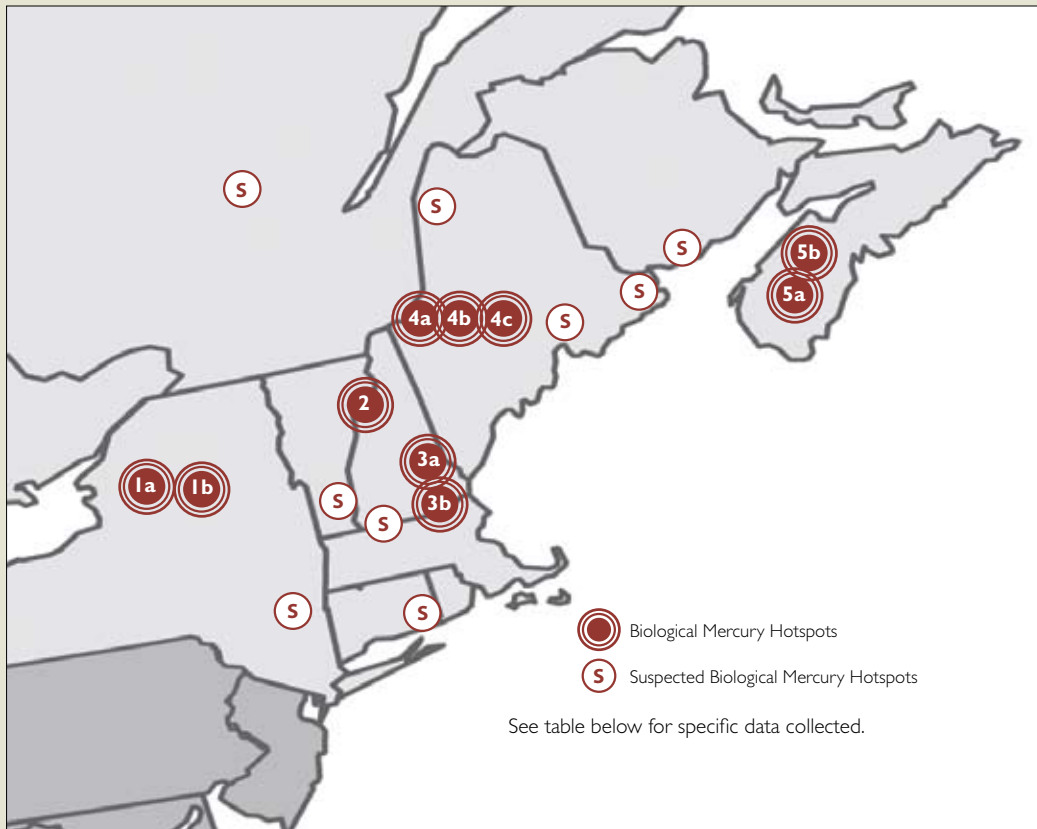
FIGURE 7: ►

The HBRF team identified five confirmed and nine suspected biological mercury hotspots in the Northeast.



BIOLOGICAL MERCURY HOTSPOTS

The HBRF team used a new method to determine biological mercury hotspots. In this method, a biological mercury hotspot of human health concern occurs where there are 10 or more independent sites with yellow perch concentrations above 0.3 ppm within grids that average 890 square miles in size (30 minutes by 30 minutes). A biological mercury hotspot of ecological concern emerges where 25 percent or more of the common loons sampled in a grid containing at least 14 samples have blood mercury levels above 3.0 ppm.



Mercury Levels in Biological Hotspots

Biological Hotspot	State/Province	Yellow Perch		Common Loon		
		Average (ppm)	Range (ppm)	Average (ppm)	Range (ppm)	% of loons > adverse effect level
1a. Adirondack Mountains – west	NY	0.73	0.57 - 0.96	1.5	1.1 - 2.1	0%
1b. Adirondack Mountains – central	NY	0.54	0.39 - 0.80	2.0	0.3 - 4.1	25%
2. Upper Connecticut River	NH,VT	0.35	0.14 - 0.58	1.1	0.1 - 2.9	0%
3a. Merrimack River – middle	NH	0.78	0.05 - 5.03	2.6	0.7 - 7.1	28%
3b. Merrimack River – lower	MA, NH	0.65	0.23 - 3.81	no data		
4a. Upper Androscoggin River	ME, NH	0.44	0.21 - 1.25	1.9	0.15 - 5.5	14%
4b. Upper Kennebec River – west	ME	0.40	0.24 - 0.52	3.1	0.6 - 14.2	43%
4c. Upper Kennebec River – east	ME	0.38	0.14 - 0.72	2.2	0.6 - 4.1	26%
5a. Kejimikujik National Park	NS	0.50	0.14 - 0.85	5.5	2.9 - 7.8	93%
5b. Central, Nova Scotia	NS	0.58	0.14 - 3.79	no data		

Source: Evers et al. 2007.

Linking Biological Mercury Hotspots and Coal-Fired Power Plants: A Case Study

The biological mercury hotspot in southern New Hampshire and northeastern Massachusetts illustrates the important connections between emissions from local coal-fired power plants, areas of high mercury deposition, and elevated mercury in fish and wildlife. By focusing on one particular biological mercury hotspot, we were able to examine closely these connections and distill the implications for public policies, such as mercury emissions trading.

Mercury Deposition

The HBRF team produced a map of mercury deposition in New Hampshire using a computer model designed to capture the impacts of local emission sources¹. With this plume model, we quantified how much airborne mercury pollution was deposited solely from sources within New Hampshire and adjacent counties in Maine, Massachusetts, and Vermont. We found that, in general, the average mercury deposition due to local sources is relatively low ($7.0 \mu\text{g}/\text{m}^2\text{-yr}$). However, we identified an area of intense deposition near Concord, New Hampshire, where we estimate that deposition reaches $76 \mu\text{g}/\text{m}^2\text{-yr}$ – four to five times higher than the EPA’s estimate of 15 to 20 $\mu\text{g}/\text{m}^2\text{-yr}$ for the same region (Figure 8).

Based on the data from the computer analysis, we determined that roughly 65 percent of all the mercury deposited to this area of high deposition near Concord, New Hampshire, is attributable to local (and some regional) sources, and that global sources therefore play a much smaller role. These results suggest that EPA may have underestimated total mercury deposition and the impact of domestic coal-fired power plants on mercury deposition in areas near large emission sources.

Mercury in Fish and Wildlife

Mercury levels are extremely high in fish and wildlife inhabiting waters within the biological mercury hotspot spanning southern New Hampshire and northeastern Massachusetts. The average mercury concentration in yellow perch reaches 0.78 ppm – more than 2.5 times higher than the EPA human health criterion, and twice the regional average. The loons that feed on these fish reflect the high mercury levels in their blood. Of the 39 loons we sampled in the hotspot area, 28 percent had blood mercury levels of 3.0 ppm, or higher. One loon found in Swains Lake in Barrington, New Hampshire, had a blood mercury level of 7.1 ppm – among the highest levels recorded in North America.

But the picture need not look so grim. Monitoring data show that as atmospheric emissions and deposition from local sources decline, mercury levels in fish and wildlife can improve rapidly. Mercury emissions from New Hampshire sources that are upwind of the biological mercury hotspot declined 45 percent between 1997 and 2002. Average loon blood mercury concentrations from ten study lakes in the hotspot decreased 64 percent between 1999 and 2002. Yellow perch from Massachusetts study lakes in the hotspot showed a 32 percent decrease during roughly the same period (Smith and Hutcheson 2006). These

reductions in mercury in fish and wildlife were much greater than observations elsewhere in the Northeast.

¹ Industrial Source Code Short Term (ISCST3) model.

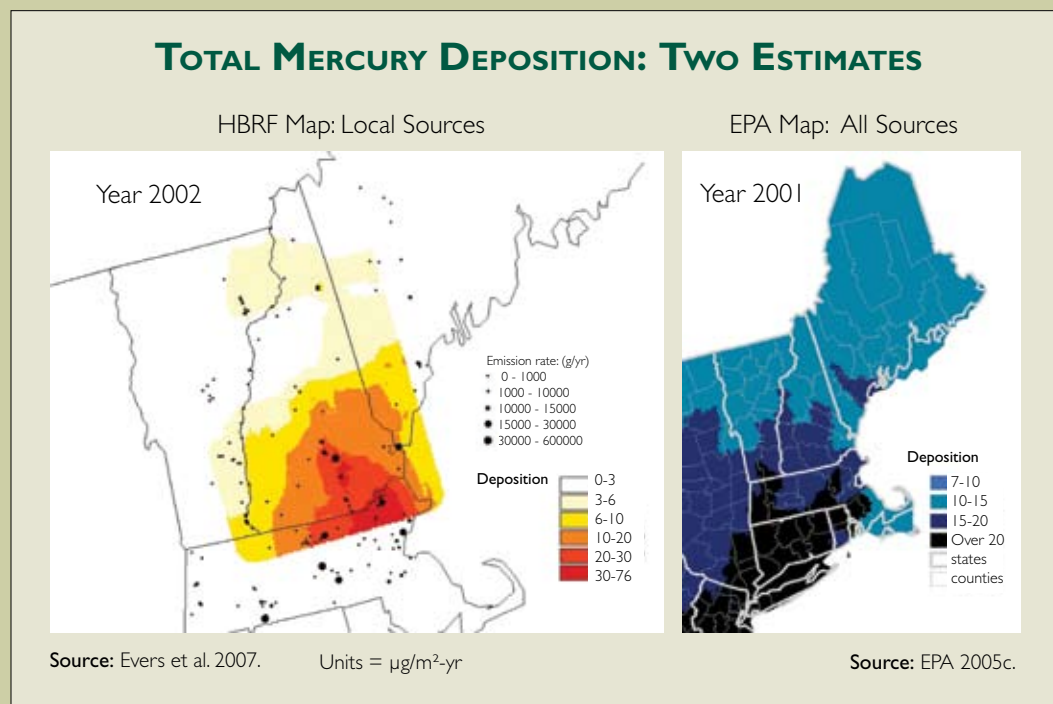


FIGURE 8: A model used to quantify local sources of airborne mercury pollution (left) showed deposition levels four to five times higher than EPA estimates (right).

Emissions Reductions from Coal Plants

Next, we used the same computer model to evaluate the impact of local coal-fired power plants on mercury deposition in New Hampshire. Using 2002 emissions data as a base case, we simulated the effect of cutting mercury emissions from four coal-fired power plants by 50 and 90 percent. The analysis showed that the greatest decrease in deposition would occur near Merrimack Station in Bow, New Hampshire – the largest coal-fired power plant in the study area. At this location, mercury deposition would decrease by 23 percent and 41 percent for the 50 and 90 percent emissions cuts respectively (Figure 9).

Based on this simulation, we determined that emissions from local coal-fired power plants account for roughly 40 percent of the total mercury deposition in this study area that is derived from local sources. This finding appears to contradict an EPA conclusion that coal-fired power plants in the United States contribute less than 5 percent of the total mercury deposition in the same area (EPA 2005c).

Pulling together the model results and biological trends data, we find that reductions in emissions from coal-fired power plants near this biological mercury hotspot would have a proportional impact on both mercury deposition and mercury in fish and wildlife.

Policy Implications

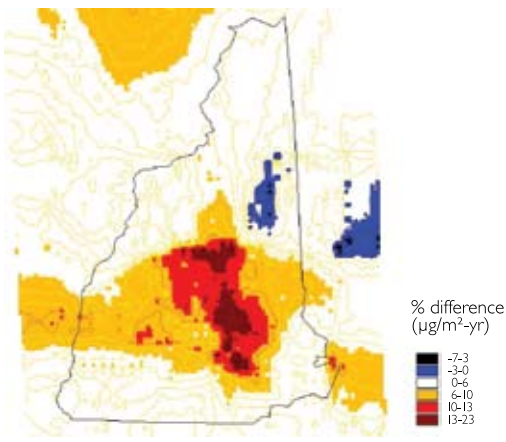
The case study findings are particularly important in light of recent federal policy. In May 2005, the EPA adopted the Clean Air Mercury Rule (CAMR) to reduce mercury emissions from the pool of coal-fired power plants by 70 percent by 2025. CAMR also includes a cap on national mercury emissions from coal-fired power plants, but allows individual facilities to buy and sell emissions credits to meet the cap rather than reduce actual emissions.

The New Hampshire case study holds important lessons for mercury policy. The results highlight the substantial role that local coal-fired power plants can play in local mercury deposition as well as fish and wildlife mercury levels. As such, these findings cast doubt on the effectiveness of unconstrained cap-and-trade programs that could allow emissions at some facilities to continue unabated.

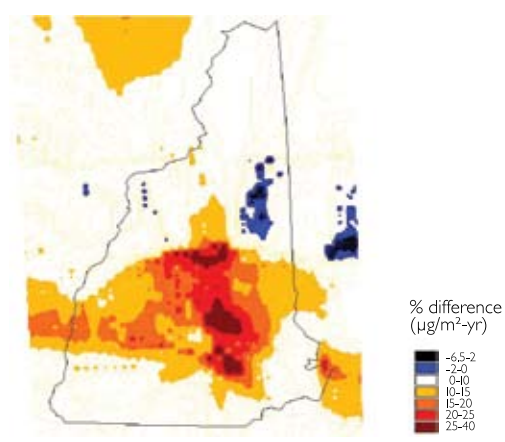
The EPA has responded to concerns over mercury trading by using results from its own national-scale deposition model to conclude that mercury hotspots, as EPA defines them, will not occur as a result of CAMR (Federal Register 2006). The results of the New Hampshire case study suggest that by using a large-grid model, the potential effects of mercury trading may not be fully evident in the EPA analysis.

DECREASES IN MERCURY DEPOSITION WITH EMISSIONS REDUCTIONS

50% Reduction Scenario



90% Reduction Scenario



Source: Han et al. 2007.

FIGURE 9:

Mercury emissions scenarios from four New Hampshire power plants show that near the largest power plant in the area, mercury deposition would decrease by 23 percent under the 50 percent reduction scenario and 41 percent under the 90 percent reduction scenario.

What Causes Biological Mercury Hotspots?

Biological mercury hotspots are associated with airborne mercury emissions and deposition that is amplified where local emissions are extremely high, ecosystems are particularly sensitive to mercury pollution, and/or reservoirs increase the availability of mercury.

Mercury pollution from atmospheric emissions and deposition is the primary driver for the biological mercury hotspots in the Northeast. The path by which mercury deposition leads to the formation of a biological mercury hotspot varies and includes: (1) extremely high deposition near large emission sources; (2) enhanced transport and bioaccumulation of mercury in sensitive watersheds; and (3) elevated production of methyl mercury in reservoirs that undergo substantial water-level fluctuations. In addition to atmospheric mercury deposition, one of the biological mercury hotspots is linked to leaching from contaminated soils at former industrial sites (Table 4).

1. High Mercury Deposition

Given the potential for mercury to deposit locally and regionally, it is not surprising that some biological mercury hotspots occur in proximity to large emission sources. The biological mercury hotspot in the lower Merrimack River watershed of New Hampshire and Massachusetts provides a clear example of a hotspot driven by elevated mercury deposition from local and regional mercury emission sources (see page 16).

2. Watershed Sensitivity

Biological mercury hotspots can occur in watersheds that receive average or even relatively low mercury deposition, but are sensitive to mercury pollution. These sensitive watersheds readily transport inorganic mercury, convert inorganic mercury to methyl mercury, and bioaccumulate this methyl mercury through the food web. The biological mercury hotspots linked to watershed sensitivity represent locations where moderate mercury deposition has generated high mercury concentrations in fish and loons compared to the surrounding landscape with similar mercury loading.

Mercury landscape sensitivity factors:

- ▶ Small lake to watershed ratio
- ▶ Waters impacted by acid deposition
- ▶ Shallow flowpaths
- ▶ Abundant shoreline wetlands
- ▶ Low nutrient inputs
- ▶ Forest cover
- ▶ Forest clearcutting
- ▶ Water-level manipulation

TABLE 4:

The primary causes of the five identified biological mercury hotspots in the Northeast are indicated. Locator numbers refer to the map on page 15.

Biological Mercury Hotspots: Primary Causes					
	Regional & global atmospheric deposition	Water-level management	Landscape sensitivity	Local air emissions	Local soil contamination
1a. Adirondack Mountains – west	x		x		
1b. Adirondack Mountains – central	x		x		
2. Upper Connecticut River	x	x			
3a. Merrimack River – middle	x			x	
3b. Merrimack River – lower	x			x	
4a. Upper Androscoggin River	x	x			
4b. Upper Kennebec River – west	x	x			x
4c. Upper Kennebec River – east	x	x			
5a. Kejimikujik National Park	x		x		
5b. Central Nova Scotia	x		x		

Source: Evers et al. 2007.

The Adirondack Mountains of New York and Kejimikujik National Park in Nova Scotia are two examples of biological mercury hotspots in sensitive watersheds. While mercury deposition to these areas is moderate, the average mercury concentrations in yellow perch caught in these areas range from 0.5 to 0.78 ppm – up to 2.5 times the EPA human health criterion. Mercury in loon blood is also elevated in these two biological mercury hotspots, reaching 7.8 ppm in Kejimikujik National Park where 93 percent of all loons sampled exceed the 3.0 ppm threshold. The dense forest cover in these regions enhances atmospheric mercury deposition; shallow soils facilitate its transport to surface waters; extensive wetlands promote its conversion to methyl mercury; and acid-impacted and/or unproductive lake chemistry greatly enhances the bioaccumulation of methyl mercury to high levels in fish and wildlife.

The rate at which mercury is supplied to surface waters and converted to methyl mercury varies from watershed to watershed. Several characteristics are widely cited as important: small watershed to lake size ratio, shallow flowpaths with reduced groundwater inputs, extensive forest and wetland land cover, and land use disturbances such as forest harvesting. Where these conditions prevail, methyl mercury production and supply to surface waters are generally high.

Another component of mercury sensitivity is “surface water sensitivity” which affects the ability of aquatic ecosystems to bioaccumulate incoming mercury to high levels in fish and wildlife. Key factors controlling surface water sensitivity include: low nutrient levels and productivity; high surface water acidity (including areas impacted by acidic deposition); and the nature and structure of the food web. To help resource managers determine which surface waters are likely to have fish with high mercury levels, the HBRF team analyzed data from across the Northeast and identified four surface water characteristics that are indicative of sensitivity and are associated with fish mercury concentrations above the EPA human health criterion of 0.3 ppm (Table 5).

The HBRF team evaluated the chemistry in Northeast lakes and found that nearly 60 percent of lakes meet one or more of the sensitivity thresholds and are therefore considered relatively sensitive to mercury pollution. The 28 water bodies contained within the biological mercury hotspots in the Adirondacks and in Kejimikujik National Park have average water chemistry values that meet all the thresholds for the four indicators and are therefore considered highly sensitive to mercury pollution.

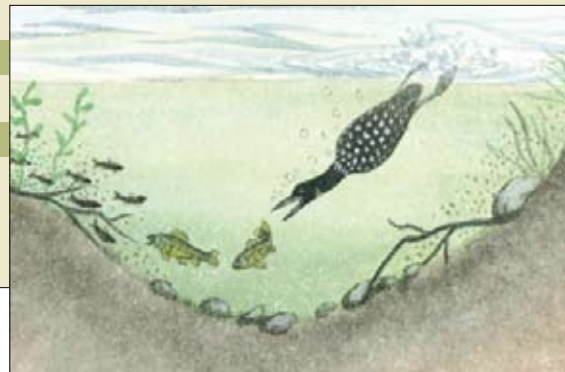
Given the potential for mercury to deposit locally and regionally, it is not surprising that some biological mercury hotspots occur in proximity to large emission sources.

TABLE 5: Water quality indicators that coincide with elevated concentrations of mercury in fish. Sixty percent of lakes in the Northeast meet one or more of the sensitivity thresholds.

Indicators of Surface Water Sensitivity

Indicators	Thresholds
▶ Total phosphorus	< 30 µg/L
▶ Dissolved organic carbon	> 4 mg/L
▶ Surface water pH	< 6.0
▶ Acid-neutralizing capacity	< 100 µequiv./L

Source: Driscoll et al. 2007.



The Importance of Improved Mercury Monitoring

The biological mercury hotspots analysis presented in this report was made possible by an extensive data gathering effort supported by the Northeastern Ecosystem Research Cooperative (NERC), with funding from the USDA Forest Service's Northeastern States Research Cooperative. While the data and information generated by this project provide insights into the nature and extent of mercury pollution across the region, many data gaps remain and most other regions of the United States and Canada do not have such a large biological data set from which to evaluate biological mercury hotspots. In addition, the current Mercury Deposition Network is too sparse and limited by its focus on wet deposition in rural areas to provide a detailed understanding of deposition patterns and their connection to local sources in the United States.

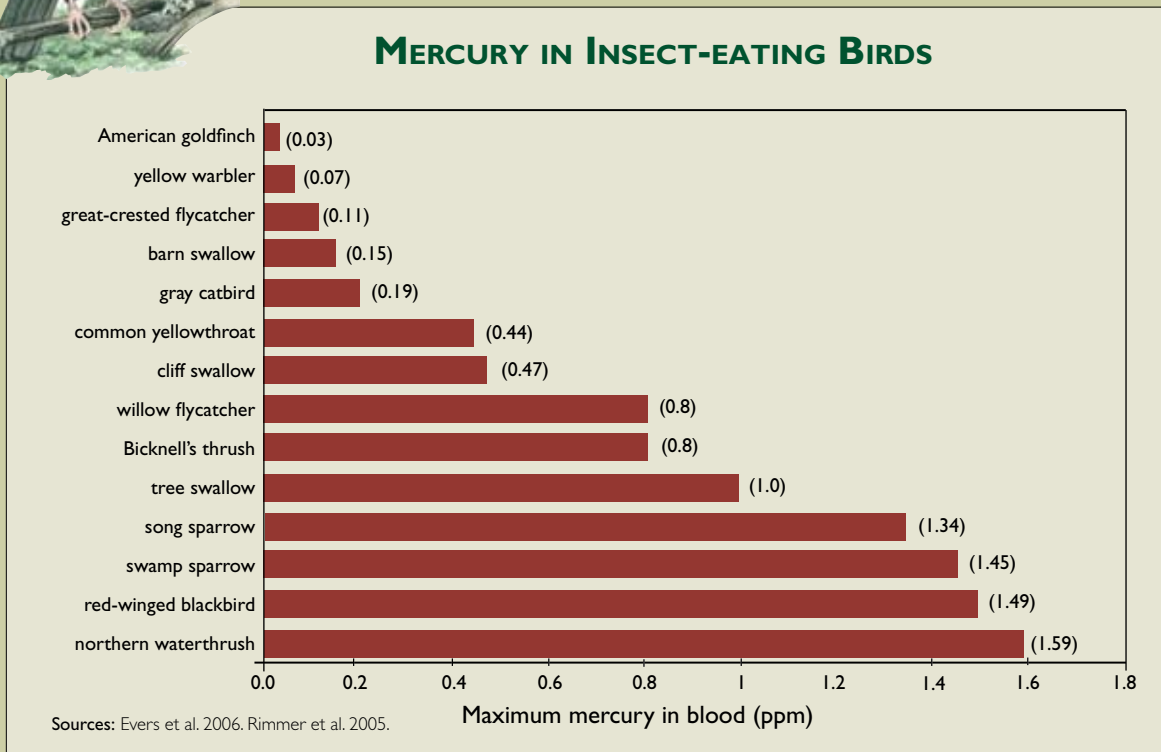
The problem of insufficient mercury monitoring was recently echoed in a report by the EPA Inspector General which states, "Without field data from an improved monitoring network... 'utility-attributable' hotspots that pose health risks may occur and go undetected." The reports goes on to say: "We recommend that EPA develop and implement a mercury monitoring plan to (1) assess the impact of Clean Air Mercury Rule (CAMR) on mercury deposition and fish tissue; and (2) evaluate and refine mercury estimation tools and models" (EPA 2006).

A comprehensive long-term mercury monitoring program focused on mercury deposition, watershed cycling, and biological effects would allow scientists to conduct a national scale assessment of biological mercury hotspots, and to link changes in emissions and deposition with ecosystem effects and response. At present, scientists must rely on limited information to make these important linkages. Increased mercury monitoring should extend to forest ecosystems where recent research revealed elevated mercury in insect-eating songbirds (Figure 10). Little information exists, however, to determine how mercury accumulates in terrestrial food webs and what levels are harmful to these birds.

A roadmap for a comprehensive national mercury monitoring program was developed by a team of scientists and is detailed in the 2005 paper "Monitoring the Response to Changing Mercury Deposition" published in the journal *Environmental Science & Technology*. The proposed program emerged from an EPA workshop in 2003 that brought together 32 scientists from across the United States to devise a national mercury monitoring program.



FIGURE 10: Recent research shows elevated levels of mercury in some songbirds.

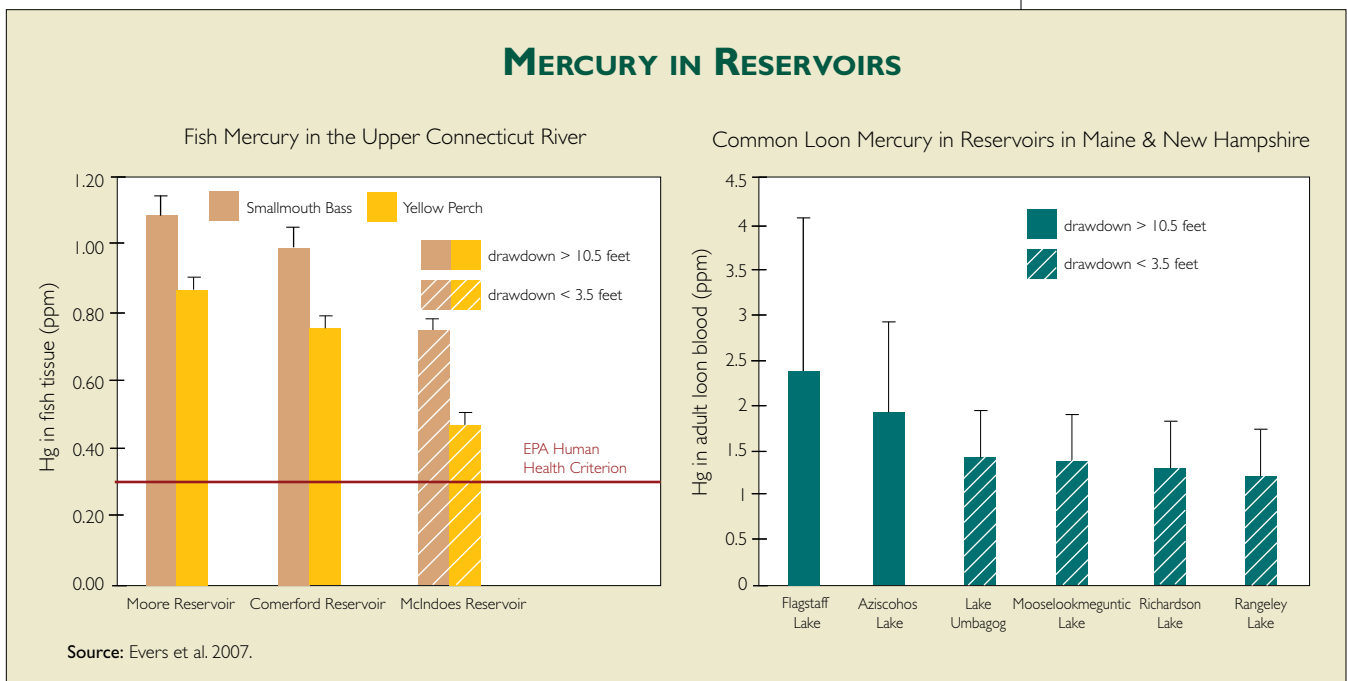


3. Reservoir Water Level Management

Several reservoirs in the Connecticut River in New Hampshire and the upper Androscoggin and Kennebec Rivers in Maine were identified as biological mercury hotspots. Mercury that is deposited to the landscape and transported to a reservoir can be readily converted to methyl mercury and mobilized under changing water levels. By exposing and then re-wetting large areas of shore land, fluctuating reservoirs provide prime conditions for the bacteria that produce methyl mercury. The methyl mercury formed in this shoreline environment can then be released to reservoirs during rain events or reservoir refilling.

A study of five reservoirs within a biological mercury hotspot in Maine shows that loon mercury concentrations increase with greater reservoir fluctuation. Mercury concentrations in loon blood are significantly higher in reservoirs that have summertime (June through September) drawdowns of 10.5 feet or more, than in reservoirs with drawdowns of 3.5 feet or less (Figure 11). Similar patterns in fish mercury concentrations were documented for smallmouth bass and yellow perch in three Connecticut River reservoirs within a biological mercury hotspot in New Hampshire. Researchers in Minnesota report that when reservoir fluctuations were dampened, fish mercury levels decreased (Sorensen et al. 2005). These findings suggest that fish mercury concentrations may be reduced by modifying water-level management regimes in certain reservoirs.

FIGURE 11:
Studies show that mercury concentrations in fish and loons are highest in reservoirs that have large water-level fluctuations, which provide prime conditions for bacteria that convert inorganic mercury to methyl mercury.



Conclusions

Mercury pollution is a complex problem involving different sources of mercury, diverse mercury deposition patterns, and wide-ranging ecological effects. While many questions remain regarding the science of mercury pollution, this much is clear:

- ▶ Mercury contamination is widespread in the United States, as evidenced by the fish consumption advisories that blanket the nation.
- ▶ Mercury emissions in the United States are the largest source of mercury deposition in many parts of the nation and in the Northeast, and domestic coal-fired power plants represent the single largest source of human-caused mercury emissions.
- ▶ Biological mercury hotspots exist across the northeastern United States and southeastern Canada, and represent areas where mercury levels in biota are high compared to the surrounding landscape; these hotspots pose serious risks to human and ecological health.
- ▶ Biological mercury hotspots are driven primarily by airborne mercury emissions and deposition that is amplified by large local mercury emission sources, high ecosystem sensitivity, and/or large water-level fluctuations in reservoirs.
- ▶ National and regional scale mercury models can underestimate mercury deposition near large emission sources, and fail to predict the relative contribution of emission sources such as coal-fired power plants.
- ▶ The case study in New Hampshire and Massachusetts demonstrates that emissions reductions from high-emitting sources near biological mercury hotspots in the United States will yield beneficial improvements in both mercury deposition and mercury levels in fish and wildlife.
- ▶ The case study further demonstrates that local coal-fired power plants are a significant contributor of some biological mercury hotspots, and reductions in mercury contamination may not be realized if a cap-and-trade policy allows emissions at these facilities to continue unabated.
- ▶ A national mercury monitoring network, coordinated with other international programs, should be established to better quantify total mercury deposition, identify potential additional biological mercury hotspots, and assess the environmental response to federal and state mercury emission policies.



Source Documents

The content of this report is based on three peer-reviewed scientific papers written by its authors with support from the Hubbard Brook Research Foundation. Unless otherwise as noted, all text, tables, and figures are adapted or reprinted from these papers:

- Driscoll, C.T., Y-J. Han, C. Chen, D. Evers, K.F. Lambert, T. Holsen, N. Kamman, and R. Munson. 2007. Mercury Contamination in Remote Forest and Aquatic Ecosystems in the Northeastern U.S.: Sources, Transformations and Management Options. *BioScience*. Volume 57, Issue 1.
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How to Reach Us

Hubbard Brook Research Foundation
16 Buck Road, Hanover, NH 03755
Telephone: (603) 653-0390
Facsimile: (603) 653-0391
Email: hbrook@hbresearchfoundation.org
Website: www.hubbardbrook.org/hbrf

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Pleasant View Farm Manager / Educator

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HUBBARD BROOK RESEARCH FOUNDATION

HEADQUARTERS

16 Buck Road, Hanover, NH 03755
(603) 653-0390

FIELD OFFICE

Pleasant View Farm
RR 1, Box 791
Campton, NH 03223

www.hubbardbrook.org/hbrf

