TESTIMONY TO
THE ENVIRONMENT AND PUBLIC WORKS COMMITTEE
SUBCOMMITTEE ON
CLEAN AIR AND NUCLEAR SAFETY

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Thank you Senator Carper, Senator Barasso and members of the Senate Environment and Public Works Committee Subcommittee on Clean Air and Nuclear Safety, for the opportunity to speak with you today about the science of mercury. My name is Charles T. Driscoll, Jr. I am a University Professor in the Department of Civil and Environmental Engineering at Syracuse University and a member of the National Academy of Engineering. I have studied the transport, fate and effects of mercury in the environment for more than 25 years, and published over 50 peer-reviewed scientific papers on the subject.

I'd like to start by pointing out that in many regions of the U.S., the fresh waters and coastal waters that provide food, recreation, and employment to millions of people have been contaminated by mercury inputs. The major source of this mercury contamination is atmospheric deposition. Mercury emissions from coal-fired electric utilities are the largest single source in the U.S. (Schmeltz et al., 2011). As a result of these long-term mercury inputs, there are hotspots and whole regions, such as the Adirondacks of New York, the Great Lakes region of the Midwest and large portions of the Southeast where the fishery is contaminated with mercury. Indeed every state in the U.S. has some sort of fish consumption advisory, and many states have blanket advisories (Schmeltz et al., 2011). There are more fish consumption advisories in the U.S. for mercury than all other contaminants combined. As a result, consumption of nutritionally important fish and the health of our nation's fish and wildlife resources are compromised by high concentrations of methyl mercury. The good news is that the science emerging from large-scale data synthesis efforts in the U.S. underscores the point that controlling U.S. sources of mercury emissions will decrease mercury contamination in the environment locally and regionally. This is what I would like to talk about today.

1. ***Are U.S. sources important to mercury deposition in the U.S.?***

Mercury is released to the environment in several ways, but the dominant pathway is airborne emissions and deposition (Fitzgerald et al., 1998; UNEP, 2003). One key to understanding the importance of U.S. sources is mercury transport (Figure 1).

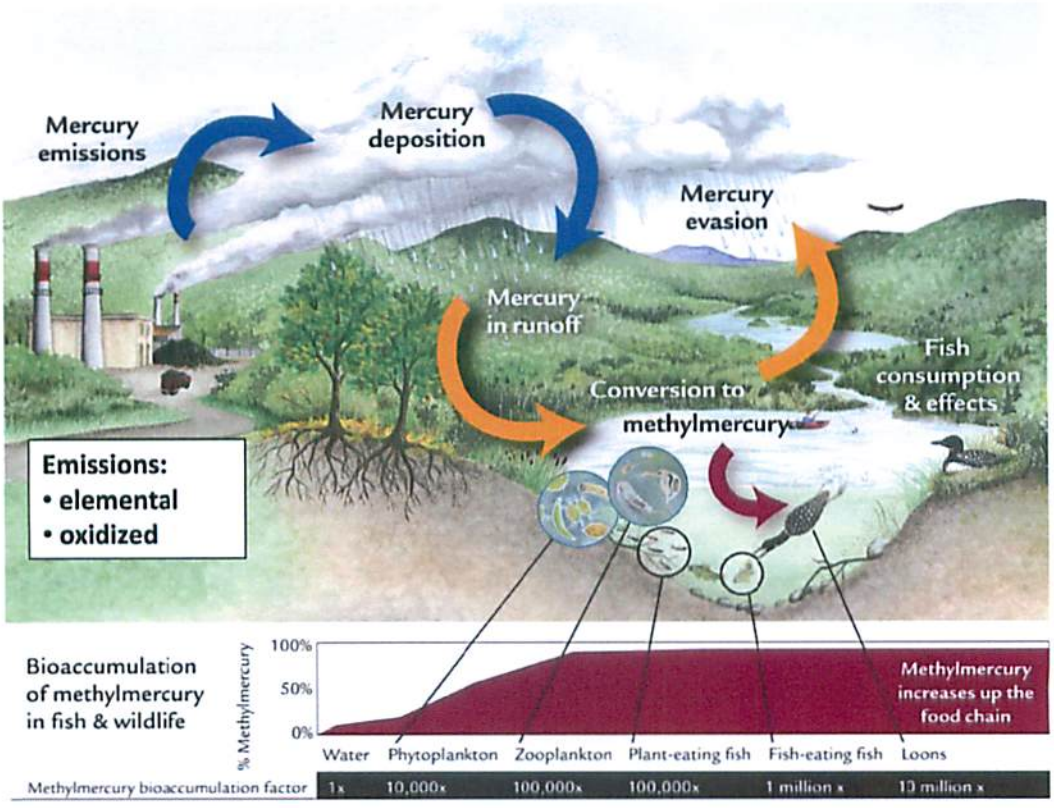

Figure 1. A simplified mercury cycle showing how mercury enters and cycles through ecosystems, biomagnifies up the food web, and bioaccumulates in fish and wildlife.

Mercury is emitted to the atmosphere in several different forms; elemental mercury, reactive gaseous mercury, and particulate mercury. The latter two forms together are known as oxidized (or ionic) mercury. Oxidized mercury is more chemically reactive and soluble in water than elemental mercury, and therefore deposits more rapidly and closer to the emission source (Keeler et al., 2006; Driscoll et al., 2007a,b,c). Elemental mercury is a relatively inert gas that does not readily dissolve in water. Therefore, it can undergo long-range transport. These distinctions between different forms of mercury become important when evaluating the relative importance of mercury emitted in the U.S. to deposition in the U.S.

While these general atmospheric transport distances have been well-researched, there are important deviations from these patterns that contribute to increased

local and regional deposition of mercury from U.S. sources. While elemental mercury does indeed have the ability to disperse globally, it may also deposit near its source or be readily converted to the oxidized forms that tend to readily deposit. For example, scientists have identified pathways for direct deposition of elemental mercury that decrease its transport distance and increase the probability of local deposition. Trees and other vegetation scavenge elemental mercury out of the atmosphere with its rough leaf surfaces, or through gas exchange in pores on the leaf surface known as stomates (Rea et al., 2002; Driscoll et al., 2007b). This pathway is one of the reasons that seemingly pristine areas like the Adirondacks and southern Appalachians receive large inputs of mercury. In forests of the Northeast and the Great Lakes region, it is estimated that up to 70% of total mercury deposition may occur through this "dry deposition" process (Miller et al., 2005; Risch et al., 2011).

Also although mercury may be emitted in the elemental form, it does not necessarily remain in that form. Elemental mercury can be converted to oxidized mercury in the atmosphere in areas where ground-level ozone is high or sea salt is prevalent (such as the coastal zone; Driscoll et al., 2007a,b). These conditions of elevated ozone and sea spray aerosols are common in the eastern U.S.

Based on what is known about how the various forms of mercury are transported or are converted in the atmosphere and the importance of dry deposition to forest lands in the Midwest and eastern U.S., it can be concluded that all forms of mercury may deposit locally or regionally. Coal-fired power plants play a particularly important role given the forms and amount of mercury they emit and their prevalence in certain regions of the U.S.

The tendency for U.S. emissions to deposit within the U.S. has been highlighted in several region-specific studies by different investigators using diverse approaches,

including the examples below.

- Han et al. (2008) conducted detailed plume modeling for southern New Hampshire and northeastern Massachusetts for the period 1996 to 2002 and determined that local emission sources are responsible for approximately 65 percent of the mercury deposited to that study area. They further estimate that nearby coal-fired power plants account for 40 percent of that locally derived mercury deposition (Han et al., 2008; Driscoll et al., 2007a).

- Keeler et al. (2006) investigated the sources of mercury in wet deposition near Steubenville, Ohio and determined that approximately 70% of the mercury was derived from coal combustion from local and regional sources.

- Bookman et al. (2008) studied long term patterns of mercury deposition to lakes in central New York and observed that these temporal patterns could largely be explained by mercury emissions from local and regional sources.

- Choi et al. (2008) conducted back-trajectory analysis from data on atmospheric concentrations of mercury species at the Huntington Forest, in the Adirondack region of New York. They found that for all three forms of mercury, elevated atmospheric concentrations appear to originate from states with high emissions of mercury, including Pennsylvania, Ohio, Indiana, Kentucky and West Virginia (Figures 2, 3 and 4). This analysis suggests that these regions are important sources of mercury to New York.

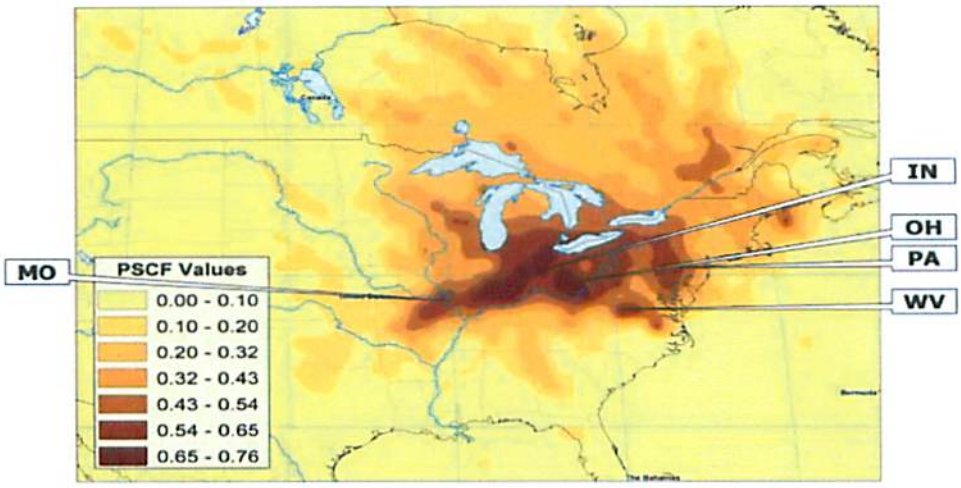

Figure 2. Sources of elemental mercury emissions to air at the Huntington Forest in the Adirondacks, based on back-trajectory analysis (after Choi et al., 2008).

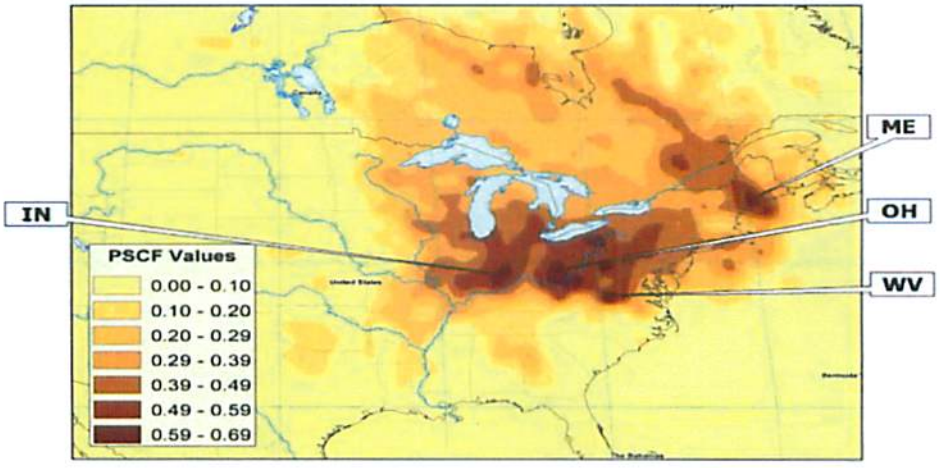

Figure 3. Sources of reactive gaseous mercury emissions to air at the Huntington Forest in the Adirondacks, based on back-trajectory analysis (after Choi et al., 2008).

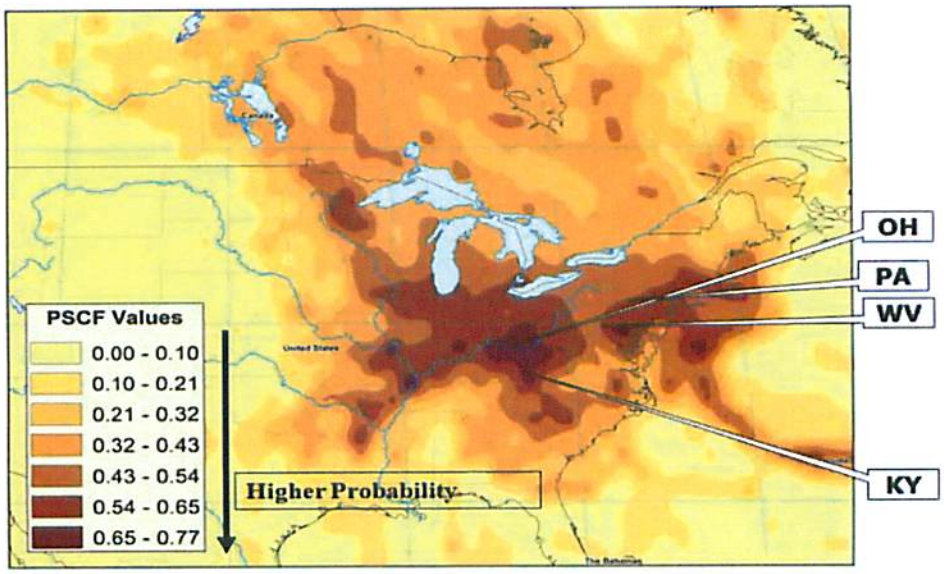

Figure 4. Sources of particulate mercury emissions to air at the Huntington Forest in the Adirondacks, based on back-trajectory analysis (after Choi et al., 2008).

2. *How widespread and severe is the mercury issue in the U.S.?*

Given the atmospheric transport of mercury and the sensitivity of large regions of the U.S. to mercury inputs, mercury is a widespread problem and the costs extend well beyond the effects on IQ quantified in the U. S. EPA benefits assessment (U.S. EPA, 2011). The deposition of mercury onto the landscape is just one step in the complex transformation of mercury from an inert element in the Earth's crust to a harmful contaminant in fish and wildlife (Figure 1). Most mercury entering the environment from atmospheric deposition occurs as ionic mercury that poses no direct health risk. However, as this relatively benign form of mercury is transported with water through the watershed, it comes into contact with bacteria that process sulfate in wetlands and lake or river sediments, and can be converted to the more bioavailable methyl mercury form by bacteria (including sulfate originating from power plant emissions; Figure 1). Sites where methylation of mercury readily occurs are wetlands and stream and lake sediments. Methyl mercury is of particular concern because methyl mercury strongly bioaccumulates through the food web.

Concentrations of methyl mercury increase by a factor of one million to 10-million from water to fish tissue (Driscoll et al., 2007a, c). Exposure to mercury largely occurs as methyl mercury.

Much of the mercury entering the environment from atmospheric deposition is retained in soil and sediments (e.g., Demers et al., 2007). This mercury represents a long-term legacy of atmospheric emissions and deposition. Some of this mercury deposited to the land surface is converted to elemental mercury and re-emitted back to the atmosphere. The extent to which mercury deposited to the land surface is ultimately transported to downstream surface waters is generally small. Note the mobilization of this legacy mercury in soil would delay the recovery of contaminated ecosystems after the implementation of controls on mercury emissions.

The sensitivity of ecosystems to atmospheric mercury deposition is reflected in their ability to transfer mercury inputs to methyl mercury and ultimately to bioaccumulate this methyl mercury in fish tissue. Conditions resulting in mercury sensitivity are common but are not uniform across the landscape, which is why it is possible to identify certain surface waters, perhaps even near power plants, where methyl mercury conditions are low and seemingly unresponsive to cuts in emissions. The characteristics that increase ecosystem sensitivity to mercury deposition include abundance of forest and wetland land cover, shallow hydrologic flowpaths, and water quality conditions that include low nutrient inputs, modest sulfate inputs and acidic conditions.

Several studies indicate a linkage between acidic deposition and mercury concentrations in fish. Atmospheric deposition of sulfate associated with sulfur dioxide emissions provides a necessary substrate for methylating bacteria (Gilmour et al., 1992). Methylating bacteria convert ionic mercury into methyl mercury, the form of mercury which bioaccumulates in fish and other wildlife.

Jeremiason et al. (2006) experimentally added sulfate to a wetland, observing increased methylation and increased export of methyl mercury. They inferred that increasing sulfur dioxide emissions and sulfate deposition would result in increases in methyl mercury in the fish of receiving waters (Jeremiason et al., 2006). Similar experiments have been conducted in Sweden and Canada (Branfireun et al., 1999; 2001). Drevnick et al. (2007) showed that decreases in fish mercury concentrations in Isle Royal were coupled with decreases in atmospheric sulfate deposition.

Hrabik and Watras (2002) used reference data and data from an experimentally acidified Little Rock Lake, Wisconsin, to examine the relative contribution of atmospheric mercury deposition and acidic deposition in regulating changes in fish mercury concentrations. They observed that decreases in fish mercury in an experimentally de-acidified basin exceeded those in the reference basin. Specifically, they found that approximately one-half of the changes in fish mercury concentrations over a six-year period could be attributed to de-acidification (Hrabik and Watras, 2002). This study suggests that acidification of lakes by acidic deposition has enhanced fish mercury concentrations and that concentrations of mercury in fish are likely to decrease with decreasing acidic deposition associated with controls on emissions from electric utilities.

Several large datasets have been synthesized in recent years to describe conditions and detect trends that demonstrate this variability in mercury sensitivity. Biological mercury hotspots have been identified in the northeastern U.S. and southeastern Canada using a dataset of biotic Hg concentrations (Evers et al., 2007). Eight layers representing three major taxa and >7,300 observations were used to locate five biological mercury hotspots and nine areas of concern (Evers et al., 2007; Driscoll et al., 2007c). The biological mercury hotspots include the western and central Adirondacks, the upper Connecticut River, the Merrimack River, the upper Androscoggin and Kennebec rivers in Maine, and southern and central Nova Scotia. Yellow perch and common loon were chosen as indicator species for human and ecological effects of mercury, respectively. Thresholds of 0.30 μg/g in yellow perch

fillets and 3.0 μg/g in common loon blood were used in the analysis. The biological mercury hotspots receive elevated atmospheric mercury deposition, have high landscape sensitivity to mercury deposition, and/or have reservoirs which experience large water-level fluctuations and enhance production of methyl mercury. These biological mercury hotspots represent distinct locations where there is a high density of independent surface waters with mercury concentrations in yellow perch above the EPA human health criterion of 0.3 parts per million (ppm) or where 25 percent or more of the common loons sampled have blood mercury concentrations above the adverse effect level of 3.0 ppm (Evers et al., 2007). The biological mercury hotspots were attributed to regional atmospheric mercury emissions combined with local sensitivity driven by the abundance of forests and wetlands and by the acidic water chemistry and associated simplified food web (Driscoll et al., 2007a).

A recent comprehensive synthesis effort in the Great Lakes region provides another useful study that depicts regional conditions (Evers et al., 2011). A screening analysis of the potential risk to human health posted by methyl mercury in fish in the Great Lakes region was conducted by comparing mercury concentrations in the fillet of six common game fish species (lake trout, largemouth bass, muskellunge, northern pike, smallmouth bass, and walleye) with specific risk categories. Mercury concentrations in 25,177 throughout the inland lakes of the Great Lakes region showed that 61 percent of the study area with sufficient data had average mercury concentrations in fillet of more than 3.0 ppm (the EPA human health criterion; Evers et al., 2011; Zananski et al., 2011; Monson et al., 2011; Figure 5). An analysis of spatial patterns in fish mercury showed that the higher fish mercury concentrations occurred in the inland lakes in the northern part of the Great Lakes region where there is high forest cover and abundant wetlands.

Note that the impacts of mercury extend beyond human health and risks from exposure through fish consumption. Recent science has demonstrated extensive effects of mercury on fish and wildlife that include decreased spawning success in

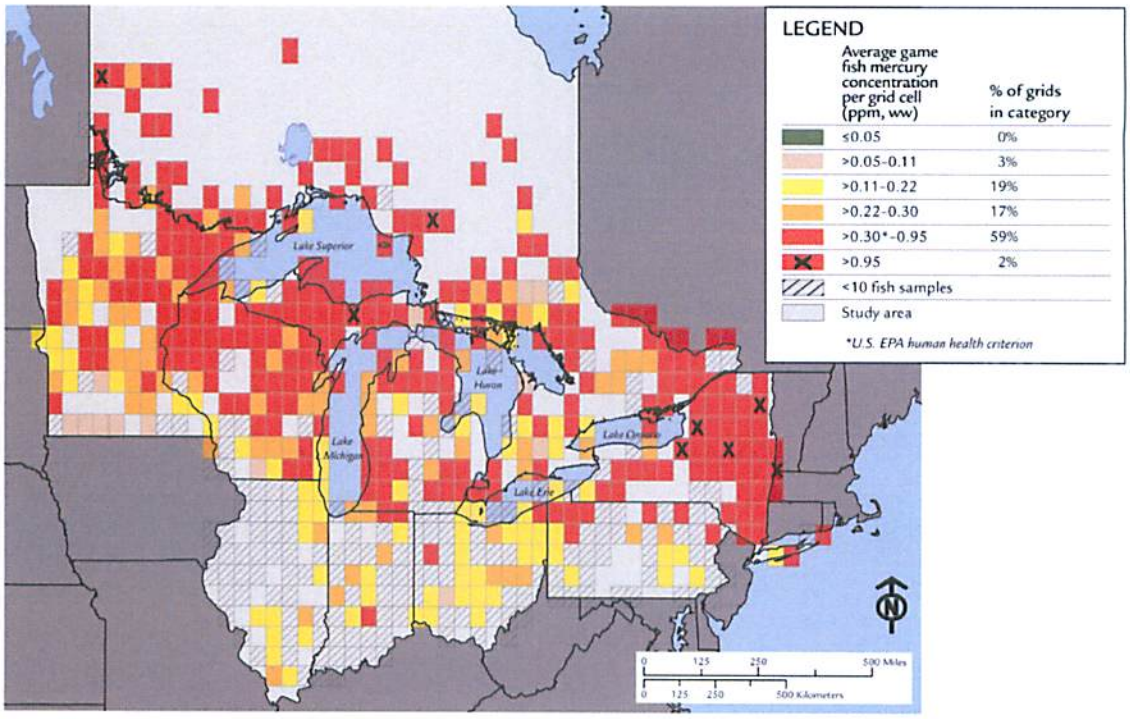

Figure 5. The mean mercury concentration in 30x30 minute grid cells for six common game fish species (lake trout, largemouth bass, muskellunge, northern pike, smallmouth bass, and walleye). Each study grid cell's color represents the mean mercury concentration of the game fish fillet samples taken from within the grid cell. A total of 25,177 fish samples were included across the region (1990-2008; data are from state and other fish monitoring programs). Grid cells with fewer than ten samples were excluded from analysis. Sixty-one percent of the study grid cells had an average mercury value in game fish fillets of more than 0.30 ppm (Evers et al. 2011 based on Zananski et al. 2011 and Monson et al. 2011).

fish (Beckvar et al., 2005; Dillon et al., 2010; Sandheinrich and Wiener, 2011) and fewer fledged young in fish-eating birds such as the common loon (Nocera and Taylor, 1998; Evers et al., 2005). The potential risk to fish from elevated methyl mercury concentrations was also evaluated in the Great Lakes region. An analysis of the commercially and recreationally important species, walleye, shows that in 53 percent of the study area, fish of reproductive size had methyl mercury concentrations above 0.2 ppm (whole body; wet weight; adapted from Sandheinrich et al., 2011; Evers et al., 2011) – the level at which adverse effects on growth,

behavior and reproduction occur (Beckvar et al., 2005; Dillon et al., 2010). These impacts to fish are particularly important for a region with a significant freshwater sport fishery that is estimated to have an economic impact across the eight Great Lakes state of $20 billion annually (Allen and Southwick, 2008).

Birds are also affected. For example, in the Great Lakes region, Rutkiewicz et al. (2011) reported that 14 to 27 percent of the bald eagles in a Great Lakes regional study had tissue burdens at or above proposed risk threshold for birds. Scientists have shown that methyl mercury also accumulates along the terrestrial food chain. Elevated concentrations have been observed in song birds in habitats at high elevations and songbirds and bats in wetlands (Rimmer et al., 2005; Evers et al. 2012).

Note that these and other ecological effects are not included in the EPA benefits analysis for the mercury and air toxics rule. The benefits analysis did a good job for what it represented, but it did not consider effects on fish and wildlife and the environment and therefore underestimated the benefits of decreased mercury emissions.

3. ***Will decreases in U.S. emissions lead to environmental improvements in the U.S.?***

Historical emissions and deposition have accumulated in soil and sediments resulting in a legacy of mercury contamination that will gradually become available and supply mercury into the environment. Nevertheless, a retrospective analysis shows that past decreases in U.S. emissions have led to beneficial improvements in the U.S. There are limited long-term data sets for methyl mercury in fish and wildlife, but lake sediments provide an important quantitative measure of how mercury inputs have changed over time. For example, the recent research from the Great Lakes region shows that as mercury emissions from sources in the Great Lakes region declined, so did mercury levels in this environment (Figure 6). A

comprehensive analysis of sediments taken from 91 inland lakes shows that mercury loading to the Great Lakes region increased about five-fold from the mid-1800s to peak values in the mid-1980s. Sediment mercury deposition has decreased about 20 percent from peak levels (Drevnick et al., 2011). These recent declines in mercury in lake sediments were concurrent with a 48 percent decrease in U.S. mercury emissions in the Great Lakes region, even as there was a 17 percent increase in global emissions (largely from Asia). The findings from this comprehensive review of mercury flux from sediments across the region have important policy implications. First, they suggest that local and regional mercury emissions are important of sources mercury to the Great Lakes region. Second, they suggest that recent controls on atmospheric emissions from sources in the Great Lakes region have been effective in decreasing the amount of mercury delivered to lakes across the region (Drevnick et al., 2011).

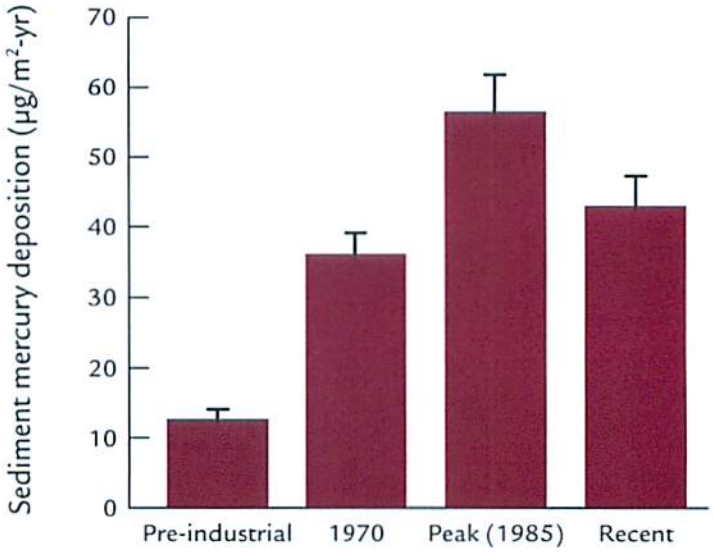

Figure 6. Atmospheric mercury that is deposited to inland lakes and accumulates in bottom sediments forms a record of historical mercury through time. Sediment cores taken from 91 inland lakes around the region indicate that the highest atmospheric mercury deposition occurred around 1985. Recent deposition of mercury is about 20 percent lower, but still three to four times greater than pre-industrial (~1850) levels.

Importantly, mercury concentrations in some fish and fish-eating birds in the region have declined from 1967 to 2009, mirroring the trends in mercury inputs and mercury in lake sediments. For example, mercury concentrations in walleye and largemouth bass from different parts of the Great Lakes region declined during this period and are now approximately 25 percent lower today than when measurements began (Monson et al., 2011; Weseloh et al., 2011; Figure 7). These data are characteristic of the regional trend of decreasing mercury concentrations in fish and wildlife in recent decades. While there may be a number of contributing factors, much of this decrease has been attributed to decreases in mercury emissions from U.S. sources in the Great Lakes region (Evers et al., 2011).

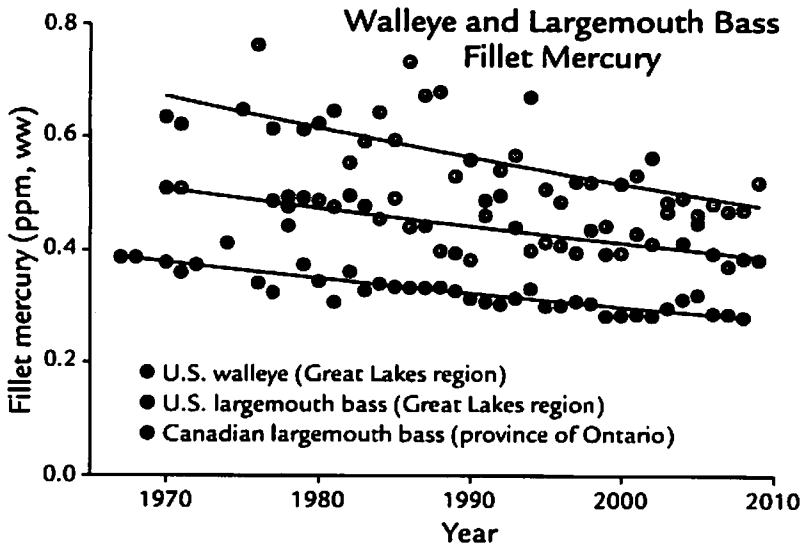

Figure 7. Temporal trends in fish fillet mercury concentrations (walleye and largemouth bass, averaged by year across multiple sites in the Great Lakes and inland water bodies in the U.S. Great Lakes states and the province of Ontario; Monson et al., 2011). These data are characteristic of the regional trend of decreasing mercury concentrations in fish and wildlife in recent decades. Much of this decrease has been attributed to reductions in regional mercury emissions, although there may be other contributing factors as well (Weseloh et al., 2011).

Thank you again for the opportunity to share some of this recent mercury science with you. I hope it is helpful to you in your deliberations.

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SUBCOMMITTEE ON
CLEAN AIR AND NUCLEAR SAFETY

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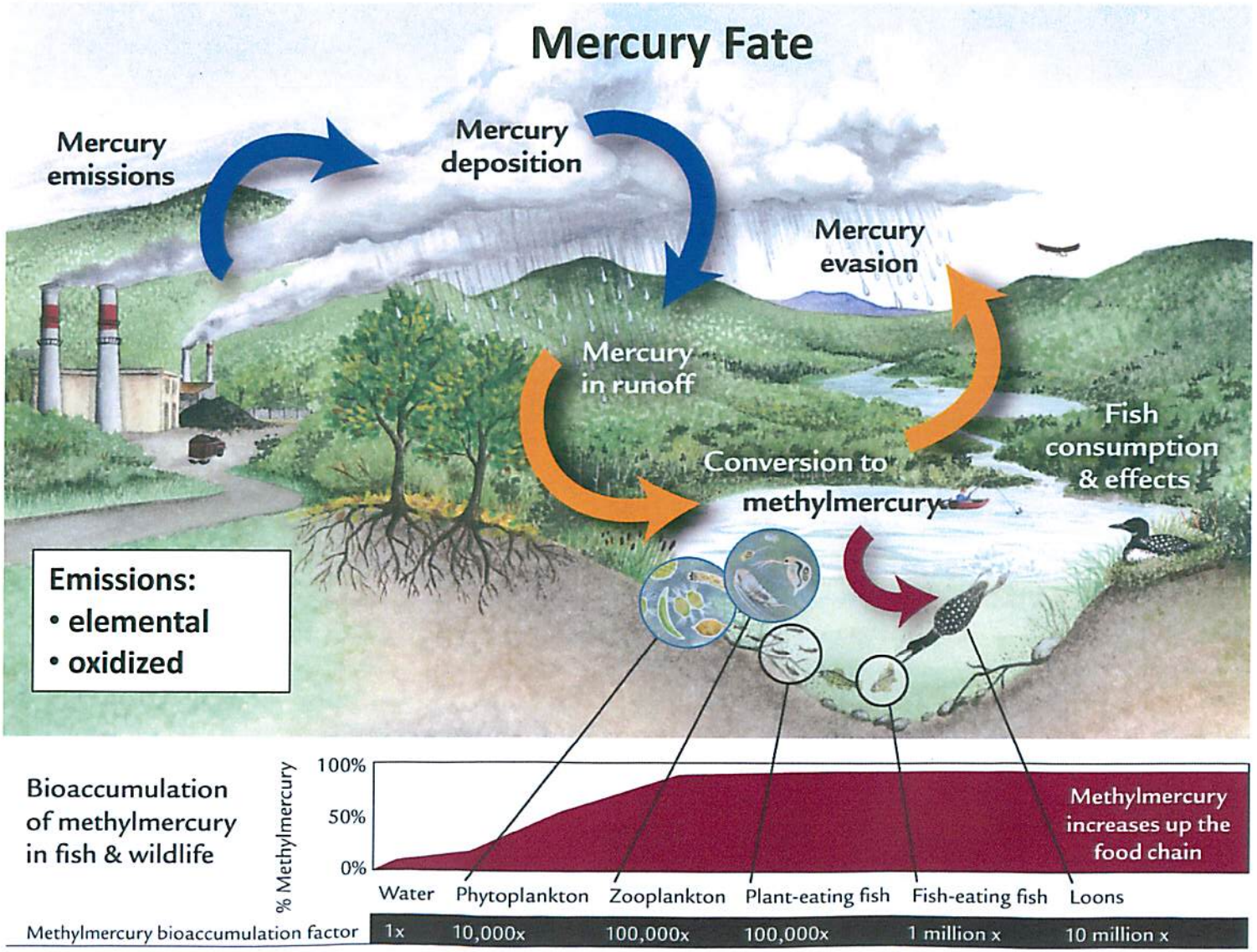
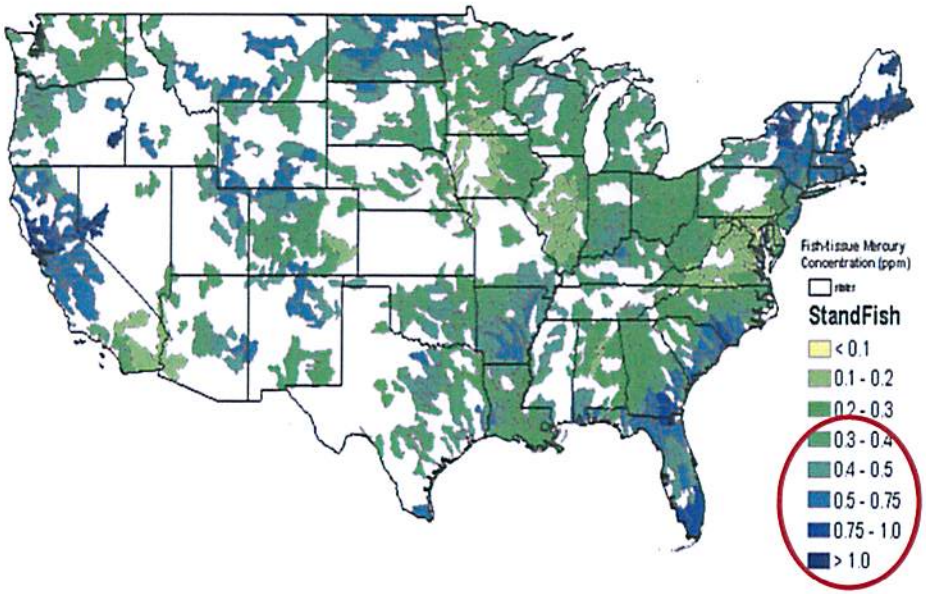
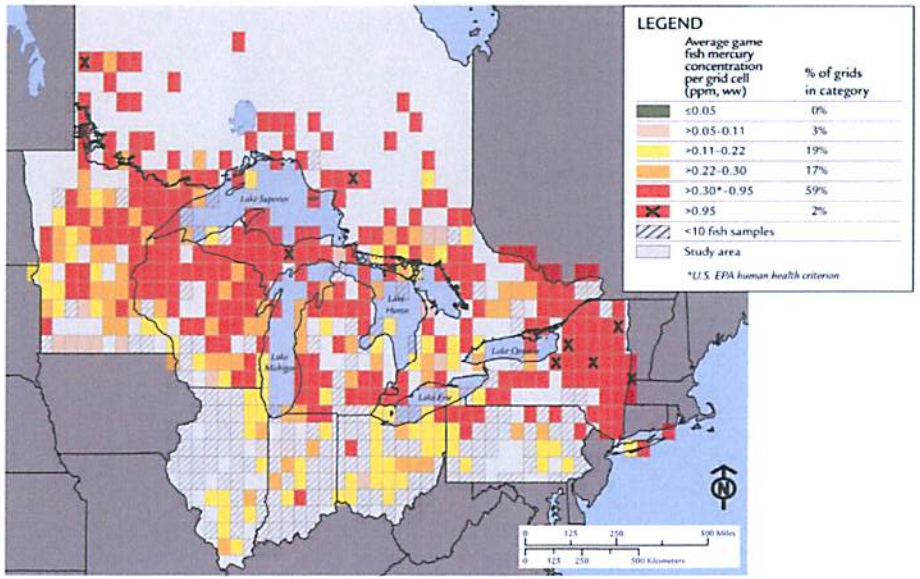
Are U.S. mercury emissions a major source of mercury inputs to the U.S.?



How widespread and severe are the impacts of mercury?

Mercury in Fish





Will decreases in U.S. emissions lead to environmental improvements in the U.S.?

Mercury Trends