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Does Mercury in Fish Come from the Air?

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Executive Summary

Concerns with public health risks associated with mercury-contaminated fish have prompted a variety of proposals to cut or eliminate mercury emissions. As a step toward assessing how such reductions could affect fish contamination, we develop a cross-sectional epidemiological model of mercury levels in fish. Using data on stream characteristics, land use, the presence of point sources and both measured and modeled atmospheric deposition of mercury, we explain two-thirds of the variation in mercury levels in fish. We find that greater mercury deposition is not generally associated with higher mercury levels in fish. These results suggest that reductions in deposition (and emissions) may affect mercury levels in fish only slightly or with a significant delay.

1. Introduction

Mercury in the environment has provoked substantial concern because an organic form, methylmercury, accumulates up the food chain. Chronic low-dose prenatal exposure to methylmercury from maternal consumption of fish has been associated with subtle neurotoxic effects in children.[1] States have issued more than 1,900 fish consumption advisories covering nearly the entire East Coast[2], the Gulf of Mexico, and the Great Lakes[3] to limit or avoid human consumption of specific fish from certain bodies of water. Congress is considering several bills that would reduce mercury emissions by 90 percent or more from coal-fired utilities,[4] which were responsible for about a third of all U.S. emissions in 1994-95[5] and are not subject to mercury regulations. In December 2000, the Environmental Protection Agency (EPA) will determine whether regulating emissions from coal-fired utilities under the Clean Air Act (CAA) is appropriate and necessary.[6] Behind these legislative and regulatory efforts is a little tested assumption that mercury in fish comes from the air.

Despite recent research efforts,[7] there is substantial uncertainty about the relationship between mercury emissions and environmental and health effects. The most important pathway for mercury emissions to affect human health is consumption of fish contaminated with mercury, nearly all of which is methylmercury.[8] Yet a recent review indicates "[t]he primary mechanisms controlling the accumulation of methylmercury and

[1] See National Research Council (2000).
[2] See U.S. Environmental Protection Agency (1999b). Excludes Maryland and Delaware.
[3] See U.S. Environmental Protection Agency (1999b). Excludes Ohio.
[4] The Clean Power Plant and Modernization Act of 1999 (S 1949) sponsored by Senator Leahy would require the removal of 90% of the mercury otherwise present in the fuel. The Clean Smokestacks Act of 1999 (HR 2900) sponsored by Congressman Waxman would cut emissions to only 10 percent of 1997 emissions. The Electricity Consumer, Worker and Environmental Protection Act of 1999 (HR 2645) sponsored by Congressman Kucinich would require the complete elimination of mercury emissions from electrical utilities by the year 2010. For a discussion of emissions reductions options, see U.S. Environmental Protection Agency (1999a).
[5] See U.S. Environmental Protection Agency (2000, p. II-7). Implementation of regulations addressing mercury from other sources will raise the share of mercury from coal-fired plants above this estimate.
[6] See Natural Resources Defense Council & Sierra Club v. U.S. Environmental Protection Agency and Carol Browner consent decree (November 17, 1998).
[7] See, for example, Jay, Morel, and Hemond (2000), Rea, Lindberg and Keeler (2000), and U.S. Environmental Protection Agency (2000, pp II-4 to II-19) for a recent survey. See Porcella, Huckabee, and Wheatley (1995) for earlier work.
[8] See U.S. Environmental Protection Agency (1997, Vol. 1 p. 2-5).

inorganic mercury in aquatic food chains are not sufficiently understood."[9] In a comprehensive report to Congress, EPA acknowledged, "remaining questions include…what affects the formation of methylmercury in water bodies and its bioaccumulation in fish."[10] Although a recent EPA report concluded there is a "plausible link" between emissions and fish-tissue concentrations, it provided no empirical evidence quantifying such a link.[11]

To estimate the benefits of reducing mercury emissions, researchers need a quantitative estimate of the effect of emissions on mercury levels in fish. As a first step in developing such an estimate, we construct an epidemiological model of mercury concentrations in fish by combining four data sets. The data sets describe mercury concentrations in fish, field measurements of mercury deposition, model-based estimates of deposition, chemical characteristics of streams, land use patterns and the presence of point sources.

A key advantage of our model is that it could help provide a summary estimate of how much mercury from the air affects mercury levels in fish, an estimate that may be crucial in calculating the benefits of further controls on mercury emissions. Stream chemistry and land use play an important role in determining mercury concentrations in fish. In our sample, a ten percent increase in land under cultivation in the watershed is associated with about a 30 percent increase in mercury levels in fish. We also find that mercury concentrations are higher in fish caught near pulp and paper mills. Although our model explains more than two-thirds of the variation in the log of mercury concentrations in fish, we find no evidence that increased mercury deposition is generally associated with higher mercury concentrations in fish. Thus, reductions in deposition (and emissions) may affect mercury levels in fish only slightly or with a significant delay.

2. Analysis

Using cross-sectional data, we develop a multivariate regression model of the determinants of mercury in fish. We use geographic variations in mercury deposition to

[9] See Mason, Reinfelder and Morel (1996, p. 1835).
[10] See U.S. Environmental Protection Agency (1998, pp. ES 18-19).
[11] See U.S. Environmental Protection Agency (2000), U.S. Environmental Protection Agency (1998), and U.S. Environmental Protection Agency (1999a)

develop a relationship between deposition and mercury concentrations in fish, holding constant other variables identified in the literature, as discussed below. Our data sources for deposition are the National Atmospheric Deposition Program (2000) and the Regional Lagrangian Model of Air Pollution (RELMAP) that EPA used in its 1997 report to Congress. We also use the U.S. Geological Service (USGS) National Stream Water Quality Monitoring Networks (1996) and EPA's *National Study of Chemical Residues in Fish* (1992).

Our approach is most closely related to Evers et al., who linked spatial variations in mercury levels in common loons to atmospheric deposition of mercury.[12] Although they found a geographic stratification from west to east that resembles EPA-modeled predictions of total deposition, they report that within-region blood mercury concentrations were less influenced by variations in geographic mercury deposition than by hydrology and lake chemistry.

Data

The atmospheric deposition data are from the Mercury Deposition Network (MDN), which is managed by the National Atmospheric Deposition Program. This network—the first attempt to develop a national database of mercury in precipitation—consisted of thirty-nine sites throughout the United States in 1999.[13] We considered only the twenty-seven U.S. sites with at least forty-eight weeks of data.

Since the field monitors that measure wet mercury deposition are not always near the sites where fish are caught, we also use EPA's predictions of total mercury deposition developed from its RELMAP model. EPA derived these predictions assuming that 1994-1995 emissions occurred in a year with 1989 weather patterns.[14]

Data from two USGS national stream water-quality networks, the Hydrologic Benchmark Network and National Stream Quality Accounting Network provide water body characteristics information. These two networks consist of water quality monitoring stations throughout the United States and provide national and regional descriptions of water-quality conditions and trends. The resulting databases provide information on

[12] See Evers et al. (1998).
[13] See U.S. Department of Commerce (2000) for a complete description of data collection methods.
[14] See U.S. Environmental Protection Agency (1997, Vol. 2 and Vol. 3 p. 4-2).

sixty-three physical, chemical, and biological properties analyzed during more than 60,000 stream visits using consistent sampling and analytical methods.[15] In our model we use data on pH, the percent of land under cultivation, and the levels of dissolved organic carbon, sulfate, and chloride.

The EPA *National Study of Chemical Residues in Fish* provides data on mercury concentrations in fish, fish species, and information about the presence of potential sources of pollution.[16] EPA collected fish samples primarily in 1987 at 388 locations nationwide. EPA Regional Offices were responsible for fish sample collection, which typically consisted of two representative composite samples of bottom feeders and game fish per site. Each composite sample contained three to five adult fish of similar size and from the same species at a given site. Both fillets and whole body samples were used. For mercury, the analytical procedure was based on flameless atomic absorption. Locations included sites relatively free of pollution sources and sites near potential point and nonpoint sources. For the two observations with mercury levels reported to be below the limit of detection, we assume levels equal to one half the lowest value reported in the sample—0.01 parts per million. EPA has recently published a more comprehensive assessment of mercury in fish that we plan to use in a subsequent analysis.[17]

We combine these four data sets by using a geographic information system. We consider only fish tissue samples collected within 200 km of the nearest mercury deposition monitoring station and in watersheds for which we have water quality information from USGS. Fifty fish tissue samples satisfy these conditions. We match these fish tissue samples with water quality data from the nearest water quality monitoring station in the same watershed, and with mercury deposition data from the nearest deposition monitoring station. We link all these data with model-based estimates of mercury deposition at the exact latitude and longitude where the fish were caught. We derive these model-based estimates by interpolating the total mercury deposition that EPA's RELMAP model forecasted at the four corners of a rectangular grid surrounding the fish collection site.

[15] See U.S. Geological Survey (1996).
[16] See U.S. Environmental Protection Agency (1992).
[17] See U.S. Environmental Protection Agency (1999c). Note that these data, unlike the earlier study that we use, lack information about the presence of potential point sources of mercury.

A drawback of these data is that they represent different time periods. The fish tissue data were collected as early as 1987, while the deposition data are for 1998 and 1999. Other data are for years between these dates. The different periods imply the conceptually correct variables are measured with errors and suggest the coefficient estimates may be biased towards zero. This bias may be limited to the extent that mercury deposition has been relatively constant over time and that bioaccumulation and up-take in predator fish species depends on exposure over longer periods. There is, however, little evidence about mercury deposition over the periods in question. Available evidence from the longest operating monitoring station, located in Underhill, Vermont, does not show long-term trends since 1992, except perhaps for a downward trend for vapor phase mercury.[18]

Choice of Variables

We include variables in the model if there is reasonable evidence suggesting they affect mercury in the environment or methylation.

Atmospheric deposition appears to provide a substantial relative contribution of mercury loadings to land and water.[19] Although mercury deposition can be wet or dry, we focus on wet deposition because no monitoring data on dry deposition are available. EPA concluded "wet deposition apparently is the primary mechanism for transporting mercury from the atmosphere to surface waters and land."[20] Recent mass balance studies for Lake Michigan indicate that about 80 percent of total deposition is wet.[21] We also consider, however, modeled total deposition of mercury, both wet and dry.

We include dummy variables for the presence of other possible sources of mercury. These include various point sources such as publicly owned treatment works and pulp and paper mills.[22]

We also include a variable for the percent of land that is under cultivation. There are several reasons to expect a positive association between it and mercury in fish. First,

[18] See U.S. Environmental Protection Agency (2000, p. II-11).
[19] See U.S. Environmental Protection Agency (1997).
[20] See U.S. Environmental Protection Agency (1997, Vol. 1 p. 2-4).
[21] See Landis (1998).
[22] A recent study by the Association of Metropolitan Sewerage Agencies indicates that domestic discharges of mercury are a major source of mercury to the environment. See Association of Metropolitan Sewerage Agencies (2000).

this variable may be a proxy for erosion and as EPA noted, "[b]oth watershed erosion and direct atmospheric deposition can be important sources of mercury to the water body, depending on the relative sizes of the water body and the watershed."[23] Land under cultivation may be a measure of agricultural use of fungicides containing mercury.[24] Finally, in its summary of several studies of Lake Champlain, EPA reports "urban and agricultural systems may retain less atmospheric mercury than forested systems,"[25] thereby providing yet another justification why more cultivated watersheds may have higher mercury levels in fish.

The most bioavailable form of mercury, methylmercury, accumulates in fish at higher levels in the food chain. EPA previously reported that mercury levels for piscivorous/predatory fish were about 0.3 parts per million, while levels for a lower trophic level were about 0.08 parts per million.[26] We categorize fish by trophic level, following a classification that includes five levels,[27] although virtually all fish that EPA sampled were either invertivores or carnivores.[28]

As mentioned above, Mason, Reinfelder and Morel describe chloride as an important factor in methylmercury accumulation. In fact, their studies indicate "passive uptake of uncharged, lipophilic chloride complexes is the principal accumulation route of both methylmercury and inorganic mercury in phytoplankton." [29]

Sulfate appears to be another critical factor in the methylation process because of its relationship to sulfate-reducing bacteria. Recent USGS studies in the Florida Everglades region have found correlations between sulfate levels and methylmercury concentrations.[30] While various processes can methylate mercury, the USGS reports that "scientists generally agree that methylation by sulfate-reducing bacteria is most important."[31]

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[23] See U.S. Environmental Protection Agency (1997, Vol. 3 p. ES-6).
[24] See, for example, U.S. Environmental Protection Agency (1997, Vol. 3, p. 2-6).
[25] See U.S. Environmental Protection Agency (2000, p. II-15).
[26] See U.S. Environmental Protection Agency (1997, Vol. 6 p. ES-9).
[27] See Goldstein and Simon (1999).
[28] It is often difficult to classify individual species in a single category because different species can often perform the same or similar trophic function at different times and different places. When species were listed for multiple trophic levels, we classified the species in the highest level listed.
[29] See Mason, Reinfelder and Morel (1996, p. 1835).
[30] See Zaneski (1999).
[31] See U.S. Geological Survey (1999, p. 1).

Mercury concentrations in fish are likely to depend on pH also. According to Mason, Reinfelder and Morel, "Mercury concentrations in fish are ultimately determined by methylmercury accumulation at the base of the food chain, which is governed by water chemistry, primarily pH and chloride concentration."[32] Typically, higher methylmercury content in fish tissue is found in more acidic lakes. Low pH may increase bacterial methylation rates, therefore increasing methylmercury availability.[33]

Dissolved organic carbon has been proposed as a primary mechanism for the transport of mercury in aquatic systems and generally increases the mercury concentrations in water.[34] EPA included DOC as a water body characteristic that affects methylation and demethylation in the water column.[35] However, the U.S. Geological Survey also reports, "Depending on local conditions, the amount of DOC-mercury binding can either increase or reduce mercury uptake by organisms."[36]

In figure 1 we present a map showing for each state in our sample, the average mercury level in fish and the average mercury deposition. Summary statistics of the variables used in this analysis appear in table 1.

The Model

As there is no simple correlation between mercury deposition and mercury levels in fish (see figure 2) we develop a multivariate regression model. We estimate the model using natural logarithms, so as to facilitate the interpretation of the coefficients and to ensure the errors are normally distributed. Given the uncertainty associated with the determinants of mercury in fish, we follow an empirical approach to model selection, focusing primarily on one that explains the data well. This approach means that estimated confidence intervals must be interpreted with substantial caution.

Measures of stream characteristics perform well in model 1 (see table 2), which has an R^2 of 0.65. In this regression, pH has the expected negative effect, and dissolved organic carbon has the expected positive effect. A dummy variable for carnivores indicates that predator fish have log mercury levels 1.1 times greater than other fish.

[32] See Mason, Reinfelder and Morel (1996, p. 1835)
[33] See U.S. Environmental Protection Agency (1997, Vol. 1 p. 3-18).
[34] See U.S. Geological Survey (2000).
[35] See U.S. Environmental Protection Agency (1997, Vol. 1 p. 3-18).
[36] See U.S. Geological Survey (1999).

Sulfate is not significantly associated with mercury levels in fish. In model 1, a 10 percent increase in dissolved chloride is associated with a five percent decrease in mercury concentrations. This finding differs from Mason, Reinfelder and Morel, whose model showed that chloride was positively associated with mercury in fish. Their model, however, differs from ours. It could "explain the variability of mercury concentrations in fish within, but not among different lake regions."[37]

Several potential anthropogenic sources have significant effects on mercury levels in fish.[38] In model 1, pulp and paper mills, which EPA has listed as sources of mercury,[39] are shown to be associated with statistically higher mercury concentrations in fish. Pulp and paper mills that do not use chlorine are associated with mercury levels in fish about 2.9 times higher than fish caught far from any pulp and paper mills; for pulp and paper mills that use chlorine the ratio is 1.7.[40] In addition, a 10 percent increase in land under cultivation within the watershed is associated with a 30 percent increase in predicted mercury levels in fish. This result is consistent with Balogh et al., who conclude that watershed characteristics, especially agricultural land use, can significantly influence mercury mobility.[41] The presence of a sewage treatment plant is associated with lower mercury levels in fish, but the effect is not statistically significant.

Mercury deposition in this model has an unexpected negative association with mercury levels in fish. Moreover, the effect is quantitatively large and statistically significant. We have no ready explanation for this result but note that it occurs in a broad variety of the models that we considered. A statistical interpretation of this result is that the waterbodies in our sample with high mercury deposition happen to be inefficient at moving mercury to the water and at methylation; these inefficiencies are not reflected in our other explanatory variables. This statistical explanation is unsatisfying, however, because it does not identify exactly what measurable characteristics of these waterbodies need to be included in the model for it to generate the expected positive correlation between mercury deposition and mercury concentration in fish.

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[37] See Mason, Reinfelder, and Morel (1996, p. 1835).

[38] We varied this model to include dummy variables for the presence of Superfund sites and other industrial sites but found that other models performed no better.

[39] See U.S. Environmental Protection Agency (1997, Vol II p. ES-6 and pp. 4-43 to 4-44.)

[40] Pulp and paper mills may have an association with mercury in fish, even holding constant measured mercury deposition, if their emissions have relatively high concentrations of divalent mercury ($mercury^{2+}$).

Measurements of mercury deposition used in model 1 may be as much as 200 km from the fish collection sites. In model 2 we instead use mercury deposition forecasts from EPA's RELMAP, interpolated to apply to each fish collection site. Although the range in modeled mercury deposition is much greater than in measured mercury deposition, the results are generally similar to model 1, with minor changes in estimates of coefficients and standard errors and a slightly lower R^2. Since this model performs no better than model 1, we concentrate on models with mercury deposition measured at the nearest point within 200 km.

Given the uncertainty over how sulfate affects methylation, in model 3 we introduce an interaction term to allow the effect of mercury deposition to vary with sulfate levels. The term is defined as the product of the natural log of measured deposition and the natural log of sulfate, and its effect is statistically significant at the 95 percent confidence levels. The effect of measured deposition on fish varies with sulfate levels, but equals -0.841 at the sample mean sulfate level. At sulfate levels equal to 84 parts per million (ppm), roughly 1.5 standard deviations greater than mean sulfate levels, the point estimate of the effect of deposition on mercury levels in fish becomes positive. At sulfate levels of 128 ppm, the highest level in our sample, mercury in fish would rise by 0.4 percent for a one percent increase in mercury deposition.

We conducted several sensitivity tests on model 3. Using Ramsey's test, model 3 rejects the hypothesis of omitted variables.[42] A Cook-Weisberg test indicates heteroscedasticity,[43] but after correcting for heteroscedasticity using White's robust estimators[44] the results are essentially unchanged. A visual examination of the data revealed no unduly influential data points. Deleting the data point with the greatest leverage from the regression did little to change the results.

Since the effect of publicly owned treatment works is inconsistent with our expectations, we delete this variable in model 4. As shown, the results are largely unchanged, with slightly greater coefficients for carnivorous fish and pulp and paper mills.

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[41] See Balogh, Meyer, and Johnson (1998).
[42] See Ramsey (1969).
[43] See Cook and Weisberg (1983).
[44] See White (1980).

Since some research suggests that forests can retain more mercury than agricultural land,[45] we allow land under cultivation to modify the association between mercury deposition and mercury in fish. In model 5 the effect of an interaction term defined as the product of land under cultivation and measured mercury deposition is statistically significant and positive. Thus in watersheds that are heavily cultivated, there is a positive association between mercury deposition and mercury in fish. In particular, model 5 implies that the association between mercury deposition and mercury in fish is positive in watersheds with more than 54 percent of land in cultivation; this level of cultivation is about two standard deviations above the mean level of cultivation in our sample.

Collinearity prevents more detailed analysis of such interactions. In models with two interactions terms (for both mercury deposition and sulfates, and mercury deposition and land under cultivation) neither is statistically significant and mercury deposition is negatively associated with mercury in fish.

An arbitrary aspect of this research is the inclusion of fish caught up to 200 km from the nearest deposition monitoring station. In model 6, we further restrict the distance between the fish collection site and the nearest deposition monitoring station to 150 km. Although the sample size falls to thirty-six data points, the regression changes little; coefficients and standard errors both increase modestly.

3. Conclusions

In an effort to provide a single summary measure of the effect of mercury deposition on mercury concentrations in fish, we develop an epidemiological model of mercury concentrations in fish using available data. We find no evidence that mercury deposition is generally positively associated with mercury concentrations in fish tissue. Indeed our model, which performs fairly well with respect to both the nature and magnitude of the effects of explanatory variables other than mercury deposition, shows that greater deposition is on average associated with reduced mercury levels in fish. This unexpected negative association between mercury deposition and mercury levels in fish

[45] See U.S. Environmental Protection Agency (2000, p. II-15).

appears to be attenuated by sulfate concentrations. In particular, though mercury deposition lowers mercury levels in fish at the sample mean sulfate level, for relatively high sulfate levels (i.e., > 85 ppm), greater mercury deposition is associated with higher mercury levels in fish. The negative association may also be attenuated by the percent of land in the watershed that is cultivated. The negative association between mercury deposition and mercury levels in fish vanishes for watersheds with more than 54 percent of land under cultivation, a level approximately two standard deviations above the sample mean.

The lack of a positive association between measured or modeled mercury deposition, and mercury levels in fish may be due in part to deficiencies in the deposition data. Measurements of wet mercury deposition are for dates several years after the time the fish were collected. Total mercury deposition forecasts produced by EPA's air quality models rely on emissions estimates for years after the fish were collected. We have no data on cumulative mercury deposition for the years (or decades) prior to when the fish were caught, though such data may be most pertinent to predictions of mercury levels in fish.[46]

These results suggest that reductions in deposition (and emissions) may affect mercury levels in fish only slightly or with a significant delay. Furthermore, because other variables successfully explain a majority of the cross-sectional variation in mercury concentrations, our research suggests that land use patterns, point sources and stream chemistry may play a role as important as air deposition. Substantially more research is needed to better understand how human activity contributes to mercury contamination of fish.

[46] There is ample evidence that mercury levels in fish in reservoirs decline to background levels only years or decades after impoundment. See, for example, Anderson et al. (1995).

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Figure 1
Geographic Distribution of Mercury Deposition and Mercury Levels in Fish
in the United States

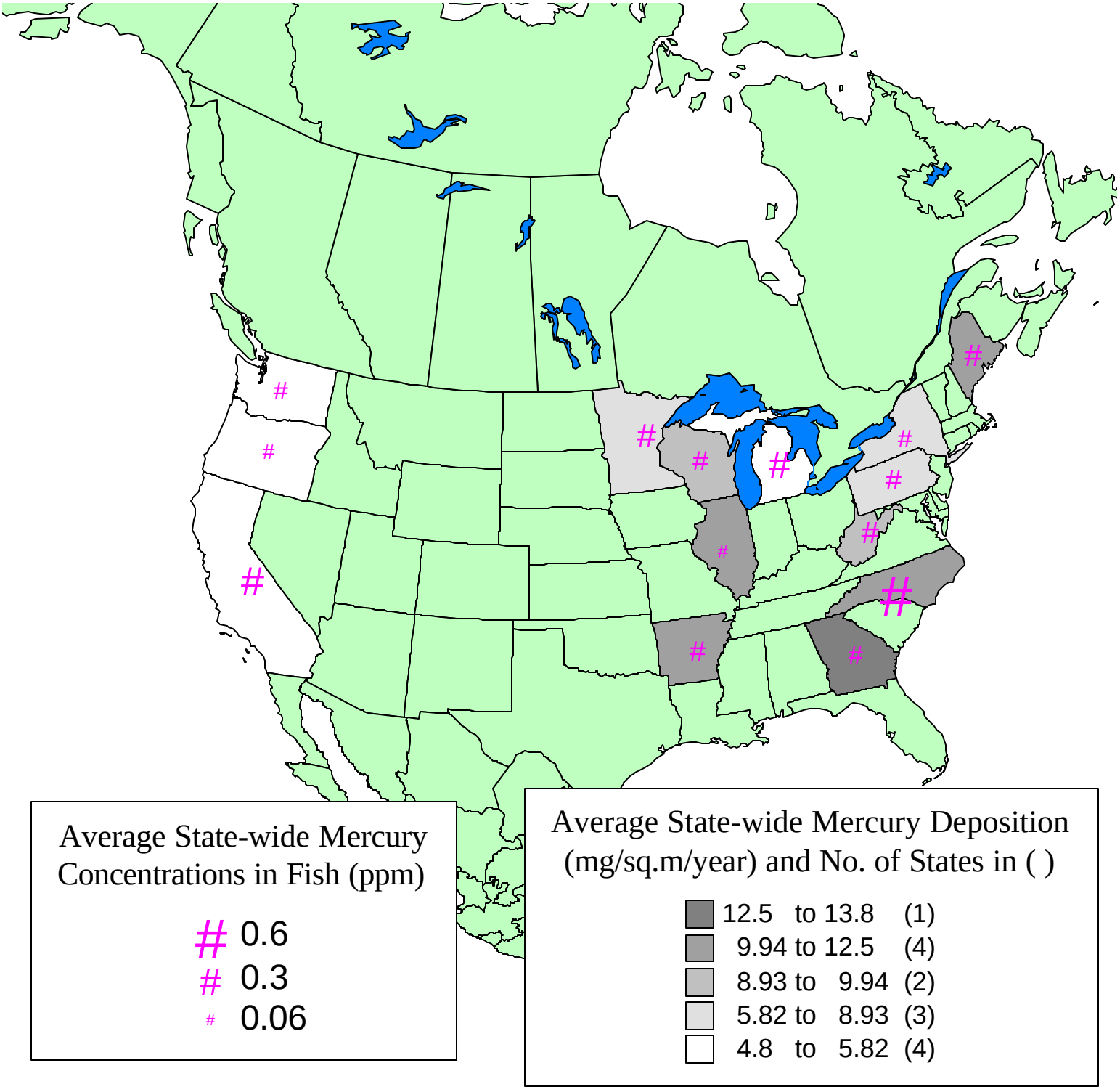
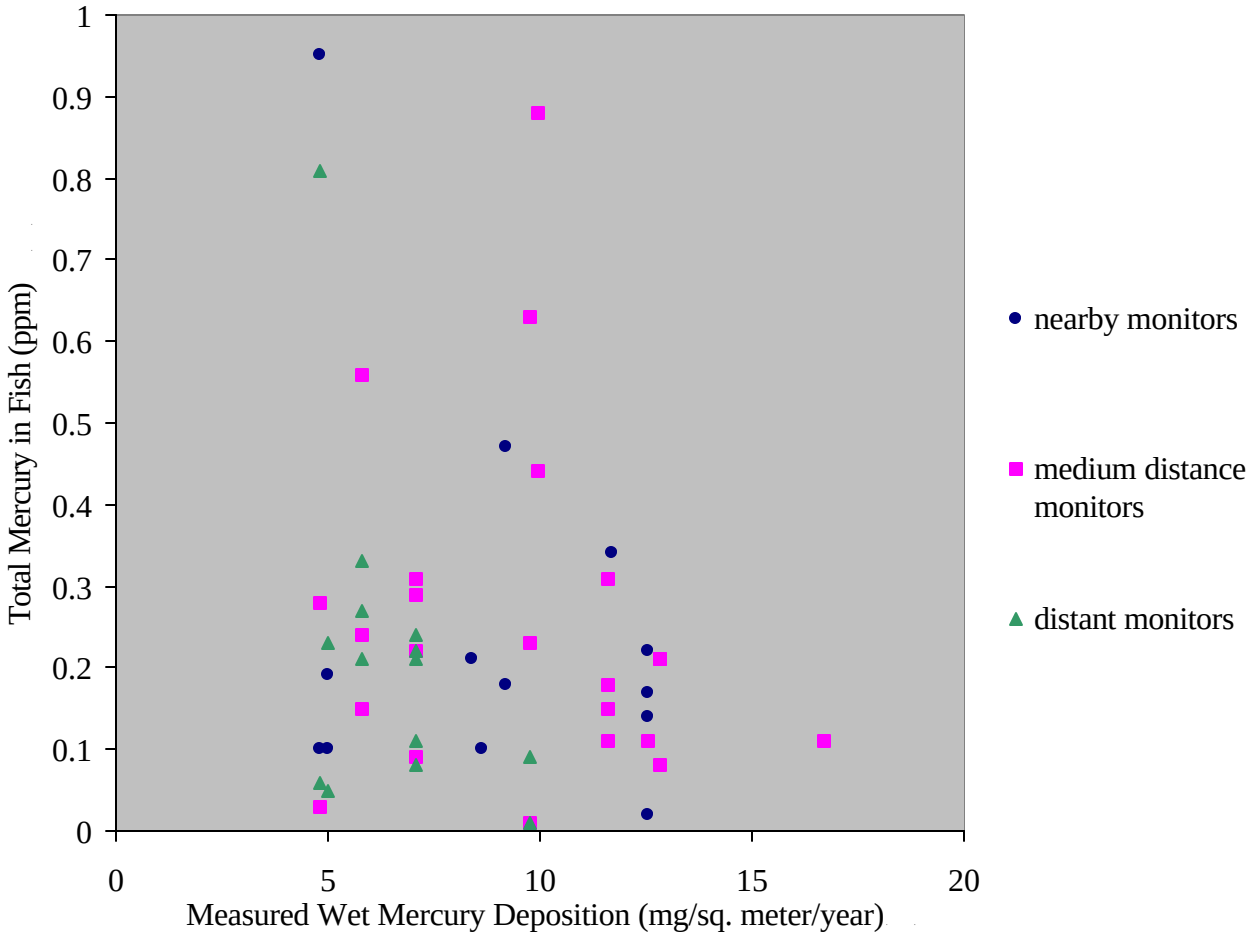


Figure 2

Wet Mercury Deposition and Mercury Levels in Fish



Note: There is no apparent relationship between mercury deposition and mercury levels in fish, regardless of the distance between the fish collection site and the deposition monitor. The nearby monitors were less than 75 kilometers from the fish collection sites. The distant monitors were more than 150 kilometers from the fish collection sites. The medium distance monitors were between 75 km and 150 km from the fish collection sites.

Table 1. Summary Statistics

Variable	Mean	Std. Dev.	Min	Max
Natural log of mercury concentration in fish, in micrograms/gram, 1987-1992.	-1.80	0.97	-4.61	-0.05
Natural log of total annual measured mercury deposition, relative to mean of annual measured mercury deposition. 1998.	-0.06	0.36	-0.58	0.67
Natural log of total mercury deposition projected at the fish collection site.	2.49	0.90	0.61	3.79
Dummy variable for the presence of a publicly owned sewage treatment facility.	0.36	0.49	0.00	1.00
Dummy variable for the presence of pulp and paper mills operating without chlorine.	0.12	0.33	0.00	1.00
Dummy variable for the presence of paper mills operating with chlorine.	0.40	0.49	0.00	1.00
Dummy variable for the presence of any paper mill.	0.52	0.50	0.00	1.00
Percentage of land in the watershed that is under cultivation. 1987.	20.23	15.34	0.57	63.88
Dummy variable for carnivorous fish, (mainly bass, catfish, walleye, crappie and trout).	0.46	0.50	0.00	1.00
Natural log of dissolved chloride relative to mean dissolved chloride in the sample, in milligrams per liter, 1985-1992.	-0.29	0.84	-2.87	1.26
Natural log of dissolved sulfate relative to mean dissolved sulfate, in milligrams per liter, 1987-1992.	-0.52	1.07	-2.15	1.35
Interaction defined as the product of the log of sulfate and the log of measured deposition.	0.21	0.50	-0.64	1.24
Ph, Standard Units, 1987-1992.	7.69	0.47	6.64	8.44
Natural log of dissolved organic carbon in milligrams per liter, 1987-1992.	1.89	0.65	0.71	3.16

Table 2. Regressions Equations For Mercury Levels In Fish
Coefficients and Standard Errors in ()

Variables	Models					
	1	**2**	**3**	**4**	**5**	**6**
Distance from fish collection site to deposition monitor	<200km	NA	<200km	<200km	< 200km	<150km
Log of measured mercury deposition	-1.30**		-0.841	-0.952**	-2.57**	-1.12
	(0.420)		(0.438)	(0.438)	(.651)	(0.709)
Log of forecast mercury deposition		-0.563**				
		(0.191)				
Sewage treatment works	-0.271	-0.218	-0.305			-0.456
	(0.221)	(0.227)	(0.208)			(0.299)
Pulp and paper mill without chlorine	1.06**	0.624	1.27**	1.40**	1.49**	1.65**
	(0.380)	(0.379)	(0.368)	(0.362)	(0.374)	(0.591)
Pulp and paper mill with chlorine	0.544*	0.245	0.415	0.499*	0.711**	0.390
	(0.243)	(0.259)	(0.235)	(0.231)	(0.229)	(0.364)
Percentage of land under cultivation	0.0266*	0.0136	0.0258*	0.0258*	.0239*	0.0278
	(0.0109)	(0.0102)	(0.0103)	(0.0105)	(.0105)	(0.0153)
Carnivorous fish	1.14**	1.26**	1.30**	1.37**	1.29**	1.34**
	(0.205)	(0.215)	(0.204)	(0.201)	(0.191)	(0.271)
Log of chloride levels	-0.353*	-0.386*	-0.471**	-0.505**	-0.504**	-0.478*
	(0.137)	(0.142)	(0.138)	(0.138)	(0.138)	(0.189)
Log of sulfate levels	-0.0146	0.0912	0.0832	0.0688	0.120	0.263
	(0.140)	(0.160)	(0.138)	(0.140)	(0.148)	(0.220)
Log of sulfate x log of mercury deposition			0.911*	0.874*		1.09*
			(0.3725)	(0.377)		0.5331
Percent of land under cultivation x log of mercury deposition					0.0480*	
					(0.0208)	
PH	-0.936**	-0.575*	-1.18**	-1.20**	-1.20**	-1.38**
	(0.335)	(0.280)	(0.331)	(0.336)	(0.336)	(0.397)
Log of dissolved organic carbon	0.772**	0.740**	1.17**	1.16**	0.989**	1.21**
	(0.198)	(0.197)	(0.248)	(0.251)	(0.210)	(0.341)
Constant	2.43	0.0235	3.39	3.36	3.75	4.80
	(2.31)	(1.99)	(2.21)	(2.24)	(2.28)	(2.66)
R^2	0.65	0.64	0.69	0.67	.68	0.69
Number of Observations	50	50	50	50	50	36

Note: The dependent variable is the natural log of mercury in fish. The symbol * indicates that an association is statistically significant at the 95 percent level, while ** denotes statistical significance at the 99 percent level.