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LANDSCAPE-LEVEL PATTERNS OF MERCURY CONTAMINATION OF FISH IN NORTH TEXAS, USA

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Abstract—Mercury (Hg) is a toxic metal that is found in aquatic food webs and is hazardous to humans. An emerging conceptual model predicts that the areas of the landscape that have the potential to contain food webs with elevated concentrations of Hg are those that receive high amounts of Hg and sulfate deposition and have high coverage of forests and wetlands and low coverage of agriculture. The objective of the present study was to test this conceptual model using concentrations of Hg in largemouth bass (*Micropterus salmoides*) from 145 reservoirs in four ecoregions of North Texas. The highest level of Hg contamination in fish was in the South Central Plains, the ecoregion that receives the highest levels of Hg and sulfate deposition and contains extensive forest and wetland habitat and little agriculture. The present study has important implications for other areas of the United States, because the South Central Plains extend into parts of Oklahoma, Louisiana, and Arkansas, covering a total area of 152,132 km^2 of the southern United States. Environ. Toxicol. Chem. 2011;30:2041–2045. © 2011 SETAC

Keywords—Mercury Atmospheric deposition Ecoregion Largemouth bass Land cover

INTRODUCTION

Because of its extreme toxicity and its widespread presence in aquatic food webs, methyl mercury (MeHg) poses a threat to human health. The primary pathway of MeHg into humans is through the consumption of MeHg-contaminated fish [1,2]. Human fetuses are particularly sensitive to MeHg, and prenatal exposure to MeHg can cause developmental and cognitive problems [1,2]. Warning the public about exposure to harmful levels of mercury (Hg) depends on identification of water bodies with elevated concentrations of Hg in fish, followed by the issuance of fish consumption advisories [3]. Because it is impractical to sample Hg in all water bodies where fishing may occur, the ability to predict which areas of the landscape are likely to contain water bodies with high fish Hg burdens is critical.

An emerging conceptual model predicts that areas of the landscape with elevated Hg and sulfate deposition, high coverage of forests and wetlands, and low coverage of agriculture are most likely to contain food webs with elevated Hg concentrations [4,5]. Atmospheric deposition is the primary source of Hg to aquatic systems [6]. Mercury contamination of fish has been correlated with deposition of atmospheric Hg [7], but sulfate deposition also affects Hg in fish [8], because sulfate availability enhances Hg methylation by sulfate-reducing bacteria [8]. Landscapes can also vary in their sensitivity to Hg deposition [4,5]. Mercury-sensitive landscapes are those in which relatively small inputs of total Hg can cause significant contamination of fish in upper trophic levels [4,6]. Mercury sensitivity of landscapes is determined in part by land cover type. Some land cover types, such as forests and wetlands, promote Hg contamination of food webs, whereas other land cover types, such as agricultural areas, reduce Hg contamination of food webs [4].

Most of the research leading to the conceptual model predicting spatial patterns of Hg contamination of food webs has been conducted in the northeastern United States [5], but applicability of this model to other areas of the country has not been tested. North Texas is an ideal area for testing this conceptual model because of the extreme west-to-east gradients of deposition of atmospheric Hg and sulfate pollution and land cover types associated with Hg sensitivity (Fig. 1). Because ecoregions denote areas of general similarity in land cover types [9], we used ecoregion as the unit of analysis for the present study. Here we show that the ecoregion with the highest level of Hg contamination in fish is the South Central Plains, an Hg-sensitive landscape that receives high levels of Hg and sulfate deposition. The present study has important implications for other areas of the United States, because the South Central Plains extend into parts of Oklahoma, Louisiana, and Arkansas, covering a total area of 152,132 km^2 of the southern United States.

MATERIALS AND METHODS

We focused on largemouth bass (*Micropterus salmoides*) because it is widely distributed [10] and is an economically important species of freshwater game fish that is commonly included in fish tissue contaminant databases [7,11]. As adults, largemouth bass are piscivorous top predators, often having high Hg concentrations relative to other fish species [12]. We used a data set of 2,803 largemouth bass collected from 145 reservoirs in Texas (Supplemental Data, Table S1). Relative to other types of aquatic systems, reservoirs can have biota with elevated Hg concentrations [11].

Forty-five percent of the largemouth bass (1,265 fish) were collected by biologists from the Texas Parks and Wildlife

All Supplemental Data may be found in the online version of this article.

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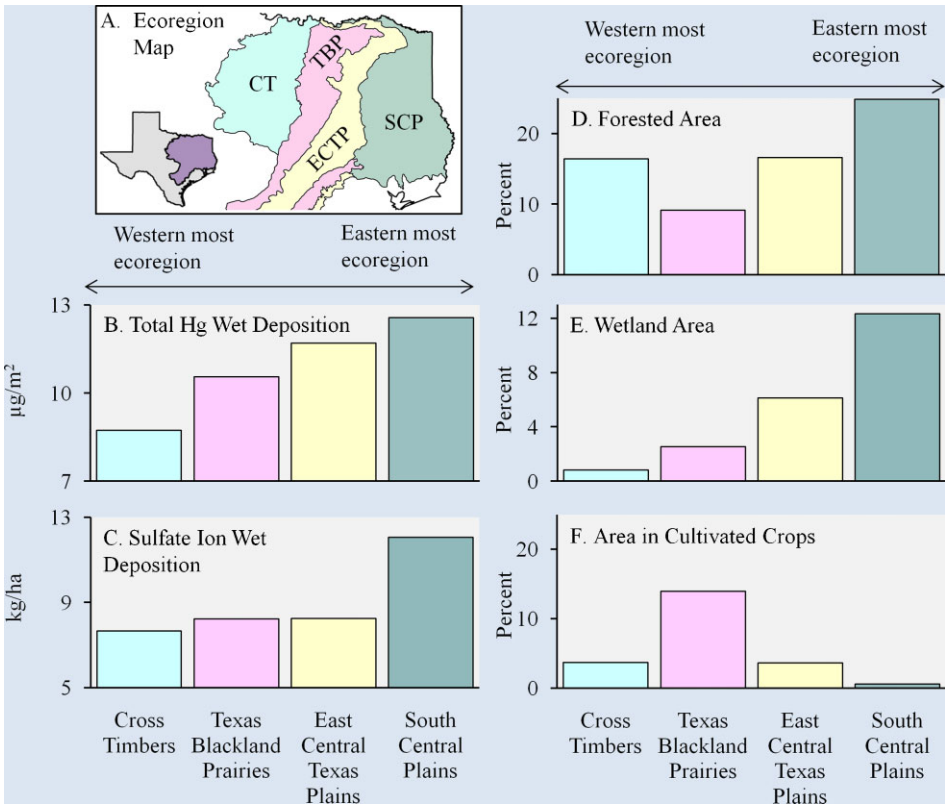

Fig. 1. (**A**) Map showing four U.S. Environmental Protection Agency level III ecoregions: Cross Timbers (CT), Texas Blackland Prairies (TBP), East Central Texas Plains (ECTP), and South Central Plains (SCP). Total Hg wet deposition (**B**) and sulfate ion wet deposition (**C**) in 2008 in the four ecoregions (http://nadp.sws.uiuc.edu). Percentage coverage by forested area (**D**), wetland (**E**), and cultivated crops (**F**) in 2001 (http://www.epa.gov/mrlc/nlcd-2001.html) in the four ecoregions. [Color figure can be seen in the online version of this article, available at wileyonlinelibrary.com]

Department (TPWD) during annual electrofishing surveys from 2004 to 2008 (Supplemental Data, Table S1) and analyzed for Hg concentrations in our laboratory. Fish were placed on ice in the field and later frozen for subsequent Hg analyses. Fillets were dissected from each fish, and a small subsample of epaxial muscle was collected from the center of each fillet for Hg analysis.

Total Hg concentrations were analyzed with a DMA-80 (Milestone) that uses thermal decomposition, gold amalgamation, and atomic absorption spectrometry [13]. We used total Hg as a proxy for MeHg, because Bloom [14] estimated that MeHg accounted for 95% of the total Hg in several species of fish (including largemouth bass), and the U.S. Environmental Protection Agency (U.S. EPA) [15] recommends analyzing total Hg in fish tissues as a proxy for MeHg. All Hg concentrations in the present study are total Hg and are reported as nanograms per gram wet wt. Detailed information about reference materials and quality assurance is supplied in the Supplemental Data.

Mercury concentration data for 55% of the largemouth bass (1,538 fish) were obtained from a published report [16], paper [17], federal database [18], and state databases, including the Texas Commission on Environmental Quality (TCEQ) database (P. Bohannon, TCEQ, personal communication), the Texas Department of State Health Services (TDSHS) database (K. Wiles, TDSHS, personal communication), and the TPWD database (R. Mills, TPWD, personal communication). These fish were collected between 1985 and 2009 (Supplemental Data, Table S1). All data were from analyses of Hg in skinless fillets of largemouth bass. Eighty-nine percent of samples were from individual fish, and 11% of the samples were composite samples of two to five largemouth bass. Although most states and several federal agencies routinely analyze Hg concentrations in fish, few studies have combined and evaluated these independently collected data sets [5,7,11]. In the present study, we used such data for the assessment of spatial patterns of Hg contamination of fish in North Texas.

Because fish Hg concentrations vary with length and it is difficult to obtain fish of a consistent length from all sites sampled, we used the National Descriptive Model of Mercury in Fish [19] to estimate the concentration of Hg in 46-cm-total-length (TL) largemouth bass by location and year for each reservoir. Forty-six-centimeters-TL is the largest largemouth bass commonly found in the creel in Texas (B. Farquhar, TPWD, personal communication). For reservoirs in which largemouth bass were collected in more than one year, we averaged predicted fish Hg concentrations for all years sampled to create a single value. Additional information about the National Descriptive Model of Mercury in Fish is given in the Supplemental Data.

Reservoirs sampled for largemouth bass were located using latitude and longitude coordinates and spatially mapped within ecoregions using ArcMap 9.3.1 software (Environmental Systems Research Institute). The Texas Statewide Mapping System (Lambert conformal conic projection) was used to project the data.

We examined spatial patterns of Hg in largemouth bass in four of the U.S. EPA level III ecoregions of Texas (Fig. 1), an area with a total surface area of 283,957 km^2 [9]. Ecoregions provide a pragmatic way to investigate Hg accumulation in fish, especially when site-specific data are not available [20]. Ecoregions denote areas of general similarity in ecosystems and in the type, quality, and quantity of environmental resources [9].

They are designed to serve as a spatial framework for the research, assessment, management, and monitoring of ecosystems and ecosystem components [9]. We tested for ecoregion differences in mean Hg concentrations of largemouth bass in four ecoregions in North Texas. We used univariate ANOVA followed by the Games–Howell post hoc test (SPSS version 11.5.0) to test for differences in the mean Hg concentrations of largemouth bass in water bodies from the four ecoregions. Statistical significance was determined at $p < 0.05$ for all analyses.

RESULTS AND DISCUSSION

Spatial patterns of Hg contamination

Mercury contamination varied with ecoregion (Fig. 2); the lowest and highest concentrations of Hg were in the Texas Blackland Prairies and South Central Plains, respectively (Fig. 3). The mean concentrations of Hg were significantly different between ecoregions (ANOVA, $df = 3, 141$, $F = 8.43$, $p < 0.001$; Fig. 3). The mean concentration of Hg in the South Central Plains was 490 ng/g, which was significantly greater than the East Central Texas Plains (297 ng/g; Games–Howell, $p = 0.002$), Texas Blackland Prairies (260 ng/g; Games–Howell, $p < 0.001$), and Cross Timbers (304 ng/g; Games–Howell, $p = 0.004$). These results are consistent with the conceptual model predicting that highest Hg concentrations in fish would be located in areas with high deposition of Hg and sulfate combined with Hg-sensitive landscapes.

It is important to recognize that the conceptual model predicts the potential for Hg contamination in fish in a geographic area, but the contamination levels in individual reservoirs in an ecoregion would be expected to vary. We would expect, based on the model, a lower mean Hg concentration and smaller range of Hg concentrations in regions with low rates of Hg and sulfate deposition, low levels of forests and

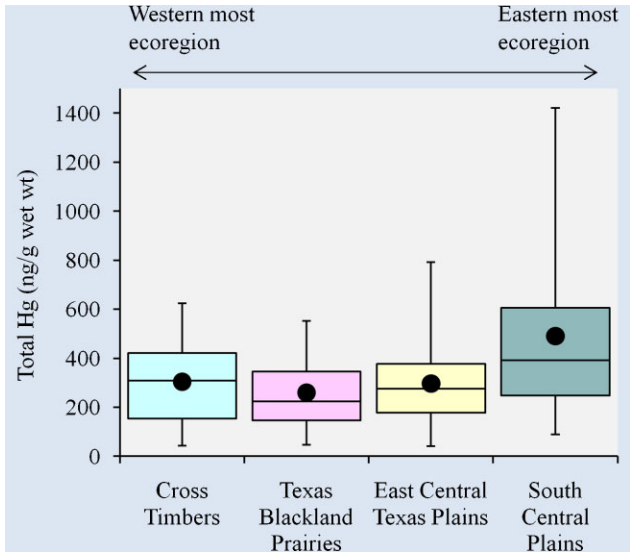

Fig. 3. Total Hg concentrations in largemouth bass from four ecoregions of North Texas, USA. Boxes, whiskers, horizontal lines, and points signify the first and third quartile, range, median and mean total Hg concentration of each ecoregion, respectively. [Color figure can be seen in the online version of this article, available at wileyonlinelibrary.com]

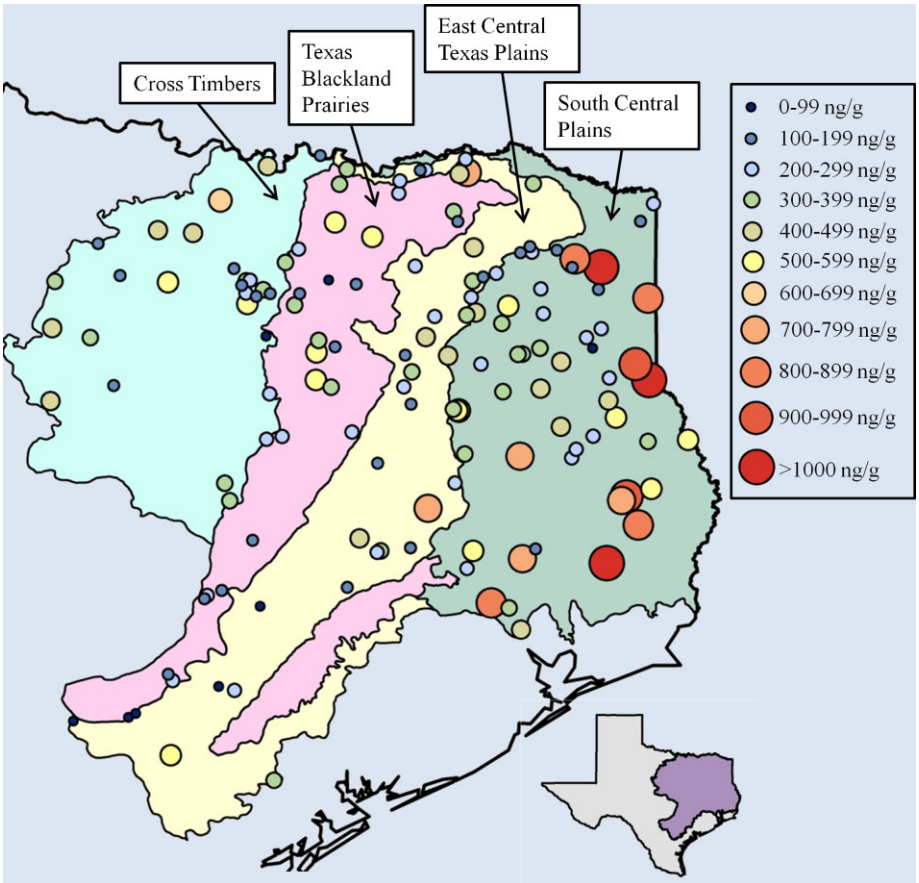

Fig. 2. Estimated total Hg concentrations in 46-cm-total-length largemouth bass from reservoirs in four ecoregions of North Texas, USA. [Color figure can be seen in the online version of this article, available at wileyonlinelibrary.com]

wetlands, and high levels of agriculture [4,5]. Conversely, we would expect a higher mean Hg concentration and greater range of Hg in regions with high rates of Hg and sulfate deposition, high levels of forests and wetlands, and low levels of agriculture [4,5]. The difference in means and ranges between ecoregions in the present study (Fig. 3) is consistent with the predictions of the conceptual model.

We found that water bodies in close proximity to one another could have different Hg concentrations in largemouth bass (Fig. 2), a result consistent with other studies of spatial patterns of Hg in fish [11,20]. The Hg concentrations of fish in neighboring lakes can vary by as much as tenfold, even when atmospheric Hg deposition is similar [21]. Although the potential for Hg contamination is set by atmospheric pollution and Hg sensitivity, it does not result in all lakes in the region having high Hg contamination of the food webs, because many other factors, working at a local scale, determine the Hg of individual water bodies [6,22]. For example, other studies have found that variables such as pH, dissolved organic carbon, and total phosphorus can account for variation in Hg contamination of biota between lakes [4,20,23,24]. Such data are not available for most of the Texas reservoirs considered in the present study, and understanding the factors responsible for interlake variability of Hg in a region was beyond the scope of the present study.

Fish consumption advisories

Fish consumption advisories are a widely used management tool to reduce the risk of adverse health effects in humans caused by consumption of Hg-contaminated fish, while avoiding potentially large costs associated with reduction of the contaminant in the environment [25]. The TDSHS considers issuing fish consumption advisories when Hg concentrations in fish exceed a screening value of 700 ng/g, but the U.S. EPA recommends that states use a screening value of 300 ng/g [26]. The TDSHS has issued fish consumption advisories for concentrations of Hg in fish above 700 ng/g for 12 reservoirs in North Texas. The present study suggests that use of the U.S. EPA screening value would result in a significant increase in the number of reservoirs with fish consumption advisories for Hg. Fifty-one percent of reservoirs had largemouth bass above the U.S. EPA screening value of 300 ng/g, and only 10% of reservoirs had largemouth bass above the TDSHS screening value of 700 ng/g (Fig. 4A). Only reservoirs in the East Central Texas Plains and the South Central Plains had 46-cm-TL largemouth bass above the TDSHS advisory level, but all four ecoregions have a significant percentage of reservoirs with largemouth bass above the U.S. EPA screening value (Fig. 4B).

Consumption advisories can be ineffective in protecting humans and wildlife. Angler compliance with fish advisories can be low, and anglers continue to consume contaminated fish from water bodies with advisories [27]. Advisories would not cover the small private ponds that are not monitored by the state, but these ponds numerically dominate the landscape [28] and may have high levels of Hg contamination [29]. Moreover, advisories would not protect fish and wildlife that consume Hg-contaminated prey and suffer Hg-related health consequences [30,31]. The results of the present study are consistent with the emerging conceptual model and, consequently, indicate that a reduction in atmospheric Hg and sulfate loading would help to reduce fish Hg burdens in Texas. Mercury being deposited in this area is coming from the global Hg pool and North American sources [32], but the relative contribution of these sources to water bodies in Texas is unknown.

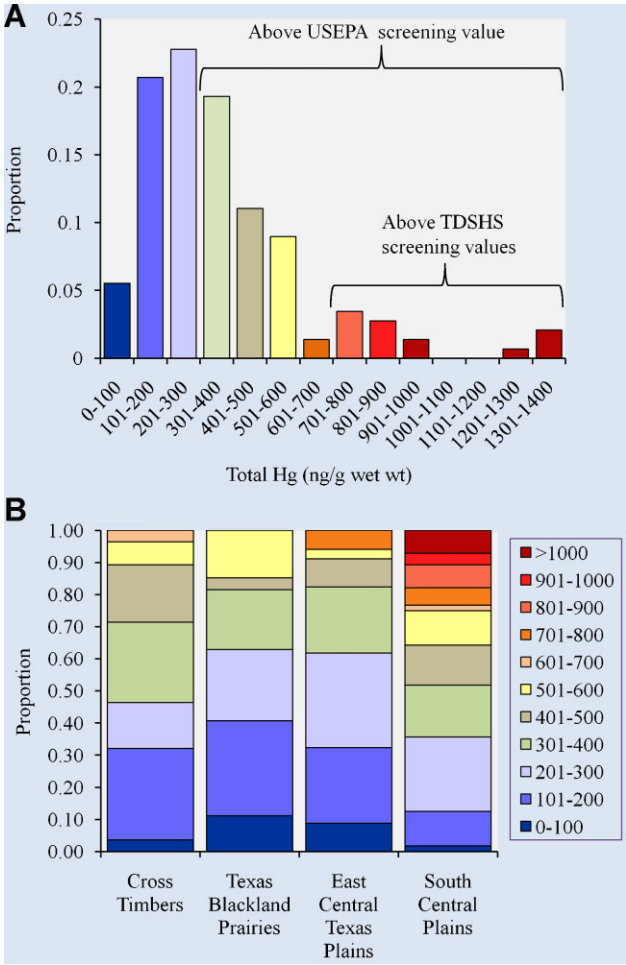

Fig. 4. (**A**) Proportion of 46-cm-total-length largemouth bass having estimated total Hg concentrations from 0 to 1,400 ng/g. Proportion of fish with Hg concentrations exceeding U.S. Environmental Protection Agency and Texas Department of State Health Services screening values (the benchmarks used by the two organizations to issue fish consumptions advisories) are indicated by brackets. (**B**) Proportion of 46-cm-total-length largemouth bass in 100 ng/g categories in the four ecoregions of North Texas. [Color figure can be seen in the online version of this article, available at wileyonlinelibrary.com]

CONCLUSIONS

We have shown that some reservoirs in the South Central Plains in East Texas are highly contaminated with Hg. This ecoregion receives high rates of wet Hg and sulfate deposition (http://nadp.sws.uiuc.edu) and is Hg-sensitive because of its forests, wetlands, and low levels of agricultural vegetation. The present study has implications beyond Texas, because the South Central Plains extends across parts of Oklahoma, Arkansas, and Louisiana, covering a total area of 152,132 km^2. Like Texas, these three states also receive relatively high rates of wet Hg and sulfate deposition (http://nadp.sws.uiuc.edu). If the other areas of the South Central Plains ecoregion are as contaminated as the Texas portion, this ecoregion would be one of the largest geographic areas with highly Hg-polluted water bodies yet identified in the United States.

SUPPLEMENTAL DATA

Table S1. Data sources used in the present study (48 KB XLS).

Fig. S1. Predicted fish-mercury concentrations as a function of length for skin-off fillet cuts of 11 frequently sampled species (102 KB DOC).

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REFERENCES

1. National Research Council. 2000. *Toxicological Effects of Methylmercury*. National Academy, Washington DC.
2. Mergler D, Anderson HA, Chan LHM, Mahaffey KR, Murray M, Sakamoto M, Stern AH. 2007. Methylmercury exposure and health effects in humans: A worldwide concern. *Ambio* 36:3–11.
3. U.S. Environmental Protection Agency. 2009. 2008 Biennial national listing of fish advisories. EPA-823-F-09-007. Washington, DC.
4. Driscoll CT, Han Y, Chen CY, Evers DC, Lambert KF, Holsen TM, Kamman NC, Munson RK. 2007. Mercury contamination in forest and freshwater ecosystems in the northeastern United States. *BioScience* 57:17–28.
5. Evers DC, Han Y, Driscoll CT, Kamman NC, Goodale MW, Lambert KF, Holsen TM, Chen CY, Clair TA, Butler T. 2007. Biological mercury hotspots in the northeastern United States and southeastern Canada. *BioScience* 57:29–43.
6. Wiener JG, Krabbenhoft DP, Heinz GH, Scheuhammer AM. 2003. Ecotoxicology of mercury. In Hoffman DJ, Rattner BA, Burton GA Jr, Cairns J Jr, eds, *Handbook of Ecotoxicology*, 2nd ed. Lewis, Boca Raton, FL, USA.
7. Hammerschmidt CR, Fitzgerald WF. 2006. Methylmercury in freshwater fish linked to atmospheric mercury deposition. *Environ Sci Technol* 40:7764–7770.
8. Drevnick PE, Canfield DE, Gorski PR, Shinneman ALC, Engstrom DR, Muir DCG, Smith GR, Garrison PJ, Cleckner LB, Hurley JP, Noble RB, Otter RR, Oris JT. 2007. Deposition and cycling of sulfur controls mercury accumulation in Isle Royale fish. *Environ Sci Technol* 41:7266–7272.
9. Griffith GE, Bryce SA, Omernik JM, Comstock JA, Rogers AC, Harrison B, Hatch SL, Bezanson D. 2004. Ecoregions of Texas. U.S. Geological Survey, Reston, VA.
10. Thomas C, Bonner TH, Whiteside BG. 2007. *Freshwater Fishes of Texas: A Field Guide*. Texas A&M, College Station, TX, USA.
11. Kamman NC, Burgess NM, Driscoll CT, Simonin HA, Goodale W, Linehan J, Estabrook R, Hutcheson M, Major A, Scheuhammer AM, Scruton DA. 2005. Mercury in freshwater fish of northeast North America—A geographic perspective based on fish tissue monitoring databases. *Ecotoxicology* 14:163–180.
12. Chumchal MM, Hambright KD. 2009. Ecological factors regulating mercury contamination of fish from Caddo Lake, Texas, USA. *Environ Toxicol Chem* 28:962–972.
13. U.S. Environmental Protection Agency. 1998. Method 7473: Mercury in solids and solutions by thermal decomposition, amalgamation, and atomic absorption spectrophotometry. Washington, DC.
14. Bloom NS. 1992. On the chemical form of mercury in edible fish and marine invertebrate tissue. *Can J Fish Aquat Sci* 49:1010–1017.
15. U.S. Environmental Protection Agency. 2000. Guidance for assessing chemical contaminant data for use in fish advisories. EPA-823-B-00-007. Washington, DC.
16. Twidwell S. 2000. Bioaccumulation of mercury in selected east Texas water bodies. AS-180. Texas Commission on Environmental Quality, Austin, TX, USA.
17. Chumchal MM, Drenner RW, Fry B, Hambright KD, Newland LW. 2008. Habitat-specific differences in mercury concentration in a top predator from a shallow lake. *Trans Am Fish Soc* 137:195–208.
18. U.S. Environmental Protection Agency. 2009. National Lake Fish Tissue Study. EPA-823-R-09-006. Washington, DC, USA.
19. Wente SP. 2004. A statistical model and national data set for partitioning fish-tissue mercury concentration variation between spatiotemporal and sample characteristic effects. Scientific Investigation Report 2004-5199. U.S. Geological Survey, Reston, VA.
20. Sackett DK, Aday DD, Rice JA, Cope WG. 2009. A statewide assessment of mercury dynamics in North Carolina water bodies and fish. *Trans Am Fish Soc* 138:1328–1341.
21. Swain EB, Jakus PM, Rice G, Lupi F, Maxson PA, Pacyna JM, Penn A, Spiegel SJ, Veiga MM. 2007. Socioeconomic consequences of mercury use and pollution. *Ambio* 36:45–61.
22. Munthe J, Bodaly RA, Branfireun BA, Driscoll CT, Gilmour CC, Harris R, Horvat M, Lucotte M, Malm O. 2007. Recovery of mercury-contaminated fisheries. *Ambio* 36:33–44.
23. Lange TR, Royals HE, Connor LL. 1993. Influence of water chemistry on mercury concentration in largemouth bass from Florida lakes. *Trans Am Fish Soc* 122:74–84.
24. Hanten RP, Neumann RM, Ward SM. 1998. Relationships between concentrations of mercury in largemouth bass and physical and chemical characteristics of Connecticut lakes. *Trans Am Fish Soc* 127:807–818.
25. Jakus PM, Dadakas D, Fly JM. 1998. Fish consumption advisories: Incorporating angler-specific knowledge, habits, and catch rates in a site choice model. *Am J Agric Econ* 80:1019–1024.
26. U.S. Environmental Protection Agency. 2001. Mercury update: Impact on fish advisories. EPA-823-F-01-011. Washington, DC.
27. Jakus P, Downing M, Bevelhimer M, Fly M. 1997. Do sportfish consumption advisories affect reservoir anglers' site choice? *Agric Res Econ Rev* 26:196–204.
28. Smith SV, Renwick WH, Bartley JD, Buddemeier RW. 2002. Distribution and significance of small, artificial water bodies across the United States landscape. *Sci Total Environ* 299:21–36.
29. Blackwell BD, Drenner RW. 2009. Mercury contamination of macroinvertebrates in fishless grassland ponds. *Southwest Nat* 54:468–474.
30. Wolfe MF, Schwarzbach S, Sulaiman RA. 1998. Effects of mercury on wildlife: A comprehensive review. *Environ Toxicol Chem* 17:146–160.
31. Scheuhammer AM, Meyer MW, Sandheinrich MB, Murray MW. 2007. Effects of environmental methylmercury on the health of wild birds, mammals, and fish. *Ambio* 36:12–18.
32. Selin NE, Jacob DJ. 2008. Seasonal and spatial patterns of mercury wet deposition in the United States: Constraints on the contribution from North American anthropogenic sources. *Atmos Environ* 42:5193–5204.