Mercury Contamination in Sport Fish in the Northeastern United States: Considerations for Future Data Collection

JESSE M. LEPAK, HANNAH A. SHAYLER, CLIFFORD E. KRAFT, AND BARBARA A. KNUTH

The northeastern United States is influenced by the atmospheric deposition of mercury. Subsequent integration of methylmercury into aquatic food webs results in contamination levels in fish that are high enough to present health concerns for humans who consume fish. Resource and sampling limitations have hindered a comprehensive understanding of mercury in the environment and relative levels of methylmercury exposure. Because of these limitations, data collection should maximize the benefits of information gained through monitoring programs. In this article we review recent efforts to collect and integrate fish mercury data and offer suggestions to improve and focus future research and monitoring efforts to better address threats to human health. By selecting appropriate target species—those species and sizes of fish harvested for consumption and those with the highest and most variable mercury concentrations in a given location—health and fisheries professionals can more comprehensively advise fish consumers and protect human health.

Keywords: mercury, methylmercury, fish consumption, sport fish, human health

Atmospheric deposition of mercury (Hg) in the northeastern United States is a threat to human health. Methylmercury (MeHg) is integrated into aquatic food webs, resulting in contamination levels in fish that are high enough to present a risk for humans who consume the fish. Despite two decades of Hg research and monitoring efforts, no consensus has been reached about which fish species should be targeted for monitoring or what criteria should be used to issue fish consumption advisories. Thus, different states issue disparate consumption advisories and inconsistently define consumer groups at risk from Hg exposure. Moreover, because financial and logistical issues constrain the scope of Hg testing, it is particularly important to identify fish species, sizes, and testing locations that will provide the most relevant, beneficial information to safeguard human health.

Three important factors to consider when determining which fish species to monitor and the appropriate locations for data collection are (1) the rate at which a given fish species is consumed by humans at a given location, (2) the concentration and variability of MeHg in the fish consumed, and (3) the minimum size (length) a fish must attain to be legally harvested for consumption. We recommend that future data collection efforts take these three factors into account if the ultimate goal is to protect human health, and we present our rationale for these priorities in this article.

Although Hg deposition and its bioaccumulation in aquatic systems cause concern throughout much of the United States, in this article we focus on Hg contamination in freshwater systems in northeastern North America. Over the last two decades, many scientists have studied the factors leading to high concentrations of MeHg, a highly toxic Hg species, in biota consumed by humans and wildlife. Every state in the northeastern United States has developed fish consumption advisories to protect consumers from potential health threats, particularly from sport-caught fish. Mercury contamination is also salient with policymakers at the national level, as evidenced by federal legislation proposed in 2007 to establish a comprehensive national Hg monitoring program (H.R. 1533 and S. 843; see *http://thomas.loc.gov*). Recent efforts by researchers, state and federal agencies, and various governmental authorities emphasize the ongoing need to address the issue of Hg contamination at the national scale and in regions with high Hg levels in biota, such as the northeastern United States.

BioScience 59: 174–181. ISSN 0006-3568, electronic ISSN 1525-3244. doi:10.1525/bio.2009.59.2.10

In this article we offer criteria for researchers, agencies, and governments to use in selecting appropriate target species for Hg testing to ensure that the data sets on which fish consumption advisories are based are relevant to consumers and as complete as possible. We emphasize that from the standpoint of risk assessment and the protection of human health, it is especially important to collect data for the species and sizes of fish that humans at particular locations consume.

We provide a brief background of Hg contamination in fish, then focus on three related initiatives: (1) monitoring programs in northeastern North America to identify areas of high Hg concentration in fish and other biota (Driscoll et al. 2007, Evers et al. 2007), (2) an effort to establish a uniform total maximum daily load (TMDL) methodology across the northeastern United States (NEIWPCC 2007), and (3) development of a comprehensive national Hg monitoring network (Harris et al. 2007). By clearly synthesizing and communicating available information, and by identifying and understanding the strengths and limitations of recent efforts, scientists, policymakers, public health agencies, resource managers, and fish consumers can more comprehensively address the challenges presented by Hg contamination.

Mercury in the environment and subsequent effects on human health

Many aspects of Hg contamination have been evaluated during recent decades. For example, it has been shown that the northeastern United States is influenced by atmospheric deposition of Hg (NADP 2008), and subsequent integration into aquatic food webs results in high Hg concentrations in aquatic biota (Driscoll et al. 1994, Chen et al. 2005, Kamman et al. 2005). Fishes and other aquatic organisms bioaccumulate Hg in their tissues as the contaminant moves through food webs (USEPA 2001a, Power et al. 2002). The characteristics of the fish itself (i.e., its diet, age, and size), the Hg input to a particular area, and the biogeochemical dynamics influenced by a suite of watershed characteristics all affect the MeHg concentration in an individual fish (Driscoll et al. 1994, Power et al. 2002, Johnston et al. 2003). In general, larger, older, piscivorous fish (those that eat other fish) tend to have elevated Hg concentrations, which makes them a greater risk to human consumers relative to younger, smaller fish that are herbivorous or omnivorous (Bahnick et al. 1994, Power et al. 2002). It is often assumed that MeHg makes up approximately 95 percent of total Hg (T-Hg) in most fishes (Bloom 1992); however, this assumption may not hold true for all species. For example, Kannen and colleagues (1998) reported MeHg percentages in fish ranging from 45 to 124 percent of the T-Hg (with the exception of a single catfish with 20 percent MeHg), with a mean value of 83 percent. The T-Hg is often measured as a proxy for MeHg, yet the variability in the proportion of MeHg—as well as the accuracy and precision of analytical techniques—should be considered when determining Hg concentrations in fish and subsequently developing consumption advisories.

Management actions such as stocking fish and regulating harvest rates can alter the structure of lake food webs and thereby influence Hg concentrations of resident fish (Göthberg 1983, Verta 1990, Rask et al. 1996). Natural variation in food webs (e.g., fish die-offs) and lake characteristics (e.g., pH, total phosphorus) can also result in unexpected changes in Hg dynamics (Rask et al. 1996, Driscoll et al. 2007). These changes can occur rapidly, so it is important to recognize which lake and food web characteristics influence Hg bioaccumulation in fish. Despite ongoing attention to Hg pollution and its potential impacts on consumers, the degree and variability of contaminant levels in many water bodies, and popular sport fish within them, remain uncharacterized.

Methylmercury is a potent neurotoxin and a known concern for human health, particularly with regard to the nervous system during fetal and early child development (for a complete review of human health effects, see USEPA 1997, NRC 2000, Mergler et al. 2007, Nesheim and Yaktine 2007). Although MeHg is gradually eliminated from the body, it can accumulate in the bloodstream over time if consumption levels exceed the body's capacity for excretion (USEPA 2001a, USFDA and USEPA 2004). Given assumptions about the body weight of fish consumers and fish intake, the US Environmental Protection Agency (EPA) recommends that for the protection of human health, Hg concentrations in fish not exceed 0.3 parts per million (ppm), or 0.3 micrograms of MeHg per gram of fish (USEPA 2001b). The amount of fish that can be consumed without exceeding the EPA reference dose varies with a person's body weight and with the Hg concentration in the fish (NRC 2000). Despite the health concerns associated with MeHg, the nutritional benefits of fish consumption are well documented and may outweigh the health risks (Knuth et al. 2003, Mergler et al. 2007, Nesheim and Yaktine 2007). The US Food and Drug Administration and the EPA (2004) recommend that women and children consume up to 12 ounces per week of fish with low levels of MeHg, and the Dietary Guidelines Advisory Committee and the American Heart Association recommend the consumption of at least 6 ounces of fish per week to maintain a healthy and balanced diet (Nesheim and Yaktine 2007). Weighing the nutritional benefits of consuming fish against the possible negative health effects from exposure to MeHg requires that detailed information be collected and disseminated regarding patterns of fish consumption and the nutritional content (particularly levels of omega-3 fatty acids) and MeHg concentrations in the fish species humans consume.

Data collection and monitoring efforts

Driscoll and colleagues (2007) and Evers and colleagues (2007) identified, predicted, and classified areas with high concentrations of Hg in freshwater biota in the northeastern United States and southeastern Canada. They used a subset of the data compiled for the northeastern United States during a four-year effort that included more than 30,000 observations of Hg levels in biota representing 40 fish species and 44 wildlife species (Evers and Clair 2005). Specifically, Driscoll and colleagues (2007) set out to determine whether four simple indicators of water quality—dissolved organic carbon, acid-neutralizing capacity, pH, and total phosphorus—could be used to predict which aquatic systems were likely to contain fish whose Hg levels exceeded the EPA criterion of 0.3 ppm; they used measurements of Hg concentrations in the tissues of standard-age (approximately 4.5 years), standard-length (200 millimeters [mm]) yellow perch (*Perca flavescens*). Evers and colleagues (2007) relied on measurements of Hg concentrations in standard-length (200 mm) yellow perch to identify "biological Hg hotspots," then used data for yellow perch and, to a lesser extent, largemouth bass (*Micropterus salmoides*) to identify additional "areas of concern" for human health.

Efforts such as these are useful for identifying regions with the highest levels of Hg contamination in widely distributed fish species, and it is important to locate regions where MeHg concentrations in fish may pose the greatest risk to humans. However, MeHg concentrations in these species are not the sole information pertinent to assessing human health risks; what is directly pertinent to that assessment is which species are most frequently harvested and consumed by anglers, as we discuss later. By assessing fish consumption and monitoring MeHg concentrations in fish species that are harvested and consumed by humans at a particular location, public health agencies can more effectively identify where the consumption of sport fish poses threats to human health and prioritize testing in those areas.

Other efforts are assessing Hg concentrations across the northeastern United States using fish species that are more sensitive to Hg contamination. In December 2007, the EPA approved the Northeast Regional Hg TMDL as presented by state agencies of Connecticut, Maine, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont, in cooperation with the New England Interstate Water Pollution Control Commission. This plan outlines steps to reduce Hg concentrations in fish in freshwater systems throughout the Northeast in order to meet water quality standards and eventually eliminate the need for fish consumption advisories (NEIWPCC 2007). The Northeast Regional Hg TMDL is based on a compilation of data from monitoring programs conducted by state and provincial governments, as well as other large-scale research initiatives, aimed at establishing a baseline from which to assess future reductions in fish Hg concentrations. Smallmouth bass (*Micropterus dolomieu*) were chosen as the indicator species for this effort to assess improvements in water quality because this species bioaccumulates MeHg at relatively high levels and is ubiquitously distributed across the northeastern states. The Northeast Regional Hg TMDL aims to reduce Hg concentrations in 90 percent of smallmouth bass to 0.3 ppm, thereby reducing Hg levels in nearly all other species to below this threshold as well. However, the extent of human consumption was not a primary criterion considered in the selection of smallmouth bass as a target species.

In the future, the collection of regional data may also be facilitated by efforts at the national level, including federal policy initiatives. Collaborations among researchers from academia, government agencies, and other organizations have led to recommendations for a comprehensive monitoring program to determine whether Hg concentrations in air, watersheds, waters, soils, and aquatic biota are changing over time as a result of regulatory policies to reduce Hg emissions (Harris et. al 2007). These recommendations have been incorporated into legislation proposed in March 2007 to establish a comprehensive national Hg monitoring network for collecting field data from various ecoregions across the United States. However, data collected through this program may not provide information directly relevant to advising fish consumers.

Fish are important and appropriate indicators of Hg deposition because they represent the main pathway through which humans and wildlife are exposed to MeHg (Harris et al. 2007). If the proposed federal monitoring program is established, it will provide data concerning MeHg concentrations in yearling fish and Hg concentrations in commercially and recreationally important fish. However, it is unclear how the proposed monitoring program would determine which fish species are "commercially and recreationally important" at the national scale or at a given monitoring site, or whether the fish tested would be of a size consumed by humans (i.e., whether the fish would meet state minimum length regulations). We emphasize that the objective of the proposed monitoring program is to comprehensively monitor changes in atmospheric deposition and corresponding changes in biotic indicators, rather than to directly assess the exposure of fish consumers to MeHg. However, given that the ultimate goal of reducing Hg emissions and subsequent deposition is to protect human health, we argue that it is also fundamentally important for researchers, state and federal agencies, and policymakers to collectively consider the criteria described below. Specifically, we ask whether such a monitoring program for Hg should provide data to directly inform the development of comprehensive fish consumption advisories and other appropriate public policy in the short term, in addition to achieving the desired long-term monitoring goals.

Criteria for selecting target species for data collection efforts

Here we identify three criteria that could be used for selecting target species in data collection efforts.

Criterion 1: Patterns of fish consumption by humans. Concentrations of MeHg in fish are inherently variable within and across species and freshwater systems; it is therefore essential to collect data for the fish species harvested and consumed by humans at particular locations. The fish-consumption patterns and the species preferences of particular groups of consumers vary regionally and even locally, and depend on cultural factors including taste preferences, economic status, educational level, cultural beliefs, ethnicity, health awareness, income, age, and gender (Strauss 2004, Verbeke and Vackier 2005). In the northeastern United States, large, native sport-fish species, such as northern pike (*Esox lucius*) and walleye (*Sander vitreus*), and salmonids including lake trout (*Salvelinus namaycush*) and landlocked Atlantic salmon (*Salmo salar*), are generally widespread in their distribution and are heavily targeted by anglers, according to a 2001 survey conducted by the US Census Bureau (figure 1). A survey conducted between June 2001 and June 2002 of more than 4000 adults living in the states bordering the Great Lakes found that approximately 64 percent of the fish consumed by respondents who ate sport-caught fish were walleye and salmonids. Yellow perch and rainbow smelt (*Osmerus mordax*) together constituted only 21 percent of fish consumed; smallmouth bass, which were not listed individually, made up some smaller proportion of "other sport-caught fish" that together constituted approximately 10 percent of fish consumed (Imm et al. 2005).

Detailed, comprehensive angler harvest data analogous to those available for the Great Lakes are lacking from most other regions, including the northeastern United States. Obtaining information about the rates at which particular sport-fish species are consumed in a given location would facilitate targeted Hg testing, limiting unnecessary testing of fish species that are rarely consumed. Local knowledge may provide insights that could inform the development of future data collection efforts. For example, in areas of New York and Vermont, fisheries biologists have observed that some smallmouth bass fisheries may be largely caught and released (Scott Krueger, Department of Natural Resources, Cornell University, personal communication, 27 February 2008; Richard Kirn, Vermont Fish and Wildlife Department, personal communication, 6 December 2007). Furthermore, the New Hampshire Fish and Game Department (NHFG) voiced concerns about the use of smallmouth bass as an indicator species for the Northeast Regional Hg TMDL, stating that smallmouth and largemouth bass are not frequently consumed (the NHFG Department deems that approximately 95 percent of all bass caught are released; Michael Racine, NHFG, personal communication, 28 December 2007).

Although some consumer groups may harvest smallmouth bass and yellow perch, available information suggests that it is important from a human health perspective to have Hg concentration data from other fish species that are consumed more frequently in the northeastern United States. Determining which fish species are most frequently consumed in particular regions (e.g., the Adirondack region of New York) or at more specific locations (e.g., in communities in which some individuals rely on self-caught fish for a significant portion of their protein intake) will identify those species of primary importance for Hg testing in those areas. We contend that in order to assess the effects of Hg contamination on human health, fish consumption should be evaluated—both quantitatively (through consumption surveys) and qualitatively (through the experiences of agencies and fisheries biologists)—and considered to be the primary criterion in the selection of fish species and locations for monitoring. The successful implementation of such efforts will undoubtedly require additional resources and will be challenging, but the benefits gained from this type of approach, if conducted properly, will most likely be far reaching and potentially cost-effective.

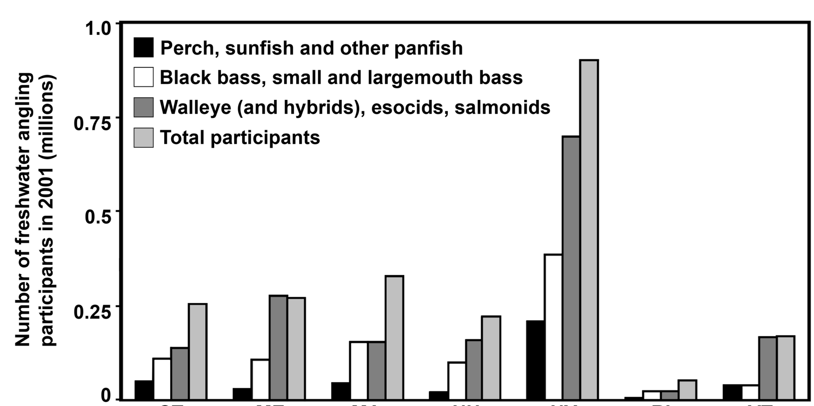

Figure 1. Groups of fish species targeted by anglers in the northeastern states of the United States, using data compiled from the US Census Bureau (2001). Participants included resident and nonresident freshwater anglers in the year 2001. Because of the nature of the data collected, species were grouped. Esocids include pike, pickerel, and muskellunge hybrids. Several groups of species are not shown because they were not addressed in this manuscript, including crappie; bullhead and catfish; white bass, striped bass, and hybrids (potentially marine); and groups designated "anything" and "other." Each of these groups represented no more than 30% of the total participants in any state. These data reflect species targeted by anglers and may not have been harvested for consumption; black bass in particular are primarily caught and released. Additionally, anglers may target multiple species, so the sum of participants for all species may exceed the total.

Criterion 2: Variability in fish MeHg concentrations. Diet is the most important factor contributing to Hg concentration in fish (Harris and Bodaly 1998, Johnston et al. 2003). Large predatory fish targeted by anglers are particularly likely to have elevated Hg concentrations because of their higher trophic level and old age (Bahnick et al. 1994, Power et al. 2002), and therefore represent a greater risk to fish consumers. Although nonnative yellow perch and smallmouth bass are ubiquitous and thus are useful for identifying areas with particularly high Hg contamination (see Driscoll et al. 2007, Evers et al. 2007), these species are not representative of entire fish communities. Freshwater systems such as lakes often support nearshore (littoral) and offshore (pelagic) food webs that overlap to varying degrees, depending on the food-web structure (Vander Zanden et al. 1999, Lepak et al. 2006). For example, smallmouth bass and yellow perch are commonly associated with nearshore or littoral habitats, so measures of T-Hg concentrations in those species sampled from nearshore areas do not directly provide information about the MeHg concentrations of frequently consumed sport-fish species such as walleye and salmonids, which often rely on offshore food webs.

In water bodies where yellow perch MeHg concentrations exceed the EPA's 0.3 ppm criterion, MeHg concentrations in larger predatory fish will typically be high enough to pose concerns for human health (Driscoll et al. 2007, Evers et al. 2007, NEIWPCC 2007). Similarly, if MeHg concentrations in smallmouth bass exceed 0.3 ppm, MeHg concentrations in other large predatory species are very likely to exceed this threshold as well. A subset of the NERC (Northeastern Ecosystem Research Cooperative) data set from northeastern North America (see Kamman et al. 2005) indicates that the top predator species (e.g., walleye, northern pike, and lake trout) with the highest concentrations of T-Hg also have the greatest variability in T-Hg concentration, despite relatively large sample sizes (figure 2). This variability can result in greater than fivefold differences in MeHg concentrations within a particular sport-fish species, making it challenging to predict the level of MeHg exposure arising from any given meal of fish, and thus to develop adequate consumption guidelines. Characterizing the variability in MeHg concentrations in fish species targeted for consumption is important for evaluating the level of confidence associated with consumption recommendations for different regions. Kamman and colleagues (2005) attributed much of the variability in T-Hg concentration in fish to the water bodies sampled, which most likely results from differences in food-web structure (Vander Zanden and Rasmussen 1996).

Criterion 3: Fish length. Most state angling regulations specify the minimum length of sport fish that can be legally harvested. For example, in 2008, the statewide minimum length for legally harvested landlocked salmon and walleye in New York was 15 inches (381 mm); for northern pike, 18 inches (457 mm); for lake trout, 21 inches (533 mm); and for black bass (large and smallmouth bass), 12 inches (305 mm) (NYSDEC 2006). These regulations promote the harvest of large fish in an attempt to protect and sustain naturally reproducing fish populations, yet these same regulations encourage the harvest of fish that present a disproportionately high risk of MeHg exposure to anglers and their families. Driscoll and colleagues (2007) specifically acknowledge that using small yellow perch as an indicator species helps identify the most polluted lakes. Although this approach is useful for locating regions that are heavily influenced by Hg contamination, particularly because of the generally widespread distribution of yellow perch and the relatively large amount of data associated with this species, using small fish as a proxy for the level of contamination within water bodies is insufficient for developing appropriate fish consumption advisories. For example, if data used to develop consumption advisories include fish shorter than current minimum lengths, the mean Hg concentrations will very likely be artificially low relative to the mean Hg concentration in fish people can legally harvest and consume.

We analyzed a subset of the NERC data set to determine how the mean T-Hg concentrations in the predatory sport-fish species most often consumed by humans changed when only fish of legal length were examined. The mean T-Hg concentrations of fish with known total lengths that met or exceeded New York's minimum legal length for harvest were significantly higher (two-sample *t*-tests, assuming equal variance; $p \leq 0.01$) in walleye, smallmouth bass, lake trout, eastern chain pickerel, and largemouth bass relative to the T-Hg concentrations when data for all fish of known lengths were considered (figure 2). The mean T-Hg concentration of northern pike with total length at or above the legal length did not differ significantly (two-sample *t*-test, assuming equal

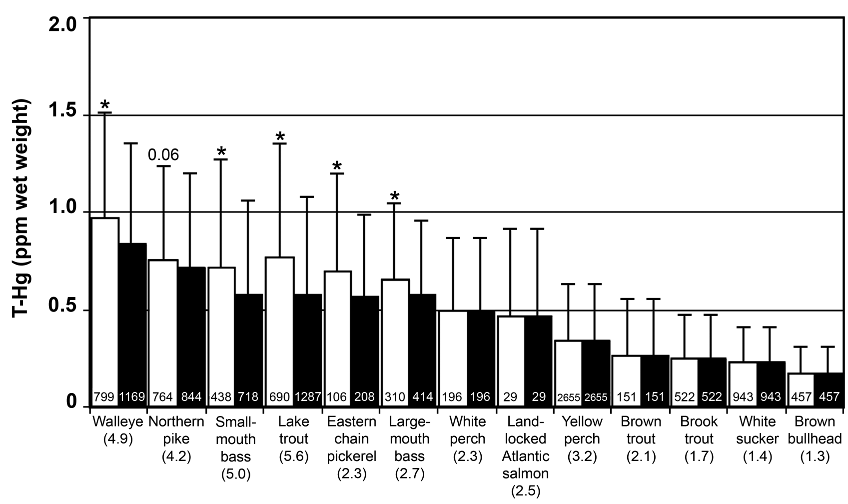

Figure 2. Mean (± standard deviation) total mercury (T-Hg) concentration (parts per million, wet weight) in sport fish species from eastern North America calculated using data for fish at or exceeding the legal length (white bars), compared with the mean T-Hg concentration of all fish, regardless of length, in the data set (black bars). Legal length was determined from the New York State Freshwater Fishing Regulations 2006–2008. *Mean values that differ significantly (*p *≤ 0.01) are indicated by an asterisk (*);* p *= 0.06 for northern pike. Only fish for which total length measurements were available were included in the analysis. Sample sizes associated with each mean are shown at the base of the bars, and the maximum value of T-Hg measured in that species in the data set is indicated below the species name. This figure was produced from a subset of the NERC (Northeastern Ecosystem Research Cooperative) data set (see Kamman et al. 2005).*

variance; $t_{1606} = 1.55$, $p = 0.06$) from the mean T-Hg concentration for all fish of known total length. Analyses for the remaining species included data only for fish of the legal length because all fish measured were above the legal length (e.g., landlocked Atlantic salmon) or because New York State has not established a minimum length for some species (e.g., white perch, yellow perch, brown trout, brook trout, white sucker, and brown bullhead). Although this analysis applies New York's length regulations to a data set including samples collected throughout the Northeast, it nonetheless illustrates the need to collect data from fish of legal length—in other words, the fish that are most likely to be consumed by humans—to inform the development of fish consumption advisories.

Further considerations for human health

Consumption advisories issued by state agencies constitute comprehensive risk communication efforts regarding levels of contaminants in sport-caught fish and the recommended levels of fish consumption for different consumer groups. However, "sensitive" populations (i.e., women of childbearing age and young children, who would potentially benefit most from limiting their exposure to Hg) are defined differently in all seven northeastern state advisories (table 1). Furthermore, state advisories may offer different consumption advice for specific fish species, sizes, water bodies, or regions. These differences are sometimes appropriately based on the availability of local Hg data (e.g., high Hg concentrations measured in a particular species from a specific water body), but are more often due to discrepancies in the thresholds of fish-tissue Hg concentration used to develop consumption advisories (table 1). By considering fish consumption information from a particular region and consistently defining particular groups of fish consumers, recommendations can be developed that are appropriate for local consumption practices, making them more protective of human health than blanket regional advisories (Burger et al. 2007).

Assessing potential health risks resulting from MeHg exposure through fish consumption necessitates consistent benchmarks of unacceptable exposure. As described above, the level of Hg concentration in fish tissue that triggers a consumption advisory currently differs in all seven of the northeastern states (table 1). With this in mind, we note that recent efforts by Driscoll and colleagues (2007), Evers and colleagues (2007), and the Northeast Regional Hg TMDL (NEIWPCC 2007) have taken an important step toward consistency by using the EPA criterion of 0.3 ppm Hg in fish tissue (USEPA 2001b) as an initial standard that signifies potential human health risks. To communicate information to particular groups of fish consumers clearly, the scientists,

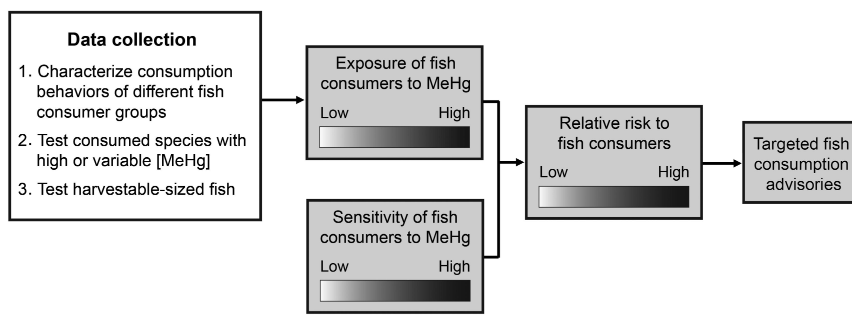

Figure 3. An approach to targeted data collection (open box) to best inform the protection of human health. The shaded boxes represent areas for further consideration beyond the scope of this manuscript. The relative risk to groups of fish consumers is determined by a combination of the level of exposure (i.e., rate of consumption of a given species with a given methylmercury concentration) and the sensitivity of an individual consumer to the health effects of methylmercury (developing fetuses and young children are the most sensitive). Characterizing the relative risks to different groups of fish consumers at particular locations will allow for targeted fish consumption advisories to more comprehensively protect human health.

Table 1. Summary of sensitive populations and fish tissue mercury concentrations considered when developing fish consumption advisories for seven states in the northeastern United States .

State	Sensitive population	Fish tissue mercury concentration (parts per million)
Connecticut	Pregnant and nursing women, women who plan to become pregnant within one year, children under 6	0.1
Massachusetts	Pregnant and nursing women, women of child-bearing age, children under 12	0.2
Maine	Pregnant and nursing women, women who may get pregnant, children under 8	0.3
New Hampshire	Pregnant and nursing women, women who may get pregnant, children under 7	0.3
New York	Women of childbearing age, infants, children under 15	1.0
Rhode Island	Pregnant and nursing women, women who plan to become pregnant within one year, young children	0.3
Vermont	Women of childbearing age (particularly pregnant and nursing women, women planning to get pregnant), children under 6	0.3

Source: NEIWPCC (2007).

public health agencies, resource managers, and policymakers responsible for identifying and managing areas where Hg contamination is a concern must make consistency an important consideration.

Conclusions

Although research to date has made notable strides toward understanding the processes affecting the bioaccumulation of MeHg in freshwater fish, the MeHg concentration present in a particular fish will always depend on a number of site-specific factors. For fish consumption advisories and public policy to be effective, it is essential to understand the inherent variability in fish MeHg concentrations, to characterize MeHg concentrations in fish consumed by humans, and to consistently communicate results from monitoring efforts. Localized information about which fish species are harvested and consumed, and in what quantities, by anglers and their families and other groups of fish consumers will directly inform assessments of the relative risk of MeHg exposure for different individuals, and lead to the development of more targeted fish consumption advisories (figure 3). Considering the legal harvest sizes for particular species when developing fish consumption guidelines will allow a more focused view of MeHg contamination in fish as it relates to human health. Integrating data on Hg levels in fish that have been collected by different entities—and for different purposes—should remain a priority. By targeting future efforts, we will greatly improve our ability to protect human health.

When collecting data to develop consumption advisories that directly protect human health, it is most important to measure contaminant levels in fish that (a) anglers and their families frequently harvest and consume from a given location; (b) represent a disproportionately high risk to human health because of high concentrations and variability of MeHg; and (c) are equal to or greater than the minimum length limit required for harvest.

Acknowledgments

We thank Jason Demers and Neil Kamman for valuable insights at the beginning of this project; Neil Kamman also generously provided a subset of the NERC data set for use in our analysis. We appreciate the comments on previous versions of the manuscript provided by Bethany Boisvert, Kurt Jirka, Jason Robinson, and Dana Warren (members of the Kraft lab group), as well as Jillian Cohen, Justin DiMatteo, and faculty and graduate students of the Human Dimensions Research Unit. We also thank three anonymous reviewers for their comments on an earlier version of the manuscript.

References cited

Bahnick D, Sauer C, Butterworth B, Kuehl D. 1994. A national study of mercury contamination of fish. Chemosphere 29: 537–546.

Bloom NS. 1992. On the chemical form of mercury in edible fish and marine invertebrate tissue. Canadian Journal of Fisheries and Aquatic Sciences 46: 1010–1017.

Burger J, Gochfeld M, Jeitner C, Burke S, Stamm T, Snigaroff R, Snigaroff D, Patrick R, Weston J. 2007. Mercury levels and potential risk from subsistence foods from the Aleutians. Science of the Total Environment 384: 93–105.

Chen CY, Stemberger RS, Kamman NC, Mayes BM, Folt CL. 2005. Patterns of Hg bioaccumulation and transfer in aquatic food webs across multi-lake studies in the northeast US. Ecotoxicology 14: 135–147.

Driscoll CT, Yan C, Schofield CL, Munson R, Holsapple J. 1994. The mercury cycle and fish in the Adirondack lakes. Environmental Science and Technology 28: 136A–143A.

Driscoll CT, Han Y-J, 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.

Evers DC, Clair TA. 2005. Mercury in northeastern North America: A synthesis of existing databases. Ecotoxicology 14: 7–14.

Evers DC, Han Y-J, 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.

Göthberg A. 1983. Intensive fishing—a way to reduce the mercury level in fish. Ambio 12: 259–261.

Harris RC, Bodaly RA. 1998. Temperature, growth and dietary effects on fish mercury dynamics in two Ontario lakes. Biogeochemistry 40: 175–187.

Harris RC, Krabbenhoft DP, Mason R, Murray MW, Reash R, Saltman T, eds. 2007. Ecosystem Responses to Mercury Contamination: Indicators of Change. New York: CRC Press.

Imm P, Knobeloch L, Anderson HA. 2005. Fish consumption and advisory awareness in the Great Lakes basin. Environmental Health Perspectives 113: 1325–1329.

Johnston TA, Leggett WC, Bodaly RA, Swanson HK. 2003. Temporal changes in mercury bioaccumulation by predatory fishes of boreal lakes following the invasion of an exotic forage fish. Environmental Toxicology and Chemistry 22: 2057–2062.

Kamman NC, et al. 2005. Mercury in freshwater fish of northeast North America—a geographic perspective based on fish tissue monitoring databases. Ecotoxicology 14: 163–180.

Kannen K, Smith RG Jr, Lee RF, Windom HL, Heitmuller PT, Macauley JM, Summers JK. 1998. Distribution of total mercury and methyl mercury in water, sediment, and fish from South Florida estuaries. Archives of Environmental Contamination and Toxicology 34: 109–118.

Knuth BA, Connelly NA, Sheeshka J, Patterson J. 2003. Weighing health benefit and health risk information when consuming sport-caught fish. Risk Analysis 23: 1185–1197.

Lepak JM, Kraft CE, Weidel BC. 2006. Rapid food web recovery in response to removal of an introduced apex predator. Canadian Journal of Fisheries and Aquatic Sciences 63: 569–575.

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.

[NADP] National Atmospheric Deposition Program. 2008. Mercury Deposition Network: A NADP Network. (18 December 2008; *http://nadp.sws.uiuc.edu/mdn/*)

[NEIWPCC] New England Interstate Water Pollution Control Commission. 2007. Northeast Regional Mercury Total Maximum Daily Load. (18 December 2008; *www.neiwpcc.org/mercury/MercuryTMDL.asp*)

Nesheim MC, Yaktine AL, eds. 2007. Seafood Choices: Balancing Benefits and Risks. Washington (DC): National Academies Press.

[NRC] National Research Council. 2000. Toxicological Effects of Methylmercury. Washington (DC): National Academy Press.

[NYSDEC] New York State Department of Environmental Conservation. 2006. Freshwater Fishing Regulations Guide 2006–2008. (18 December 2008; *www.dec.ny.gov/outdoor/7917.html*)

Power M, Klein GM, Guiguer KRRA, Kwan MKH. 2002. Mercury accumulation in the fish community of a sub-Arctic lake in relation to trophic position and carbon sources. Journal of Applied Ecology 39: 819–830.

Rask M, Järvinen M, Kuoppamäki K, Pösyä H. 1996. Limnological responses to the collapse of the perch population in a small lake. Annales Zoologici Fennici 33: 517–524.

Strauss H. 2004. Sportfish consumption surveys: A risk assessment practitioner's wish list. Human and Ecological Risk Assessment 10: 1213–1225.

US Census Bureau. 2001. National Survey of Fishing, Hunting, and Wildlife-associated Recreation (FHWAR) 2001. (18 December 2008; *www.census.gov/prod/www/abs/fishing.html*)

[USEPA] US Environmental Protection Agency. 1997. Mercury Study Report to Congress, vols. 1–8. Washington (DC): Office of Air Quality Planning and Standards and Office of Research and Development. Report no. EPA-452/R-97-005.

———. 2001a. Mercury Update: Impact on Fish Advisories. Washington (DC): Office of Water. Report no. EPA-823-F-01-001.

———. 2001b. Water Quality Criterion for the Protection of Human Health: Methylmercury. Washington (DC): USEPA. Report no. EPA-823-R-01-001. (19 December 2008; *www.waterboards.ca.gov/water_issues/programs/tmdl/records/region_1/2003/ref1799.pdf*)

[USFDA and USEPA] US Food and Drug Administration and US Environmental Protection Agency. 2004. What You Need to Know about Mercury in Fish and Shellfish. (18 December 2008; *www.epa.gov/waterscience/fishadvice/advice.html*)

Vander Zanden MJ, Rasmussen JB. 1996. A trophic position model of pelagic food webs: Impact on contaminant bioaccumulation in lake trout. Ecological Monographs 66: 451–477.

Vander Zanden MJ, Casselman JM, Rasmussen JB. 1999. Stable isotope evidence for food web shifts following species invasions of lakes. Nature 401: 464–467.

Verbeke W, Vackier I. 2005. Individual determinants of fish consumption: Application of the theory of planned behaviour. Appetite 44: 67–82.

Verta M. 1990. Changes in fish mercury concentrations in an intensively fished lake. Canadian Journal of Fisheries and Aquatic Sciences 47: 1888–1897.

Jesse M. Lepak holds a postdoctoral position at Colorado State University in Fort Collins. Hannah A. Shayler (e-mail: has34@cornell.edu) is with the Cornell Waste Management Institute in Ithaca, New York. Clifford E. Kraft is an associate professor in the Department of Natural Resources, and Barbara A. Knuth is senior associate dean of the College of Agriculture and Life Sciences at Cornell University in Ithaca, New York. Collectively, the authors' research efforts focus on food-web dynamics in aquatic systems, fisheries management, and integration of social and ecological information to study the human dimensions of natural resources.