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Baseline

Methylmercury in tissues of Atlantic sturgeon (*Acipenser oxyrhynchus*) from the Saint John River, New Brunswick, Canada

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ABSTRACT

Environmental contamination by mercury is a concern in marine food webs, and especially for large fish. We examined methylmercury (MeHg) levels in blood, muscle and liver of 35 individual Atlantic sturgeon (*Acipenser oxyrhynchus*), a commercially harvested, anadromous fish eastern Canada. Females had higher blood and liver MeHg levels than males, and in some tissues there was a suggestion of higher mercury in longer fish. Collectively, sturgeon MeHg levels were far below Canadian and international guidelines for safe consumption of fish meat.

Mercury (Hg) is an environmental pollutant which occurs naturally but is elevated in many ecosystems due to release from anthropogenic activities and long-range transport (Schroeder and Munthe, 1998; Prestbo and Gay, 2009). Environmental mercury occurs in several forms (Lindberg and Stratton, 1998; O'Driscoll et al., 2005). In its methylated form (methylmercury, MeHg), mercury readily moves into biological tissues where it binds to sulfhydryl groups in proteins (Wiener and Spry, 1996). Methylmercury biomagnifies in food chains to reach levels in upper trophic levels that can lead to deleterious neurological and reproductive effects in fish (e.g. Clarkson and Magos, 2006; Scheuhammer et al., 2007; Drevnick and Sandheinrich, 2003). Therefore, human consumption of Hg is of international concern, and many countries have established guidelines of acceptable levels of Hg in foods (Lowenstein et al., 2010). In 2013 an international agreement to reduce Hg entering the environment, was signed at the Minamata Convention on Mercury (http://mercuryconvention.org/).

Biomagnification of MeHg is particularly prominent in marine food chains (Ullrich et al., 2001), and many large, top predatory fish like tuna, swordfish (*Xiphias gladius*) and sharks have tissue levels exceeding levels considered safe for human consumption (Lowenstein et al., 2010). Local environmental conditions can also lead to markedly high Hg concentrations in freshwater fish (Kamman et al., 2005), and thus anadromous fish species moving between marine and freshwater environments can be exposed to high Hg throughout their life cycle and may have high tissue concentrations (e.g., Agusa et al., 2004; Webb et al., 2006).

In eastern North America, the combination of historic industrial activity near the Great Lakes and prevailing wind patterns moving west to east, as well as local emission sources, meant that the northeastern United States and Canadian Maritime provinces have experienced acid deposition and moderate mercury concentrations in precipitation, which combined with other ecosystem characteristics such as flat topography and low buffering capacity have resulted in high Hg accumulation in biota (Miller et al., 2005; Evers et al., 2007; Sunderland and Chmura, 2000a, 2000b; Prestbo and Gay, 2009). While wet deposition concentrations of mercury are believed to be declining, some ecosystems in this area are still showing increases of mercury in biota (Evers et al., 2007; Prestbo and Gay, 2009; Wyn et al., 2010), including coastal and marine mammals, birds and fish (e.g., Gaskin et al., 1979; Braune and Gaskin, 1987; Goodale et al., 2008; Edmonds et al., 2012; Sunderland et al., 2012).

Investigations into mercury load have been made for several species of fishes in the Bay of Fundy and Saint John River (Dadswell, 1975). Striped bass (*Morone saxatilis*) had a mercury load of 2.13 μg/g and shortnose sturgeon (*Acipenser brevirostrum*) had a lower mercury load of 1.18 μg/g and American shad (*Alosa sapidissima*) had a very low load of 0.10 μg/g (Dadswell, 1975). For shortnose sturgeon, increases in mercury were highly correlated with increased weight of the individual ($r = 0.97$). One anadromous fish which spends much of its life living in the ocean but returns to this river system to breed, and that grows to a larger length and mass than shortnose sturgeon is the Atlantic sturgeon (*Acipenser oxyrhynchus*). This species has not been assessed for Hg load,

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despite its longevity, “near threatened” status internationally (St. Pierre, 2006) and “threatened” status in Canada (COSEWIC, 2011). Moreover, Atlantic sturgeon support two small scale commercial fisheries in Canada, for human consumption. One fishery in the Saint John River harvests adults for caviar and meat products, while one in the St. Lawrence River harvests juveniles for meat products.

Sturgeon are primarily benthivores that feed at a relatively low trophic level (Sulak et al., 2012), consuming a variety of intertidal and benthic invertebrates, small fishes (Novak et al., 2017), and notably various marine worms (Miller, 2004; McLean et al., 2013). Globally, sturgeon species vary considerably in their Hg tissue concentrations (e.g., Agusa et al., 2004; Webb et al., 2006; Agah et al., 2006), with some species exceeding international guidelines (these range from 0.4–1.0 μg/g wet weight; Lowenstein et al., 2010). This species can become very large; the largest recorded Atlantic sturgeon was a female captured in the Saint John River Estuary in 1924 at 4.6 m in length and a mass of 365 kg (Scott and Scott, 1988). Most mature Atlantic sturgeon attain a length of 2–3 m total length (TL) and a mass of 100 to 200 kg for females with males being smaller at 1.4 to 2.1 m TL and 50–100 kg (Smith, 1985, Dadswell et al., 2016). In Atlantic sturgeon body length is a suitable proxy for age because sturgeon continue to grow, and their growth rate is not reduced much even after reproduction (Billard and Lecointre, 2001; Stewart et al., 2015). Maximum age for Atlantic sturgeon is reported to be 54 years for a fish captured in Minas Basin, Nova Scotia in 2010 (Dadswell et al., 2016). Consequently, long sturgeon can be decades old and could have accumulated Hg for many years.

As part of ongoing research on Atlantic sturgeon populations in the Bay of Fundy region (Apostle et al., 2013; Stewart et al., 2015), we sampled MeHg in tissues of Atlantic sturgeon caught in the St. John River, NB after they had moved into freshwater from the Bay of Fundy. We made three predictions based on evidence from earlier studies: a) Hg concentration would be highest in muscle tissue (Wiener and Spry, 1996); b) longer sturgeon would have higher concentrations of Hg (Webb et al., 2006); and c) male and female sturgeon would have similar Hg concentrations (Webb et al., 2006). We expected that Hg might be highest in muscle tissue because it is the main reservoir for MeHg in the body (Giblin and Massaro, 1973). Sturgeon are long-lived fish that feed at a relatively low trophic level (Webb et al., 2006), and thus it seemed that muscle could have higher concentration than liver (the tissue usually supporting the highest concentrations) in this species (Wiener and Spry, 1996).

We collected samples from Atlantic sturgeon harvested by fishing 28.8 cm stretch gill nets in Long Reach of the Saint John River, New Brunswick, Canada (45.47°N, 66.12°W) between May and August 2016, as part of a commercial fishery (Fig. 1). Fish were taken to a processing plant and were lined up on an antiseptic floor, measured for body length (snout to end of tail in cm) and their tails were removed. The blood sample was taken by holding a vial to the anal artery to allow it to fill with blood. When the fish were cleaned, a portion of the liver (~10 g) was removed and placed in a snap closed vial. A sample of the skeletal muscle was taken from the interior of the fish's peritoneal cavity just below the dorsal fin and placed in a snap closed vial. All individually marked samples for each fish were placed in a self-sealing plastic bag, and frozen until processing.

Samples of sturgeon blood, liver and muscle were analyzed for MeHg at the Center for Analytical Research on the Environment (CARE) at Acadia University using methods of Edmonds et al. (2012). We freeze-dried and then homogenized samples into a powder, and then weighed ~10 mg subsamples on a Sartorius ultra-microbalance, and then digested those in 2 mL polypropylene vials using 25% KOH/MeOH (Liang et al., 1994). Aliquots of digest were derivatized with sodium tetraethyl borate ($NaB(C_2H_5)_4$) purged onto Tenax traps and analyzed by gas chromatography with cold vapour atomic fluorescence spectrophotometer (GC-CVAFS Brooks Rand MERX; Bloom and Fitzgerald, 1988; Edmonds et al., 2010). Values were not recovery corrected as we achieved good recovery of DOLT-5 and DORM-4 Certified Reference Material (National Research Council of Canada, Ottawa, Canada; mean recovery 102.9 ± 0.2SD%, $n = 17$). No samples were below the mean method detection limit (MDL; 3 times the standard deviation of blanks) of 0.31 pg. We converted all values to wet weight (ww) assuming 70% moisture content for muscle and liver and 80% for whole blood (e.g., Mallory et al., 2004).

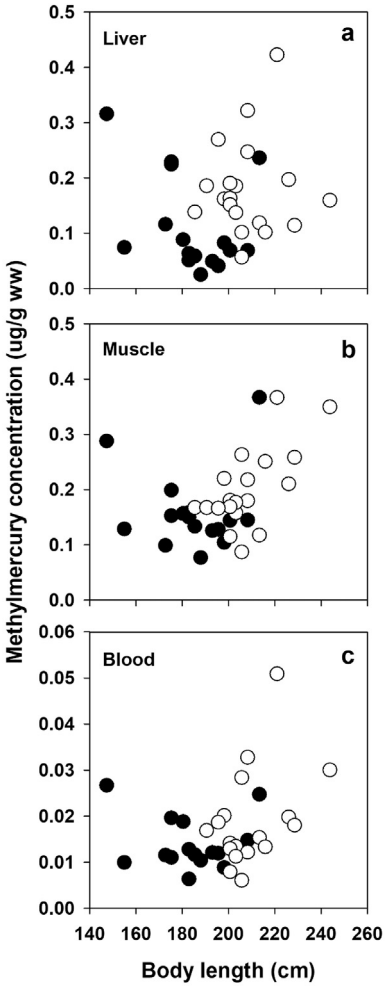

Fig. 1. Concentrations of methylmercury (MeHg; μg/g ww) in (a) liver, (b) muscle and (c) blood from Atlantic sturgeon captured in the St. John River, New Brunswick, Canada. Males are noted by black circles, females with white circles. Statistical analyses were conducted on ln-transformed values.

All statistical analyses were run in Statistica 13 (Dell, 2017). We tested data distributions using Kolmogorov-Smirnov tests, and Levene's test to assess homogeneity of variance. MeHg data were log-transformed for all analyses, after which all data approximated normal distributions (all $p > 0.1$). We used Pearson correlation and analysis of covariance to assess effects of body length and sex on MeHg concentrations in tissues.

We collected tissue samples from 16 male and 19 female sturgeon (Table 1). Mean MeHg concentration was highest in muscle tissue and then liver tissue, both of which had concentrations > 6 × higher than blood. Tissue concentrations were correlated: sturgeon with higher blood MeHg had higher liver MeHg ($r_{35} = 0.67$, $p < 0.001$) and higher muscle MeHg ($r_{35} = 0.76$, $p < 0.001$), and fish with higher muscle MeHg had higher liver MeHg ($r_{35} = 0.63$, $p < 0.001$). However, among tissues, all $r^2 \leq 0.58$, meaning that concentration in one tissue was a good predictor of concentration in another tissue, but much variation was not explained.

MeHg concentrations varied across tissues, and by sex and length of

Table 1
Descriptive statistics for body length and methylmercury (MeHg) concentrations (wet weight) in Atlantic sturgeon captured from the St. John River, New Brunswick.

Parameter	Male (n = 16)				Female (n = 19)				Pooled (n = 35)			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
Body length (cm)	185	18	147	213	208	14	185	243	197	20	147	243
Liver MeHg (μg/g)	0.111	0.087	0.024	0.315	0.180	0.087	0.057	0.423	0.150	0.093	0.024	0.423
Muscle MeHg (μg/g)	0.159	0.072	0.078	0.366	0.198	0.072	0.087	0.366	0.180	0.075	0.078	0.366
Blood MeHg (μg/g)	0.014	0.056	0.006	0.026	0.018	0.010	0.006	0.050	0.016	0.008	0.006	0.050

Table 2
Mercury concentrations (μg/g ww) in muscle of selected biota of the Bay of Fundy region (from Sunderland et al., 2012 except "worms" which include values from Sizmur et al., 2013).

Taxonomic group	THg
	Range of means
Phytoplankton	0.002–0.004
Zooplankton	0.006–0.043
Worms	0.009–0.431
Molluscs	0.016–0.111
Urchins	0.027
Lobster	0.098–0.143
Fish	0.004–0.440
Marine birds	0.037–0.606
Marine mammals	0.160–1.540

sturgeon (Table 1, Fig. 1). Longer sturgeon tended to have higher concentrations of blood MeHg (r_{35} = 0.33, p = 0.053) and muscle MeHg (r_{35} = 0.33, p = 0.056), and the correlation was positive but not significant for liver MeHg (r_{35} = 0.15, p = 0.38). This suggested we should account for body length to compare MeHg between sexes. Female sturgeon had higher concentrations of liver MeHg than males (Fig. 1a; ANCOVA; $F_{1,33}$ = 10.3, p = 0.003), but the effect of body length was not significant ($F_{1,33}$ = 1.3, p = 0.26), and the overall model explained relatively little variation (adj. r^2 = 0.22). Muscle MeHg was not explained significantly by either sex (Fig. 1b; ANCOVA; $F_{1,33}$ = 0.7, p = 0.4) or body length ($F_{1,33}$ = 1.2, p = 0.3; interaction term p > 0.1). For blood MeHg, there tended to be an interaction between sex and body length (ANCOVA; $F_{1,31}$ = 3.6, p = 0.07), so we analyzed patterns within each sex. Male sturgeon had similar blood MeHg irrespective of body length (Fig. 1c; r_{16} = −0.06, p = 0.82), whereas longer female sturgeon had higher blood MeHg (r_{19} = 0.47, p = 0.04).

Atlantic sturgeon had a mean MeHg in muscle about 67% lower than the Canadian guidelines for safe consumption (0.5 μg/g ww; Canada Food Inspection Agency, 2017), lower than all internationally recommended levels (similar to Canadian guidelines; Lowenstein et al., 2010; US Food and Drug Administration, 2017), and even the highest value we measured was 36% lower than Canadian recommendations. Note that we measured MeHg whereas guidelines are for THg, and thus our values may slightly underestimate total Hg in fish, because THg in fish is ~90% MeHg (Handy, 1996). However, as MeHg is the Hg species of most concern, regulators set guidelines assuming all Hg is MeHg (Health Canada, 2007).

As expected, Hg was highest in muscle tissue. In many fish concentrations are highest in liver tissue (Wiener and Spry, 1996), but those may often be shorter-lived species that feed at high trophic levels, and thus ingest comparably high Hg in their diet. After dietary exposure in fish, MeHg may initially be high in tissues like liver, but eventually binds to sulfhydryl groups in protein in muscle, and elimination rates of MeHg generally are lower than uptake rates (Giblin and Massaro, 1973; Wiener and Spry, 1996). We speculate that the higher MeHg concentration in sturgeon muscle than liver may result from prolonged exposure to low dietary concentrations but lower elimination rates over many years, such that MeHg becomes relatively high in muscle tissue (Wiener and Spry, 1996). Although MeHg in blood, liver and muscle tissues were positively correlated, as noted earlier there was much unexplained variation among tissues, suggesting that other physiological factors (e.g., body condition, reproductive status) influence Hg concentrations in specific tissues, as found previously (e.g., Suzuki et al., 1973; Webb et al., 2006).

Globally, mean concentrations of Hg in most wild marine fish are reported to range between 0.02 and 1.82 μg/g ww (e.g., Agah et al., 2006; Health Canada, 2007), with highest concentrations found in top predators (Lowenstein et al., 2010) like sharks and swordfish, which in some cases can exceed 3 μg/g ww (Nakagawa et al., 1997; Kojadinovic et al., 2006). Concentrations in canned fish can vary greatly, with various studies showing a range of 0.02–1.00 μg/g ww depending on species and geographic region (e.g., Plessi et al., 2001; Burger and Gochfeld, 2004; Ikem and Egiebor, 2005). Freshwater fish species also exhibit concentrations > 1.0 μg/g ww (Kamman et al., 2005), with piscivorous species having higher concentrations than non-piscivorous species (Peterson et al., 2007). In the Gulf of Maine/Bay of Fundy region, Atlantic sturgeon had lower mean MeHg levels than THg in spiny dogfish (a shark; *Squalus acanthias*; 0.27 μg/g ww), but higher than other anadromous fish including Atlantic salmon (*Salmo salar*; 0.07 μg/g) and alewife (*Alosa pseudoharengus*; 0.06 μg/g) (THg; Sunderland et al., 2012). Values of THg across the trophic web of the Bay of Fundy are summarized in Table 2 and show that our Atlantic sturgeon Hg

Table 3
Mean and maximum values of THg in muscle tissue, as well as mean body length in the sample, of various sturgeon species from different locations around the world. All values are from animals considered adults, and males and females have been pooled. Note that the values from this study are for MeHg.

Species	Mean THg (μg/g ww)		Mean length (cm)	Reference
	Mean	Maximum		
Persian sturgeon (*Acipenser persicus*)	0.33	1.6	97–147	Agusa et al. (2004)
Russian sturgeon (*Acipenser gueldenstaedtii*)	0.32	1.2	92–145	Agusa et al. (2004)
Beluga sturgeon (*Huso huso*)	1.4	3.5	175–222	Agusa et al. (2004)
Ship sturgeon (*Acipenser nudiventris*)	0.67	1.9	141–163	Agusa et al. (2004)
Stellate sturgeon (*Acipenser stellatus*)	0.06	0.31	107–152	Agusa et al. (2004)
White sturgeon (*Acipenser transmontanus*)	0.17	1.09	110–137	Webb et al. (2006)
Atlantic sturgeon (*Acipenser oxyrhynchus*)	0.17	–	152	Mierzykowski (2010)
Atlantic sturgeon (*Acipenser oxyrhynchus*)	0.18	0.37	197	This study

concentrations fit well within the lobster and fish THg concentration ranges measured by Sunderland et al. (2012).

In other sturgeon species, Hg concentrations vary considerably (Table 3). Agusa et al. (2004) reported muscle THg concentrations of several species from the Caspian Sea, where Persian sturgeon (*Acipenser persicus*) and Russian sturgeon (*A. gueldenstaedtii*) had concentrations just under double what we found for Atlantic sturgeon, while THg in Beluga (*Huso huso*) and ship sturgeon (*A. nudiventris*) was much higher, and concentrations in stellate sturgeon (*A. stellatus*) were considerably lower (Table 3). Agusa et al. (2004) attributed these differences to regional contamination and diets of the different species. Webb et al. (2006) reported mean muscle THg concentrations of white sturgeon (*Acipenser transmontanus*) in western North America that were remarkably similar to our overall mean values for Atlantic sturgeon (Table 1). However, the highest concentration they found in muscle was 1.09 μg/g ww in an old, mature female, three times higher than our maximum concentration of 0.37 μg/g ww. Mierzykowski (2010) sampled one dead male Atlantic sturgeon and found muscle Hg values similar to ours. Webb et al. (2006) suggested that, although concentrations of THg in sturgeon were lower than many other species examined, the long lives of sturgeon meant that they could accumulate much mercury over a lifetime. If length is a suitable proxy for age, our results suggest that older female fish have higher muscle MeHg concentrations, but still not approaching the Canadian Food Inspection Agency (2017) guidelines of 0.5 μg/g ww. Moreover, the relationship between length and MeHg was not strong and varied among tissues. Most Hg is taken up through diet (Wiener and Spry, 1996), and in the Bay of Fundy region, Hg in intertidal invertebrates is quite low (e.g., English et al., 2015), although some of the benthic polychaetes in deeper sediment had higher values (Sizmur et al., 2013). Sulak et al. (2012) found little variation in trophic position (i.e., diet) of Atlantic sturgeon irrespective of length, and thus the relationship of higher Hg with age or length may only be relevant for certain size ranges of sturgeon. We also found that female sturgeon had higher MeHg concentrations than males, contra Webb et al. (2006), but consistent with Sorensen (1991) who found higher Hg levels in females from seven of eight fish species in New York.

Collectively, Atlantic sturgeon moving in the Bay of Fundy and into the St. John River had Hg concentrations well below levels considered a risk for consumption, and below levels associated with deleterious physiological effects in fish (5–20 μg/g ww; Wiener and Spry, 1996). However, additional research is required to determine factors leading to sex-specific differences in MeHg concentrations in this species, and we also recommend testing sturgeon caviar, since this could form a Hg burden removal mechanism for females.

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References

Agah, H., Leermakers, M., Elskens, M., Fatemi, S.H.R., Baeyens, W., 2006. Total mercury and methyl mercury concentrations in fish from the Persian Gulf and Caspian Sea. Water Air Soil Pollut. 181, 95–105.

Agusa, T., Kunito, T., Tanabe, S., Pourkazemi, M., Aubrey, D.G., 2004. Concentrations of trace elements in muscle of sturgeons in the Caspian Sea. Mar. Pollut. Bull. 49, 789–800.

Apostle, R., Dadswell, M.J., Engler-Palma, C., Litvak, M.K., McLean, M.F., Stokesbury, M.J., Taylor, A.D., VanderZwaag, D.L., 2013. Sustaining Atlantic sturgeon: stitching a stronger scientific and governance net. J. Internat. Wildl. Law Policy 16, 170–197.

Billard, R., Lecointre, G., 2001. Biology and conservation of sturgeon and paddle fish. Rev. Fish Biol. Fish. 10, 355–392.

Bloom, N., Fitzgerald, W.F., 1988. Determination of volatile mercury species at the pictogram level by low-temperature gas chromatography with cold-vapour atomic fluorescence detection. Anal. Chim. Acta 208, 151–161.

Braune, B.M., Gaskin, D.E., 1987. Mercury levels in Bonaparte's gulls (*Larus philadelphia*) during autumn molt in the Quoddy region, New Brunswick, Canada. Arch. Environ. Contam. Toxicol. 16, 539–549.

Burger, J., Gochfeld, M., 2004. Mercury in canned tuna: white versus light and temporal variation. Environ. Res. 96, 239–249.

Canadian Food Inspection Agency, 2017. Standards and methods manual. http://www.inspection.gc.ca/food/fish-and-seafood/manuals/standards-and-methods/eng/1348608971859/1348609209602?chap=0, Accessed date: 29 May 2017.

Clarkson, T.W., Magos, L., 2006. The toxicology of mercury and its chemical compounds. Crit. Rev. Toxicol. 36, 609–662.

COSEWIC, 2011. COSEWIC assessment and status report on the Atlantic Sturgeon *Acipenser oxyrinchus* in Canada. Committee on the Status of Endangered Wildlife in Canada, Ottawa (xiii + 49 pp).

Dadswell, M.J., 1975. Mercury, DDT, and PCB content of certain fishes from the Saint John River Estuary, New Brunswick. In: Trans. of the Atl. Chapt. Can Soc. Of Environ. Biol. Annual meeting 3–5 November 1975, Fredericton, New Brunswick, Canada.

Dadswell, M.J., Wehrell, S.A., Spares, A.D., Mclean, M.F., Beardsall, J.W., Logan-Chesney, L.M., Nau, G.S., Ceapa, C., Redden, A.M., Stokesbury, M.J.W., 2016. The annual marine feeding aggregation of Atlantic sturgeon *Acipenser oxyrinchus* in the inner Bay of Fundy: population characteristics and movement. J. Fish Biol. 89, 2107–2132.

Dell, Inc., 2017. Corporate Services. Dell Services, Austin, Texas, USA.

Drevnick, P.E., Sandheinrich, M.B., 2003. Effects of dietary methylmercury on reproductive endocrinology of fathead minnows. Environ. Sci. Technol. 37, 4390–4396.

Edmonds, S.T., Evers, D.C., Cristol, D., Mettke-Hofmann, C., Powell, L.L., McGann, A.J., Armiger, J.W., Lane, O.P., Tessler, D.F., Newell, P., Heyden, K., O'Driscoll, N.J., 2010. Geographic and seasonal variation in mercury exposure of the declining rusty blackbird. Condor 112, 789–799.

Edmonds, S.T., O'Driscoll, N.J., Hiller, N.K., Atwood, J.L., Evers, D.C., 2012. Factors regulating the bioavailability of methylmercury to breeding rusty blackbirds in northeastern wetlands. Environ. Pollut. 171, 148–154.

English, M.D., Robertson, G.J., Mallory, M.L., 2015. Trace element and stable isotope analysis of fourteen species of marine invertebrates from the Bay of Fundy, Canada. Mar. Pollut. Bull. 101, 466–472.

Evers, D.C., Han, Y.J., Driscoll, C.T., Kamman, N.C., Goodale, M.W., Lambert, K.F., Holsen, T.M., Chen, C.Y., Clair, T.A., Butler, T., 2007. Biological mercury hotspots in the northeastern United States and southeastern Canada. Bioscience 57, 29–43.

Gaskin, D.E., Stonefield, K.I., Suda, P., 1979. Changes in mercury levels in harbour porpoises from the Bay of Fundy, Canada and adjacent waters. Arch. Environ. Contam. Toxicol. 8, 733–762.

Giblin, F.J., Massaro, E.J., 1973. Pharmacodynamics of methyl mercury in the rainbow trout (*Salmo gairdneri*): tissue uptake, distribution and excretion. Toxicol. Appl. Pharmacol. 24, 81–91.

Goodale, M.W., Evers, D.C., Mierzykowski, S.E., Bond, A.L., Burgess, N.M., Otorowski, C.I., Welch, L.J., Hall, C.S., Ellis, J.C., Allen, R.B., Diamond, A.W., 2008. Marine foraging birds as bioindicators of mercury in the Gulf of Maine. EcoHealth 5, 409–425.

Handy, R., 1996. Dietary exposure to toxic metals in fish. In: Taylor, E. (Ed.), Toxicology of Aquatic Pollution. Cambridge University Press, New York, NY, pp. 29–33.

Health Canada, 2007. Human Health Risk Assessment of Mercury in Fish and Health Benefits of Fish Consumption. Technical Report. Health Canada, Ottawa, Canada. http://www.hc-sc.gc.ca/fn-an/alt_formats/hpfb-dgpsa/pdf/nutrition/merc_fish_poisson-eng.pdf, Accessed date: 29 May 2017.

Ikem, A., Egiebor, N.O., 2005. Assessment of trace elements in canned fishes (mackerel, tuna, salmon, sardines and herrings) marketed in Georgia and Alabama (United States of America). J. Food Compos. Anal. 18, 771–787.

Kamman, N.C., Burgess, N.M., Driscoll, C.T., Simonin, H.A., Goodale, W., Linehan, J., Estabrook, R., Hutcheson, M., Major, A., Scheuhammer, A.M., Scruton, D.A., 2005. Mercury in freshwater fish of northeast North America–a geographic perspective based on fish tissue monitoring databases. Ecotoxicology 14, 163–180.

Kojadinovic, J., Potier, M., Le Corre, M., Cosson, R.P., Bustamante, P., 2006. Mercury content in commercial pelagic fish and its risk assessment in the Western Indian Ocean. Sci. Total Environ. 366, 688–700.

Liang, L., Bloom, N., Horvat, M., 1994. Simultaneous determination of mercury speciation in biological materials by GC/CVAFS after ethylation and room-temperature precollection. Clin. Chem. 40, 602–607.

Lindberg, S.A., Stratton, W.J., 1998. Atmospheric mercury speciation: concentrations and behavior of reactive gaseous mercury in ambient air. Environ. Sci. Technol. 32, 49–57.

Lowenstein, J.H., Burger, J., Jeitner, C.W., Amato, G., Kolokotronis, S.O., Gochfeld, M., 2010. DNA barcodes reveal species-specific mercury levels in tuna sushi that pose a health risk to consumers. Biol. Lett. 6, 692–695.

Mallory, M.L., Wayland, M., Braune, B.M., Drouillard, K.G., 2004. Trace elements in marine birds, arctic hare and ringed seals breeding near Qikiqtarjuaq, Nunavut, Canada. Mar. Pollut. Bull. 49, 136–141.

McLean, M.F., Dadswell, M.J., Stokesbury, M.J.W., 2013. Feeding ecology of Atlantic sturgeon, *Acipenser oxyrinchus oxyrinchus* Mitchill, 1815 on the infauna of intertidal mudflats of Minas Basin, Bay of Fundy. J. Appl. Ichthyol. 29, 503–509.

Mierzykowski, S.E., 2010. Environmental Contaminants in Tissues From an Atlantic Sturgeon (*Acipenser oxyrinchus*) Recovered in Wellfleet, Massachusetts. USFWS. Spec. Proj. Rep. FY09-MEFO-4-EC, Maine Field Office. Orono, ME, pp. 42.

Miller, M.J., 2004. The ecology and functional morphology of feeding of North American sturgeon and paddlefish. In: LeBreton, G.T., Beamish, F.W.H., McKinley, S.R. (Eds.), Sturgeons and Paddlefish of North America. Vol. 27. Netherlands, Springer, pp. 87–102.

Miller, E.K., Vanarsdale, A., Keeler, G.J., Chalmers, A., Poissant, L., Kamman, N.C., Brulotte, R., 2005. Estimation and mapping of wet and dry mercury deposition across northeastern North America. Ecotoxicology 14, 53–70.

Nakagawa, R., Yumita, Y., Hiromoto, M., 1997. Total mercury intake from fish and shellfish by Japanese people. Chemosphere 35, 2909–2913.
Novak, A.J., Carlson, A.E., Wheeler, C.R., Wippelhauser, G.S., Sulikowski, J.A., 2017. Critical foraging habitat of Atlantic sturgeon based on feeding habits, prey distribution, and movement patterns in the Saco River estuary, Maine. Trans. Am. Fish. Soc. 146, 308–317.
O'Driscoll, N.J., Rencz, A.N., Lean, D.R.S., Sigel, A., Sigel, H., Sigel, R.K.O., 2005. The biogeochemistry and fate of mercury in natural environments (Chapter 14). In: Metal Ions in Biological Systems. Vol. 43 Marcel Dekker, Inc., New York.
Peterson, S.A., van Sickle, J., Herlihy, A.T., Hughes, R.M., 2007. Mercury concentrations in fish from streams and rivers throughout the western United States. Environ. Sci. Technol. 41, 58–65.
St. Pierre, R., 2006. Acipenser oxyrinchus ssp. oxyrinchus. In: The IUCN Red List of Threatened Species 2006: e.T243A13046213.
Plessi, M., Bertelli, D., Monzani, A., 2001. Mercury and selenium content in selected seafood. J. Food Composit. Anal. 14, 461–467.
Prestbo, E.M., Gay, D.A., 2009. Wet deposition of mercury in the US and Canada, 1996–2005: results and analysis of the NADP mercury deposition network (MDN). Atmos. Environ. 43, 4223–4233.
Scheuhammer, A.M., Meyer, M.W., Sandheinrich, M.B., Murray, M.W., 2007. Effects of environmental methylmercury on the health of wild birds, mammals, and fish. Ambio 36, 12–19.
Schroeder, W.H., Munthe, J., 1998. Atmospheric mercury—an overview. Atmos. Environ. 32, 809–822.
Scott, W.B., Scott, M.C., 1988. Atlantic fishes of Canada. Can. Bull. Fish. Aquat. Sci. 219.
Sizmur, T., Canário, J., Gerwing, T.G., Mallory, M.L., O'Driscoll, N.J., 2013. Mercury and methylmercury bioaccumulation by polychaete worms is governed by both feeding ecology and mercury bioavailability in coastal mudflats. Environ. Pollut. 176, 18–25.
Smith, T.I., 1985. The fishery, biology, and management of Atlantic sturgeon, *Acipenser oxyrhynchus*, in North America. Environ. Biol. Fish 14, 61–72.
Sorensen, E.M., 1991. Metal Poisoning in Fish. CRC Press, Boca Raton, Florida, USA.
Stewart, N.D., Dadswell, M.J., Leblanc, P., Bradford, R.G., Ceapa, C., Stokesbury, M.J., 2015. Age and growth of Atlantic sturgeon from the Saint John River, New Brunswick, Canada. N. Am. J. Fish. Manage 35, 364–371.
Sulak, K.J., Berg, J.J., Randall, M., 2012. Feeding habitats of the Gulf sturgeon, *Acipenser oxyrinchus desotoi*, in the Suwannee and Yellow rivers, Florida, as identified by multiple stable isotope analyses. Environ. Biol. Fish 95, 237–258.
Sunderland, E.M., Chmura, G.L., 2000a. The history of mercury emissions from fuel combustion in Maritime Canada. Environ. Pollut. 110, 1–10.
Sunderland, E.M., Chmura, G.L., 2000b. An inventory of historical mercury pollution in Maritime Canada: implications for present and future contamination. Sci. Total Environ. 256, 39–57.
Sunderland, E.M., Amirbahman, A., Burgess, N.M., Dalziel, J., Harding, G., Jones, S.H., Kamai, E., Karagas, M.R., Shi, X., Chen, C.Y., 2012. Mercury sources and fate in the Gulf of Maine. Environ. Res. 119, 27–41.
Suzuki, T., Miyama, T., Toyama, C., 1973. The chemical form and bodily distribution of mercury in marine fish. Bull. Environ. Contam. Toxicol. 10, 347–355.
Ullrich, S.M., Tanton, T.W., Abdrashitova, S.A., 2001. Mercury in the aquatic environment: a review of factors affecting methylation. Crit. Rev. Environ. Sci. Technol. 31, 241–293.
US Food and Drug Administration, 2017. Technical information on development of fish consumption advice - FDA/EPA advice on what pregnant women and parents should know about eating fish. https://www.fda.gov/Food/FoodborneIllnessContaminants/Metals/ucm531136.htm, Accessed date: 6 March 2017.
Webb, M.A.H., Feist, G.W., Fitzpatrick, M.S., Foster, E.P., Schreck, C.B., Plumlee, M., Wong, C., Gundersen, D.T., 2006. Mercury concentrations in gonad, liver, and muscle of white sturgeon *Acipenser transmontanus* in the lower Columbia River. Arch. Environ. Contam. Toxicol. 50, 443–451.
Wiener, J.G., Spry, D.J., 1996. Toxicological significance of mercury in freshwater fish. In: Beyer, W.N., Heinz, G.H., Redmon-Norwood, A.W. (Eds.), Environmental Contaminants in Wildlife Interpreting Tissue Concentrations. Lewis, Boca Raton, Florida, USA, pp. 297–339.
Wyn, B., Kidd, K.A., Burgess, N.M., Curry, R.A., Munkittrick, K.R., 2010. Increasing mercury in yellow perch in a hotspot in Atlantic Canada, Kejimkujik National Park. Environ. Sci. Technol. 44, 9176–9181.