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Abstract

Background: North American Great Lakes are home to more than 140 types of fish and are famous for recreational and commercial fishing. However, presence of toxic substances has resulted in issuance of fish consumption advisories typically based on the most restrictive contaminant.

Objectives: We investigate if these advisories, which typically neglect existence of a mixture of chemicals and their possible additive adverse effects, are adequately protective of health of humans consuming fish from the Canadian waters of the Great Lakes.

Methods: Using recent fish contaminant monitoring data collected by the Government of Ontario, Canada, we simulated advisories using the most restrictive contaminant (one-chem) and multi-contaminant additive effect (multi-chem) approaches. The advisories from the two simulations were compared to examine if there is any deficiency in the currently issued advisories.

Results: About half of the advisories presently issued are potentially not adequately protective. Of the Great Lakes, the highest percentage of advisories affected would be in Lake Ontario if an additive effect is considered. Many fish, which are popular for consumption such as Walleye, Salmon, Bass and Trout, would have noticeably more stringent advisories.

Conclusions: Improvements in the advisories may be needed to ensure that the health of humans consuming fish from the Great Lakes is protected. In this region, total PCB and mercury are the major contaminants causing restriction on consuming fish, while dioxins/furans, toxaphene and mirex/photomirex are of a minor concern. Regular monitoring of most organochlorine pesticides and metals in fish can be discontinued.

Introduction

The Great Lakes of North America contain 21% of the world's surface fresh water and are rich in flora and fauna. The Great Lakes house more than 140 types of fish ranging from panfish to large top predatory fish (Cudmore-Vokey and Crossman 2000). The lakes have supported one of the world's largest freshwater fisheries for over a century and is valued at more than $5 billion annually (NOAA 2015). The value and total economic impacts of the recreational fisheries far exceed that of the commercial fisheries (NOAA 2015). More than 4 million adults in the U.S. Great Lakes region consume a variety of fish from the Great Lakes every year, and their consumption is related to their children's consumption (Turyk et al. 2012). There are >1 million anglers in Ontario, and Lakes Erie, Huron and Ontario are in the top 10 preferred fishing locations for Ontario anglers (Awad 2006; Fisheries and Oceans Canada 2012). Many of the more than 160 Aboriginal communities located around the Great Lakes rely on a variety of Great Lakes fish for food (Turyk et al. 2012). For example, a survey of the eating patterns of First Nations people in the Great Lakes basin found that about 84% of the participants consumed on average about 20 to 35 fish meals in one year (EAGLE 2001).

Industrial and agricultural activities have impacted water quality of the Great Lakes through the introduction of toxic substances such as polychlorinated biphenyls (PCBs), mercury, dioxins and furans, and pesticides (Bhavsar et al. 2007c; Bhavsar et al. 2008a; Bhavsar et al. 2010; Murphy et al. 2012). The elevated levels of contaminants in fish have resulted in fish consumption advisories to limit human exposure to contaminants to a safe level (OMOECC 2015; USEPA 2015). These advisories issued by the Province of Ontario for the Canadian waters and Great Lakes States for the U.S. waters of the Great Lakes are typically based on the most restrictive contaminant (GLSFATF 1993; OMOECC 2015). In this approach, fish consumption advisory benchmarks (e.g., Table S1) are utilized to derive recommended meals per month for a particular size and type of fish from a specific location, individually for all major contaminants present. The most stringent advisory (i.e., the least number of fish meals per month advised) is then selected, and the contaminant causing this restriction is considered the restrictive contaminant. The advisories are presumed adequately protective because other contaminants are present but not predominant (GLSFATF 1993), although a consideration of contaminant interactions has been suggested (Bemis and Seegal 1999).

Currently, PCBs are the major drivers of the restrictive fish consumption advisories for the Great Lakes (GLSFATF 1993; OMOECC 2015). Mercury and dioxins/furans are the secondary cause of restrictions (Bhavsar et al. 2011; OMOECC 2015). Levels of toxaphene and mirex/photomirex only occasionally cause restrictive advisories (Gandhi et al. 2014; Gandhi et al. 2015; OMOECC 2015). Exposures to these and other major contaminants detected in Great Lakes fish can cause a variety of adverse health impacts in humans (Table 1; Murphy et al. 2012). Multiple contaminants can generate health effects that are additive, more than additive (synergistic), or less than additive (i.e., some effects are alleviated). Previous studies have highlighted that PCBs and mercury are the two most important contaminants found in Great Lakes fish (Bhavsar et al. 2007c; Bhavsar et al. 2011; Gandhi et al. 2014; Gandhi et al. 2015; OMOECC 2015). Although in some cases combined effects of PCB and mercury can be less than additive or uncertain, many studies support their additive or synergistic effects (Bemis and Seegal 1999; Fischer et al. 2008; Piedrafita et al. 2008; Powers et al. 2009; Roegge et al. 2004).

It has been recognised that risk assessments of chemical mixtures usually involves substantial uncertainties (USEPA 1986, 2000). When sufficient data on the effects of a chemical mixture are not available, considering additive toxicity is recommended assuming that the chemicals in the mixture produce adverse effects using the same mode of action (USEPA 1986, 2000). Although PCB can yield widely varying effects such as impacts on the reproductive system and development, and is considered a carcinogen, both PCB and mercury have been recognized as neurotoxicants and can affect immune system (Bemis and Seegal 1999; Murphy et al. 2012; Powers et al. 2009). Further, a variety of contaminants found in Great Lakes fish can have many overlapping health effects (Table 1). As such, the assumption of additive toxicity, rather than synergistic or less than additive, presents a reasonable scenario that also incorporates scientific uncertainty. Our previous work has shown that in the absence of PCBs, mercury, toxaphene and mirex/photomirex would cause more stringent advisories than these other than PCB contaminants are at present (Bhavsar et al. 2011; Gandhi et al. 2014; Gandhi et al. 2015). However, it is not clear if consideration of additive effects of the major contaminants known to exist in Great Lake fish would result in only slightly or substantially more stringent advisories.

In this study, we investigate if the current advisories for the Canadian waters of the Great Lakes are adequately protective of human health when possible additive effects of multiple contaminants are considered. The study also investigated variation in inadequacy of the advisories under this scenario by region, fish species and size of fish. Finally, we also examined contribution of an individual contaminant to added toxicity from multiple contaminants. Using the recent fish contaminant monitoring data collected by the Government of Ontario, Canada, we simulated advisories using both the most restrictive contaminant and multiple contaminant approaches. The currently employed most restrictive contaminant approach was evaluated by comparing the simulated advisories from the two approaches. The outcome of this assessment can inform if changes to the current method of issuing fish advisories are needed to ensure that the health of humans consuming fish from the Great Lakes is adequately protected.

Methods

Dataset

Four of the five lakes in the North American Great Lakes system are shared by the U.S. and Canada (Figure S1). The U.S. waters of the Great Lakes are shared by eight states while almost all of the Canadian waters of the Great Lakes are within the boundary of the Province of Ontario. The Ontario Ministry of the Environment and Climate Change (OMOECC), in partnership with the Ontario Ministry of Natural Resources and Forestry and other agencies, has monitored contaminants in fish from all parts of the Canadian waters of the Great Lakes since 1970. The measurements collected by the Province of Ontario are analytically consistent, and the advisories are based on one method and one set of the benchmarks. As such, we focused our study on the Canadian waters of the Great Lakes.

Since fish contaminant monitoring for different areas and types of fish is conducted on a periodic basis, we considered the measurements collected between 2000 and 2015 as a reasonable recent time period to avoid historical measurements that could have been high for certain legacy contaminants (Bhavsar et al. 2007c; Bhavsar et al. 2008a; Bhavsar et al. 2010), and to maximize data coverage of fish species, their size ranges and collection areas. In total, about 145,000 data points for 26 major types of contaminants in skinless, boneless fillets from 41 types of fish >15 cm (which can be considered the most edible portion for humans) were available. This dataset did not include, for example, lipid measurements that are not a part of the advisory calculations. Next, about 85,000 measurements that were below the detection limits (mostly for organochlorine pesticides) were removed since non-detects can have a significant impact on the analysis as deliberated in the discussion section. The remaining ~60,000 measurements were then spatially classified into 60 regions used by the OMOECC for the purpose of issuing advisories (Figure S2; Gandhi et al. 2014) and were utilized for the advisory simulations.

Advisory simulations

The data collected at different time points for each fish species and location were pooled together to create a *recent* scenario. A power series regression ($C=a\ L^b$) of fish length (L) versus contaminant concentrations (C) was conducted for each available combination of contaminant, fish species and advisory region, as illustrated in Figure S3. A total of 2,457 regressions were utilized to calculate concentrations of contaminants at 5 cm fish size intervals for each of 575 combinations of species/regions (an average of approximately 5-6 sized based advisories for each of about 10 species per region). These concentrations, standardized to fish lengths (e.g., Figure S3), were then used to simulate fish consumption advisories.

The methods of advisory simulations using both the current most restrictive contaminant (one-chem) approach and multi-contaminant (multi-chem) approach are illustrated in Table 2 and in the Supporting Material. For the one-chem approach, contaminant concentrations standardised to fish lengths were classified into the advisory categories of 32, 16, 12, 8, 4, 2, 1 or 0 meals/month according to the benchmarks for the general population (GP) and sensitive population (SP; women of child bearing age and children) shown in Table S1. Then, the least number of meals/month advised for each 5 cm size category for each species and region was selected. For the multi-chem approach, an additive effect was considered. The concentrations standardised to fish lengths were first divided by the contaminant- and population-specific benchmarks for the least stringent (32 meals/month) advisory shown in Table S1. This ratio can be viewed as a contaminant-specific Hazard Quotient (HQ) for an unrestricted (32+ meals/month) advisory. The HQs for all contaminants for a particular size/species/region/population were summed to calculate a Hazard Index (HI) reflecting an additive effect of all the contaminants considered. An HI value of <1 would result in an advisory of 32 meals/month. An HI value of >1 would result in an advisory of 0, 1, 2, 4, 8, 12, or 16 meals/month as per illustration in the Supporting Material. Since the Province of Ontario does not recommend the sensitive population eating fish from the 4 and 2 meals/month advisory categories, those advisories were converted to 0 meal/month (i.e., "do not eat").

Evaluation of the advisory approaches

The adequacy of the current approach of issuing advisory based on the most restrictive contaminant (one-chem) was evaluated by comparing advisories from the two approaches, and classifying the multi-chem advisories into the categories of the same or more stringent as illustrated in Figure S4. Percent contribution of each contaminant to an HI was calculated by dividing contaminant-specific HQ with HI and multiplying by 100.

Results

Impact on the advisories

Overall, 39-65% of the advisories based on the most restrictive contaminant would be more stringent if additive adverse effect of major contaminants known to be present in Great

Lakes fish is considered (Figure 1). More advisories would be stringent for GP (45-65%) compared to SP (39-52%) (Figure 1).

A breakdown of the advisories indicated that under the multi-chem approach, 8+ meals/month advisories would decline from 58% to 43% of the advisories for GP, and from 45% to 28% for SP (Tables 3, S2; Figure S5). The “do not eat” (i.e., 0 meal/month) advisories would increase from 5% to 10% for GP and 30% to 47% for SP (Tables 3, S2; Figure S5). Although majority of the advisories (43% point of 54% for GP; 32% point of 42% for SP) would be only one category more stringent, which would typically reduce advised meals/month in half, some (10-11%) advisories would be 2+ categories more stringent suggesting that only a quarter or less of the one-chem based advised meals/month should be consumed (Tables 3, S3).

On a lake-wide basis, adoption of the multi-chem approach would have the least impact on the Lake Huron advisories (41-45% of the advisories more stringent), while Lakes Erie and Superior would have similar impacts (39-55% of the advisories more stringent) (Figure 1). For Lake Ontario, the highest percentage (52-65%) of the advisories would be more stringent (Figure 1). In all regions of the Canadian waters of the Great Lakes, >20% of the GP advisories would be more stringent, except for Lake Erie Wheatley Harbour (LE2b; 0%) and the middle corridor of the St. Lawrence River (LO13; 12%) (Figure S6). For many (21 or 35% of 60) regions,>60% the GP advisories would be more stringent (Figure S6). For SP, only 8 of 60 (13%) regions would have >60% of the advisories more stringent, and more regions (9 of 60) would be less impacted (<20% of the advisories more stringent) (Figure S6).

Contributions of contaminants

In the multi-chem advisory simulations, a contaminant-specific HQ was calculated, and then HQs for all available contaminants were summed to derive an HI that formulates an advisory. A breakdown of individual HQ contributions to HIs are presented in Figure 2, and the number of multi-chem advisories for which a contaminant was the major contributor to the overall additive effect is presented in Table S4 in order to provide insights into which contaminants drive the multi-chem based advisories. The maximum contribution of a contaminant to an HI is, on average, about 70% (standard deviation SD: 20%). These results indicate that additive toxicity would be on average about 43% greater ((100-70)/70=0.43) and could be as high as 300%. Total PCB would be generally the highest contributor to the additive toxicity (46-57%; SD: 21-22%). Average mercury contribution to the advisories for SP would be marginally greater than total PCB at 48% (SD: 34%), but lower for the GP at 37% (SD: 36%). Toxic equivalent concentrations of dioxins, furans and dioxin-like PCBs (total TEQ) would on average contribute 43% and 39% (SD: 17%) for the GP and SP, respectively. Among the dioxins and dioxin-like compounds, most of the contribution to the total TEQ is typically from the dioxin-like PCBs, and dioxin-like PCBs and total PCBs are correlated (Bhavsar et al. 2007a; Bhavsar et al. 2007b; Bhavsar et al. 2008b). As such, PCB, as a group, would be the major contaminant driving the additive toxicity of the contaminant mixture. Toxaphene would be the only other contaminant that would have >10% average contribution to the additive toxicity for both the GP and SP. Photomirex and perfluorooctanesulfonic acid (PFOS) would also have some meaningful (average >10%, N>200) contributions to the additive toxicity for the GP. Some metals would also contribute >10% on average for the GP; however, these were based on only a few advisories and almost all of the HQs for the metals were <1 (Figure 2, Figure S7) implying that their individual levels would allow for fish consumption on a daily basis (i.e., 32 meals/month).

Fish species and size specific differences

Next we examined if the multi-chem approach affected certain types and size of fish differently. Species specific impact varied dramatically and generally ranged from 20-70% (25^{th}-75^{th} percentile: 33-60% for the GP, 26-52% for the SP; Table S5). Walleye, which is the most favourite fish for anglers and Aboriginals in the region (Fisheries and Oceans Canada 2012), would have about 74% of the GP and 52% of the SP advisories more stringent (Figure 3, Table S5). Many other favourite fish such as Coho and Chinook Salmon, Smallmouth Bass and Rainbow Trout (Awad 2006) would also have noticeable impacts (>50% of the advisories more stringent; Figure 3, Table S5). Although some fish size specific differences in the impact of the multi-chem approach were observed, these differences were relatively moderate (Table S6). Generally, the largest and smallest sized fish were a little less impacted than the medium sized fish (Table S6).

Evaluation of the method

Finally, we evaluated our method of using data from 2000 to 2015 and grouping them together by advisory regions to create a reasonable recent scenario. Overall, our one-chem simulations indicated 62%, 70%, 54% and 51% of advisories were 8+ meals/month for Lakes Superior, Huron, Erie and Ontario, respectively (Figure S8). These results are reasonably similar to the corresponding values of 59%, 58%, 40% and 42% for the real, published advisories (OMOECC 2015). A greater difference for Lake Erie (54% vs 40%) is likely due to the exclusion of Lake St. Clair and St. Clair and Detroit River advisories in statistics of the published

Lake Erie advisories. Since 62% of the advisories for these excluded areas are 8+ meals/month, an inclusion of the St. Clair – Detroit River corridor could have improved the comparison.

For all multi-chem based advisories, contaminants contributing the most to the additive toxicity (i.e., HI) were tallied. A breakdown of this tally would reflect which contaminants would have caused restrictive advisories under the most-restrictive contaminant approach of the real published advisories. As shown in Figure 4, about 81%, 76% and 71% of the advisories for Lakes Ontario, Huron and Superior are driven by total PCB and total TEQ. These results are similar to 88%, 78% and 68% for the published advisories (OMOECC 2015). Mercury drove 18%, 24% and 20% of the advisories for Lakes Ontario, Huron and Superior, respectively, in our analysis (Figure 4), and are similar to the corresponding 12%, 21% and 25% for the published advisories (OMOECC 2015). This evaluation indicates that the method used in this study to group data by time and space was reasonably realistic.

Removal of the non-detects was appropriate as their detection limits could be very close to the benchmarks to change an advisory from 32 to 16 meals/month, and could produce HQs close to 1 (e.g., 4 ng/g for both detection limit and benchmark of photomirex). Retention of the non-detects in our analysis could have reduced the maximum contribution of a contaminant to an HI on average from approximately 70% to 50% (Figures 2 and S9) translating to needless on average 30% increase in the additive toxicity.

Discussion

About half of the Great Lakes advisories based on the most-restrictive contaminant would be more stringent if additive toxicity of the major current contaminants of concern is considered

(Figure 1). Although most of these advisories would result in half advised meals/month, about one tenth of the advisories would be a quarter or less meals/month (Table 3). Consumption of these more affected fish as per the one-chem based advisory would result in four or more times greater exposure to the contaminants than considered safe if their additive effects are accounted for. Such unsafe exposures to contaminants may increase potential for the adverse health effects summarised in Table 1. Therefore, a substantial number of the Great Lakes advisories are probably deficient in protecting the health of human consumers. More advisories for the GP than SP are deficient likely because a higher number of the current SP advisories are already at 0 meals/month (30% of the SP compared to 5% of the GP advisories) and cannot become more stringent.

Lake Ontario would have the highest percentage of advisories affected, which agrees with reports of a greater number of contaminants present at elevated levels in Lake Ontario fish compared to the other three lakes considered in this study (Murphy et al. 2012). The results indicated that Lake Erie Wheatley Harbour, a former Great Lakes Area of Concern, would not have any impact; however, this was a result of only three species being monitored in the recent times (Bigmouth Buffalo, Common Carp and Freshwater Drum) that generally have PCB as a dominating contaminant. Advisories for Wheatley Harbour Yellow Perch, which have minor restrictions due to both mercury and PCB, could have some impact of the multi-chem approach. However, data were not available for Yellow Perch in the Wheatley Harbour during the time period considered.

Our evaluation of the method suggested that the results of this study are reliable; however, availability of more comprehensive monitoring data for a recent period could have minor to moderate influences on the outcome of this analysis. Removal of the non-detects avoided needless increase in the additive toxicity. Most HQs for total PCB, dioxins/furans/dl-PCB, mercury, toxaphene, mirex and photomirex, and some HQs for chlordane and PFOS were >1 (Figure S7). All remaining organochlorine pesticides and metals were either below the detection limits or had HQ<1 suggesting that their individual levels would not limit consumption of Great Lakes fish beyond a meal a day (i.e., 32 meals/month). Contributions of HQs of these contaminants to HIs were generally <10% (except selenium) and can be considered of no concern. Although only limited, above detection limit measurements of metals were available in this analysis, we believe that more comprehensive data would not alter the outcome of our analysis because metals typically do not accumulate in fish muscle, and Great Lakes on a large scale are not affected by elevated metal levels (Jezierska and Witeska 2006; OMOECC 2015). As such, the regular fish monitoring of these other organochlorine pesticides and metals can be discontinued.

This analysis relied on the monitoring data collected for the Canadian waters of the Great Lakes. However, it appears that most of the Great Lakes states typically follow the most-restrictive contaminant (one-chem) approach. As such, the findings could be, to a great extent, applicable to the U.S. waters of the Great Lakes as well. However, many advisory issuing agencies incorporate certain conservative steps that could, at least to a certain extent, cover for the possible deficiencies highlighted in this study. For example, cooking fish on a grill as advised by most agencies could reduce the burden of organic contaminants by 40-60% (e.g., Sherer and Price 1993), but such a reduction is not accounted in the advisories issued by the Government of Ontario for the Canadian waters of the Great Lakes. Also, the SP is advised not to eat fish from the 1 and 2 meals/month advisory categories by turning them to 0 meals/month (OMOECC 2015). If we take this into account, 476 of 3207 (15%) of the SP advisories would not be truly more stringent (Table S3). The State of Michigan uses 90th percentile concentration when a regression between fish length and contaminant concentrations for a sampling event fails to meet a required cut-off for the coefficient of determination (State of Michigan 2014). This method would result in conservative advisories especially for smaller sized fish as they typically have lower contaminant levels (Gewurtz et al. 2011a; Gewurtz et al. 2011b).

A little conservatism in the advisories is good; however, evolving science stresses the promotion of fish consumption by considering the benefits in addition to the risks of consuming fish (Mozaffarian and Rimm 2006; Neff et al. 2014; Turyk et al. 2012). Also, possible contamination and lower nutritional quality of other replacement dietary items should be considered. As such, if the current built-in conservatism in calculating one-chem based advisories cover for the possible deficiencies highlighted in this study, then more stringent advisories may not be warranted. A better approach could be appropriately accounting of risk (and benefit if possible) at every step of the advisory calculation and removing built-in over conservatism in a scientifically defensible manner.

Lastly, it would be desired to formulate a generic statistical framework to calculate multi-chemical based advisories instead of performing the laborious steps utilized in this study. Namely, rather than developing multiple single regression models for different contaminants and locations, a more generalizable methodology would involve multivariate regression modeling, a technique that estimates single regression models with more than one dependent variables to be analyzed simultaneously. In doing so, we will be able to standardize for the length while considering the concentrations of all the contaminants within fish individuals. However, both magnitude and sign of the covariance among contaminants of concern appears to vary significantly by fish species and location. For example, top predators like Walleye typically have elevated mercury levels, while fatty fish like Trout and Salmon from the Great Lakes have elevated levels of PCBs (Bhavsar et al. 2011; Sadraddini et al. 2011a; Sadraddini et al. 2011b). Similarly, areas like the St. Lawrence River generally have higher fish mercury levels, while some areas (e.g., Hamilton Harbour) have elevated PCBs (Neff et al. 2013; Visha et al. 2016). Another solution could be to conduct event-specific regressions between length-HQ (instead of length-concentration), but this method would not capture the additive effects of multiple contaminants. Finally, a regression between length-HI could provide a simplified framework; however, a requirement for such an approach would depend on the availability of measurements for all contaminants for all samples in the event-specific analysis. This may not be achievable due to variable costs of analysis (e.g., dioxin analysis at approximately $600-1200 versus mercury analysis at approximately $30-40 per sample), and was not the case for the dataset utilized in this study.

In summary, we investigated if the current practice of issuing fish consumption advisories for the Great Lakes based on the most restrictive contaminant approach is sufficiently protective of the health of humans consuming these fish. Due to the consistency of the fish contaminant measurements, area covered, as well as advisory method and benchmarks available from OMOECC, we opted to focus our study on the Canadian waters of the Great Lakes. Compared to an individual contaminant, the presence of multiple contaminants can induce a variety of adverse impacts such as less than additive, additive or synergistic. Assuming additive effects of multiple contaminants, almost half of the current advisories may not be adequately protective. Many fish such as Walleye, Salmon, Bass and Trout, which are among the favourites for the consumption by recreational as well as subsistence fishers, would have noticeably more stringent advisories under the multi-chem approach. Our findings may also be applicable to the

U.S. waters of the Great Lakes. It is recommended that the advisory issuing agencies evaluate if any conservative steps currently employed in their advisory methods would protect from the combined effects of multiple contaminants and/or if revisions to the issued advisories are necessary.

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Table 1: "Do not eat" fish consumption advisory benchmarks used by the Province of Ontario, Canada and potential health effects for major contaminants found in Great Lakes fish (OMOECC 2015, Murphy et al. 2012, ATSDR 2015).

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Contaminant		Unit	General Popn	Sensitive Popn	Potential health effects
Mercury	Hg	ug/g	>1.8	>0.5	Neurotoxicant; can also damage immune, digestive and nervous systems
Organic / Industrial contaminants	Polychlorinated biphenyl (PCB)	ng/g	>844	>211	Neurotoxicant; Impacts reproductive and immune systems; developmental effects; potential carcinogen
	Dioxin/Furan/dlPCB Toxic Equivalent (TEQ)	pg/g	>21.6	>5.4	Neurotoxicant; Impacts reproductive, immune and endocrine systems
	Perfluorooctane Sulfonate (PFOS)	ng/g	>640	>160	Potential carcinogen, endocrine disruptions, oxidative stress
	Mirex	ng/g	>657	>164	Can affect stomach, intestines, liver, kidneys, eyes, thyroid, nervous system, and reproductive system
	Photomirex	ng/g	>122	>31	
	Toxaphene	ng/g	>1877	>469	Potential carcinogen, convulsions, liver and kidney damage
	Total Chlordane	ng/g	>469	>117	affects nervous and digestive systems, and liver
	Total ichlorodiphenyltrichloroethane (DDT)	ng/g	>93858	>23465	Affects nervous system; Potential carcinogen, developmental, reproductive effects
	Brominated diphenyl ether 47 (BDE-47)	ng/g	>939	>235	Can affect thyroid and liver; behavioral changes; may affect immune system; possible carcinogen; BDE 47 and 99 more toxic than BDE 209
	Brominated diphenyl ether 99 (BDE-99)	ng/g	>939	>235	
	Brominated diphenyl ether 153 (BDE-153)	ng/g	>1877	>469	
	Brominated diphenyl ether 209 (BDE-209)	ng/g	>65701	>16425	
	Aldrin+Dieldrin	ng/g	>939	>235	Potential carcinogen, convulsions, nervous system effects, kidney damage
	Hexachlorobenzene (HCB)	ng/g	>2534	>634	affects nervous system, liver, thyroid; possible carcinogen; endrocine disruptor
	Octachlorostyrene (OCS)	ng/g	>2910	>727	Inadequate information available
Metals	Aluminum (Al)	ug/g	>1400	>350	Possible enzyme inhibition, damage to nervous system, Alzheimer
	Arsenic (As)	ug/g	>8	>2	Carcinogen, damage to blood cells and vessels, heart and skin problems
	Cadmium (Cd)	ug/g	>2.8	>0.7	Probable carcinogen; possible kidney disease, lung damage, and fragile bones
	Chromium (Cr)	ug/g	>14	>3.5	Chromium (VI) compounds are known human carcinogens, damage to liver, kidney, circulatory and nervous systems as well as skin irritation
	Copper (Cu)	ug/g	>600	>150	Essential micronutrient, excess exposure may lead to hemolysis, headache, febrile reactions, prostration, and GI symptoms
	Lead (Pb)	ug/g	>16	>4	Mental retardation, birth defects, psychosis, autism, allergies, dyslexia, weight loss, hyperactivity, paralysis, muscular weakness, brain damage, kidney damage and may even cause death
	Manganese (Mn)	ug/g	>640	>160	Glucose intolerance, blood clotting, skin problems, skeleton disorders, birth defects, neurological symptoms
	Nickel (Ni)	ug/g	>120	>30	Damage to lungs, respiratory failure, birth defects, heart disorders and skin problems
	Silver (Ag)	ug/g	>24	>6	Cardiac abnormalities, permanent damage to brain and nervous system
	Selenium (Se)	ug/g	>24	>6	Skin and vision problems, shortness of breath, conjunctivitis, vomiting, abdominal pain, diarrhea and enlarged liver
	Tin (Sn)	ug/g	>1.2	>0.3	Depressions, liver damage, immune system problems, chromosomal damage, shortage of red blood cells, brain damage
	Zinc (Zn)	ug/g	>1400	>350	adverse human health effects are rare

Table 2: Illustration of advisory calculations using the one-chem and multi-chem approaches. Detailed explanation is provided in the supporting material.

Contaminant	PCB	Hg	Total TEQ	Toxaphene	Photomirex
Unit	ng/g	µg/g	pg/g	ng/g	ng/g
Concentration (length standardized)	75	0.81	1.2	75	5
One-chem Approach					
Individual Advisory (meals/month, using benchmarks in Table S1)	8	4	16	16	16
Advisory (meals/month)			4		
Multi-chem Approach					
Benchmark for least restrictive advisory (32 meals/month)	26	0.15	0.7	59	4
HQ (Concentration/Benchmark for least restrictive advisory)	2.88	5.4	1.71	1.27	1.25
HI (∑HQ)			12.52		
32/HI			2.56		
Advisory (meals/month)			2		

Table 3. Distribution (in %) of the advisories (meals/month) simulated using the one-chem and multi-chem approaches. The same advisories from both approaches are presented in bold, while more stringent advisories from the multi-chem approach are highlighted with gray shading. The distributions in number of advisories are presented in Table S3.

		One-chem								
	Multi-chem ↓	**0**	**1**	**2**	**4**	**8**	**12**	**16**	**32**	**Total**
General Population	**0**	**100%**	59%	4%						10%
	1		**41%**	54%	3%					10%
	2			**42%**	56%	7%	2%			16%
	4				**42%**	71%	31%	2%		21%
	8					**23%**	49%	28%		14%
	12						**19%**	28%	1%	8%
	16							**42%**	12%	10%
	32								**87%**	11%
	Total	5%	7%	13%	16%	15%	10%	21%	13%	100%
Sensitive Population	**0**	**100%**			59%	11%	2%			47%
	4				**41%**	63%	38%	5%		25%
	8					**26%**	33%	33%		12%
	12						**27%**	19%		5%
	16							**43%**	13%	6%
	32								**87%**	5%
	Total	30%			25%	17%	10%	13%	5%	100%

Figure Captions

Figure 1. Percentage of the multi-chem approach based advisories that were more stringent compared to the one-chem approach. N is for total number of advisories for each population.

Figure 2. Percent contribution of contaminant-specific Hazard Quotient (HQ) to the Hazard Index (HI) calculated in the multi-chem advisory approach. Maximum is for the highest contribution of an HQ to HI regardless of a contaminant. The solid circle indicates a mean, the line within the box indicates a median, the box indicates 25th and 75th percentile values, the whiskers indicate the highest and lowest values not classified as statistical outlier values more than 1.5 times away from the interquartile range. Non-detect values were excluded. Similar results for a dataset that included non-detects are presented in Figure S9. For contaminant abbreviations, please refer to Table 1.

Figure 3: Percentage of the multi-chem approach based advisories that were more stringent compared to the one-chem approach for favourite fish for anglers in the region. Walleye, Lake Whitefish, Lake Trout, Perch and Bass can be considered most popular among the First Nations communities around the Great Lakes (EAGLE 2001).

Figure 4. Percent of the multi-chem advisories for which a contaminant is the major contributor to the overall additive effect (assessed as a Hazard Index – HI). The contaminants not in the figure were not a major contributor to any HI. Photomirex, PFOS and total DDT were major contributors for <1% of the multi-chem advisories for Lake Ontario only. Gen: General Population; Sen: Sensitive Population. For contaminant abbreviations, please refer to Table 1. Nt: total number of advisories; Nr: number of advisories that are <32 meals/month.

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Figure 1.

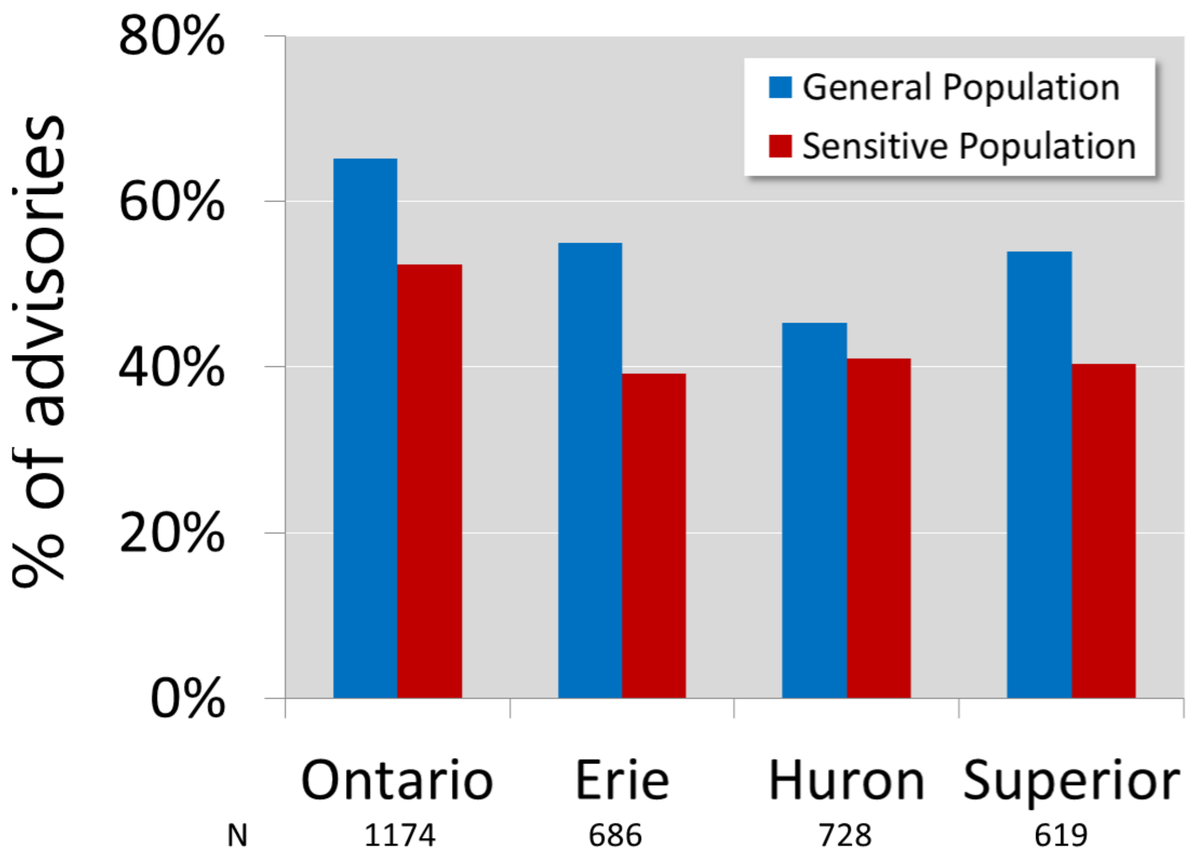


Figure 2.

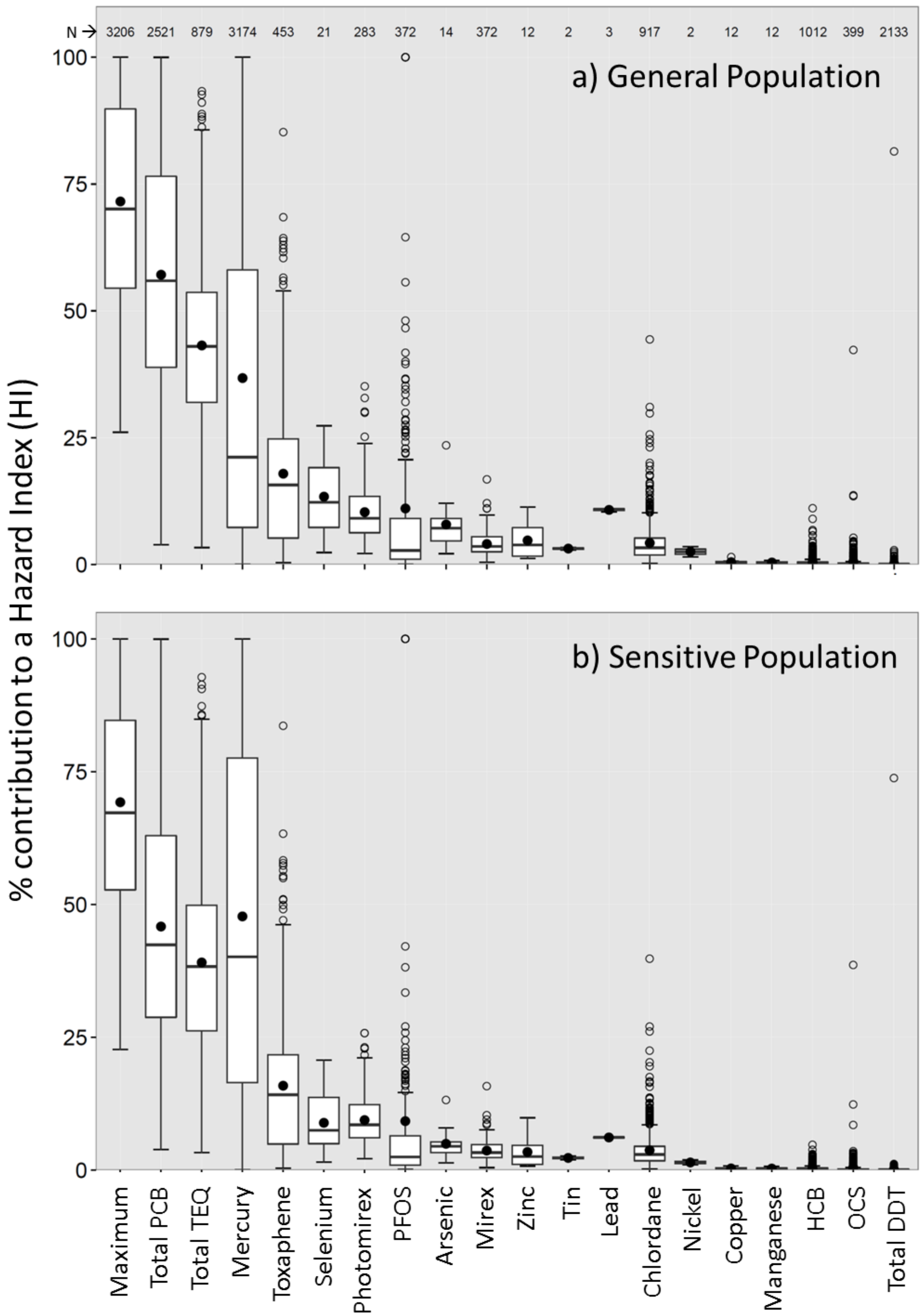

N →
3206
2521
879
3174
453
21
283
372
14
372
12
2
3
917
2
12
12
1012
399
2133
a) General Population
b) Sensitive Population
% contribution to a Hazard Index (HI)
0
25
50
75
100
Maximum
Total PCB
Total TEQ
Mercury
Toxaphene
Selenium
Photomirex
PFOS
Arsenic
Mirex
Zinc
Tin
Lead
Chlordane
Nickel
Copper
Manganese
HCB
OCS
Total DDT

Figure 3.

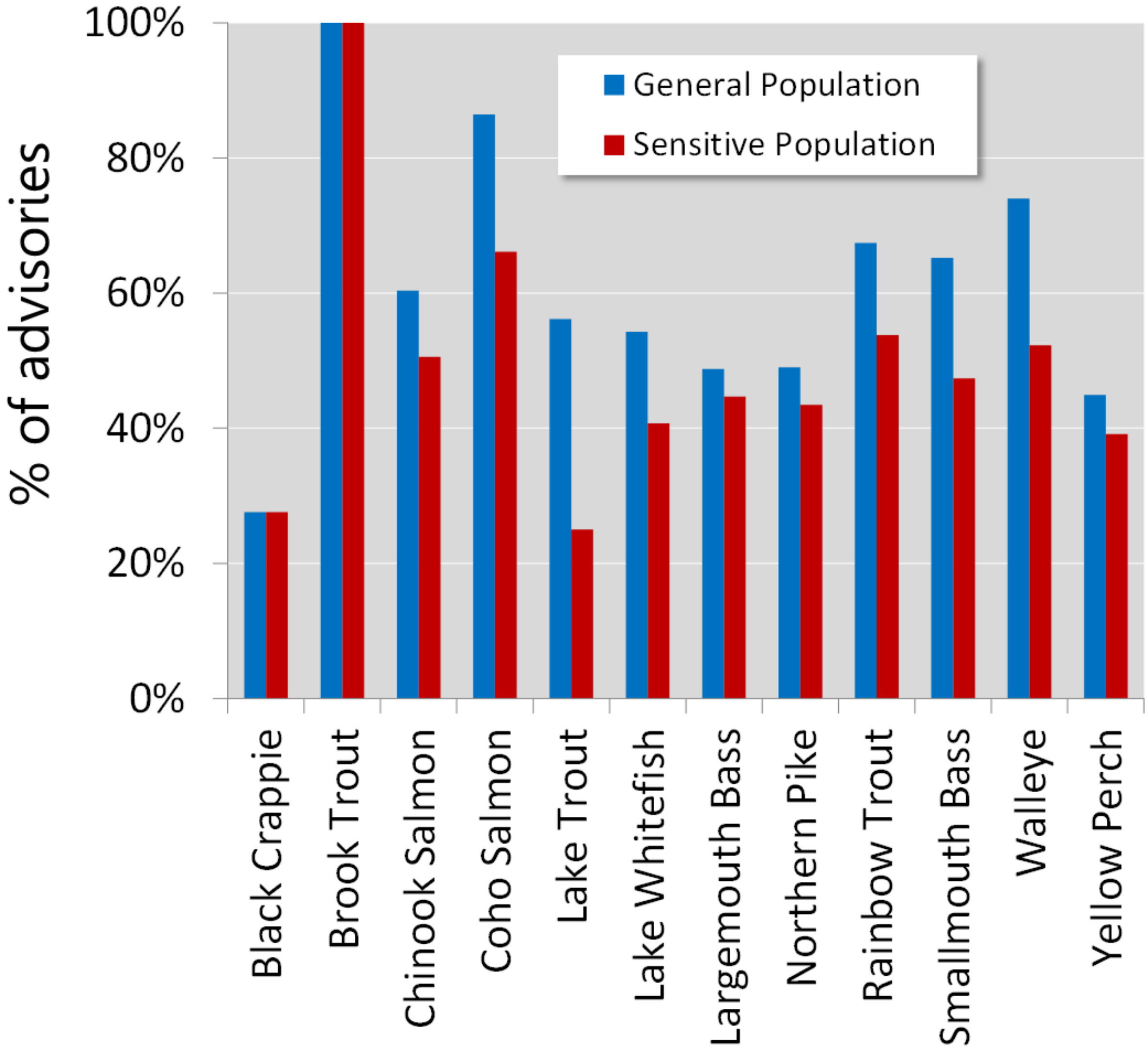
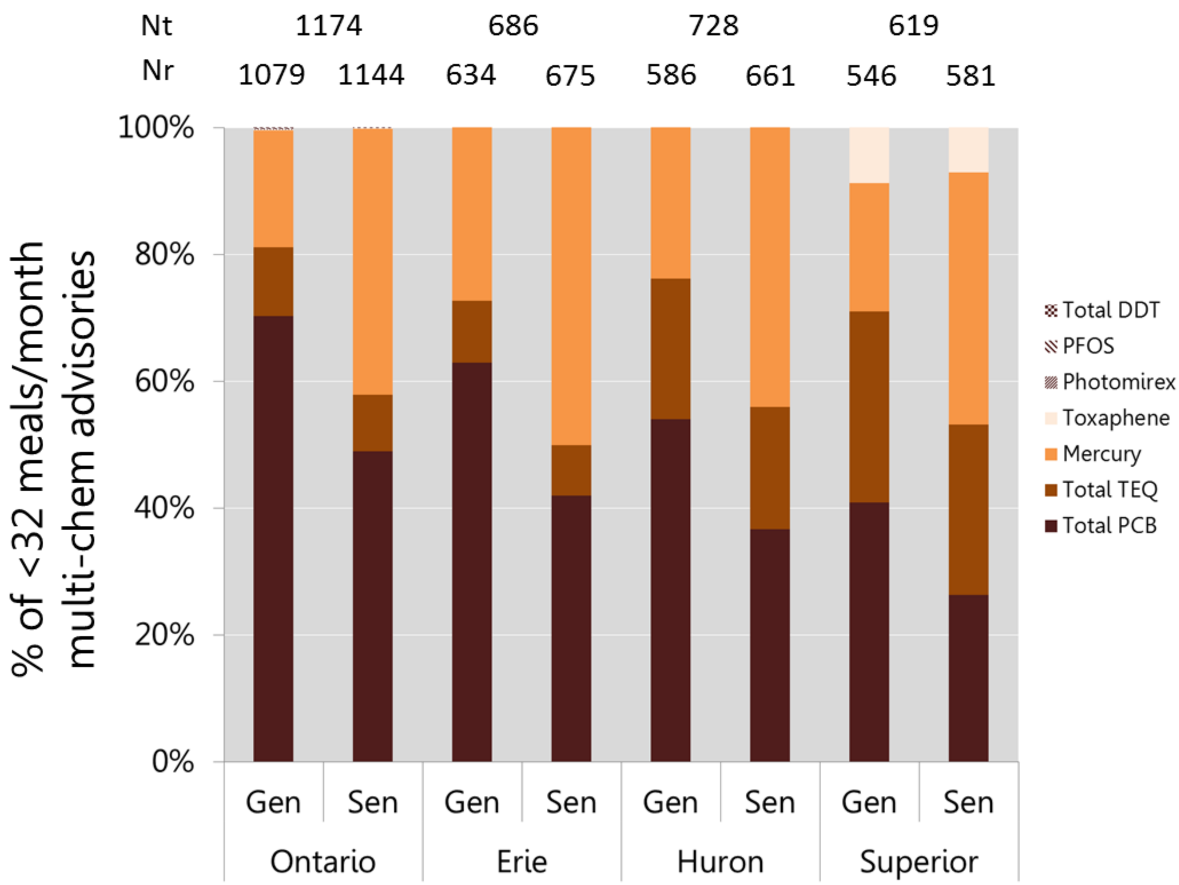

100%
80%
60%
40%
20%
0%
% of advisories
General Population
Sensitive Population
Black Crappie
Brook Trout
Chinook Salmon
Coho Salmon
Lake Trout
Lake Whitefish
Largemouth Bass
Northern Pike
Rainbow Trout
Smallmouth Bass
Walleye
Yellow Perch

Figure 4.


Nt
1174
686
728
619
Nr
1079
1144
634
675
586
661
546
581
% of <32 meals/month multi-chem advisories
100%
80%
60%
40%
20%
0%
Gen
Sen
Ontario
Erie
Huron
Superior
Total DDT
PFOS
Photomirex
Toxaphene
Mercury
Total TEQ
Total PCB