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Flesh Quality of Market-Size Farmed and Wild British Columbia Salmon

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This study compared the flesh quality of farmed and wild sources of British Columbia (BC) salmon with respect to concentrations of polychlorinated biphenyl compounds, polychlorinated dibenzodioxins/dibenzofurans and their associated toxic equivalents, total mercury (THg), methylmercury (MeHg), and selected fatty acids of known importance for human health viz., omega-3 (n-3) highly unsaturated fatty acids (n-3 HUFAs) and (n-6) fatty acids. Skinned fillets from known sources of farmed Atlantic, coho, and chinook salmon ($n = 110$) and wild coho, chinook, chum, sockeye, and pink salmon ($n = 91$) were examined. Atlantic salmon contained higher PCB concentrations (means, 28−38 ng/g) than farmed coho or chinook salmon, and levels in these latter species were similar to those in wild counterparts (means, 2.8−13.7 ng/g). PCB levels in Atlantic salmon flesh were, nevertheless, 53−71-fold less than the level of concern for human consumption of fish, i.e., 2000 ng/g as established by Health Canada and the U.S. Food and Drug Administration (US−FDA). Similarly, THg and MeHg levels in all samples were well below the Health Canada guideline (0.5 μg/g) and the US−FDA action level (1.0 μg/g). On average, THg in farmed salmon (0.021 μg/g) was similar to or lower than wild salmon (0.013−0.077 μg/g). Atlantic salmon were a richer source (mean, 2.34 g/100 g fillet) of n-3 HUFAs than the other farmed and wild sources of salmon examined (means, 0.39−1.17 g/100 g). The present findings support the recommended weekly consumption guidelines for oily fish species (includes all BC salmon sources) for cardio-protective benefits as made by the American Heart Association and the UK Food Standards Agency.

Introduction

Canadian farmed salmon and trout represented approximately 7.4% of global production for these species in 2002, with 4.7% stemming from British Columbia (BC; *1*, *2*). BC is ranked as the fourth largest producer of farmed salmon in the world (Government of BC, Ministry of Agriculture, Food and Fisheries, 2002 statistics). A recent report of polyhalogenated arylhydrocarbons (PHAHs) or organohalogen contaminant levels in farmed Atlantic salmon stocks suggested that their frequent consumption poses a greater risk of causing cancer than that of wild stocks (*3*). However, the risks of consuming farmed salmon were not compared to the considerable human health benefits that may accrue from eating salmon regardless of origin. These benefits arise primarily from their flesh content of omega-3 (n-3) highly unsaturated fatty acids (n-3 HUFAs), especially eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), and, to a lesser degree, from concentrations of linolenic acid, and monounsaturated fatty acids. The potential health benefits related to adequate weekly ingestion of oily fish such as salmon include reduced risk of cardiovascular disease (CVD) such as coronary heart disease (CHD), some cancers, and various inflammatory responses and conditions, and enhanced brain, cognitive, and ocular development and function (*4*−*11*). Some of the preceding conditions such as CVD account for considerable health care costs in nations with low annual per capita fish consumption such as the United States and Canada and many European countries versus those where frequent fish consumption is a mainstay of life, e.g., Japan (*6*, *12*, *13*).

The benefits of an oily fish diet can be counteracted when methylmercury (MeHg) levels exceed human health standards (*14*). MeHg is found principally in the low oxygen, sub-thermocline ocean region (*15*), and is present in nearly all marine fish in trace amounts (*16*). Accumulation in fish is proportional to age, size, and trophic level (*17*). Hence, MeHg levels in large, long-lived, predatory fish such as tuna, shark, or swordfish, can exceed both the Health Canada guideline (0.5μg/g) and the United States Food and Drug Administration (US−FDA) action level (1μg/g), while smaller fish at lower trophic levels, e.g., salmon, pollock, and hake, contain low MeHg levels (*18*).

Clearly, any agency or government that sets recommended consumption levels of oily fish must also weigh the risks associated with potential organohalogen intake with the known benefits derived especially from the n-3 HUFAs. The consumption levels for both wild and farmed salmon species recommended in the Hites et al. (*3*) study only considered the U.S. Environmental Protection Agency (US−EPA) guidelines for organohalogen intake. The US−EPA and Agency for Toxic Substances and Disease Registry (ATSDR) daily contaminant concentration threshold intake levels are highly conservative when compared to the guidelines for an array of other agencies/countries, e.g., Health Canada (*19*). In fact, the US−EPA draft value for tolerable daily intake of polychlorinated dibenzodioxins (PCDDs) is not yet US−EPA policy, as it is under review by the National Academy of Sciences (*20*).

Comparisons of the contaminant and nutrient levels in farmed and wild salmon have been complicated by physiological and geographical variations that exist between and within species. BC has five species of wild salmon, namely, chinook (*Oncorhynchus tshawytscha*), coho (*O. kisutch*), sockeye (*O. nerka*), chum (*O. keta*), and pink (*O. gorbuscha*). Three salmon species are currently farmed in BC, namely, Atlantic (*Salmo salar*), chinook, and coho and these are ranked respectively, first, second, and third in order of production volume/value (*1*). Previous studies (*3*, *21*) have included farmed coho and chinook in the broad category of farmed salmon without considering possible differences in

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their flesh contaminant concentrations and nutrients relative to farmed Atlantic salmon. Differences in diet, geographic origin, maturation stage, and harvest season of both farmed and wild salmon can affect contaminant levels measured between and within species as revealed by the large confidence limits noted in previous studies (*3*) and as reported by O'Neill et al. (*22*) for Puget Sound wild chinook and coho salmon. Hence, when the sample size is small, there may be under- or over-estimation of mean flesh contaminant levels and difficulty in ascertaining whether there are real (significant) differences in contaminant levels between dissimilar sources of salmon.

Additionally, within a given fish fillet, regional differences exist in lipid content (*23*) and consequently in levels of the lipophilic organohalogen contaminants. Since contaminant and nutrient concentration data (e.g., n-3 HUFAs) set recommended human consumption levels, it is important that the portion of the fish that is analyzed represents that which is consumed. Some studies have analyzed only a salmon "steak" or the epaxial muscle. To avoid regional differences in contaminants and nutrients, the whole fillet should be analyzed. Moreover, because the skin of the fillet contains adhering lipid and associated organohalogen compounds, and the skin is typically not consumed, skinless fillets should be analyzed to avoid overestimation of contaminant loads. Further, the lack of lipid concentration determinations in some of the previous investigations has made comparisons of contaminant findings with this study difficult. Thus, standardization of methodology enables more accurate comparisons between studies.

A final point of concern related to some previous studies that have reported organohalogen concentrations in the flesh of aquatic species, in particular polychlorinated biphenyl compounds (PCBs), is the frequent omission of many congeners. This has resulted in underestimation of contaminant concentrations, and consequently, in values for toxic equivalents (TEQs) of these compounds for humans. If TEQs are included in reports, it is essential to assign appropriate toxic equivalent factors (TEFs) for all congeners.

In this study, we addressed some of the limitations of past studies to present the data in an unbiased manner. Accordingly, we collected many market-size farmed salmon from eight farm sites (included all three salmon species farmed in BC). Also, we sampled eight wild salmon populations that were representative of the five salmon species found in coastal BC waters. The fish were sampled across a range of sampling dates and geographical locations mainly for determinations of fillet (flesh) contaminant and nutritional analyses. Contaminant analysis focused on full congener PCDD/Fs, full congener PCBs, total mercury (THg), and MeHg, while the nutritional analyses reported herein are specific to lipid concentrations and compositions. Our collection procedures were unique among all of the other studies on this theme since we had complete knowledge of the sample origins, handling procedures, and storage conditions. Also, the identities of all of the salmon flesh samples were unknown to the analysts (blinded study). In previous studies noted above, the fish originated mainly from retail outlets. Further, in this study, extra samples that were representative of each species from farmed and wild sources were analyzed both with and without the skin to compare the percent decrease in lipid levels due to removal of skin and associated fat, and thereby facilitate interpretation of the contaminant findings found in the present study with those of Hites et al. (*3*) (samples included the skin).

The aim of our study was to examine salmon flesh quality from a human health perspective. The aforementioned flesh quality parameters were measured in a total of 201 wild and farmed salmon and eight farmed salmon feed samples from BC. MeHg was measured in a subset of salmon ($n = 22$) and all eight farmed salmon diet samples. The findings for salmon species from all sites were used to evaluate safe consumption rates of these species using available consumption and threshold concentration guidelines from several regulatory agencies for THg, PCDD/Fs, and PCBs on a wet weight, lipid-normalized, and TEQ basis. Lipid-normalization of the data allowed for relative comparisons to be made between species for the lipophilic organohalogen contaminants. Further, since absolute concentrations of fatty acids and organohalogen contaminants are directly related to flesh lipid contents, lipid-normalization of the data permitted examination of the relative relationship between the beneficial EPA and DHA content and the contaminant content to facilitate improved understanding of the relative benefits and risks of consuming farmed and wild salmon.

Experimental Section

Sample Collection, Storage, Preparation, and Analysis. Three farmed salmon species (i.e., Atlantic, coho, and chinook), and five wild salmon species (i.e., coho, chinook, pink, chum, and sockeye) were sampled. Tables S1 and S2 and Figure S1 in the Supporting Information (SI) collectively show the species and number of farmed and wild fish sampled and their respective mean sizes and dates of sampling in relation to their geographical origins. Complete details of of the protocols used for sample collection and handling and of preparation and analysis are given in the SI.

Results and Discussion

PCBs and PCDD/F Levels in the Flesh of Farmed and Wild Salmon. In relation to farmed (F) salmon fillets, Atlantic salmon from a location in the Broughton Archipelago exhibited the highest mean values for PCBs, and Atlantic salmon from a location at Quadra Island had the highest mean values for PCDD/F concentrations (i.e., 38.3 ± 2.3 ng/g and 3.07 ± 1.27 pg/g, respectively). By contrast, the lowest mean concentrations noted for the preceding contaminants were found in farmed coho salmon from Jervis and Sechelt Inlet (i.e., 9.7 ± 2.0 ng/g and 0.73 ± 0.25 pg/g respectively) (Figure 1).

With respect to wild (W) salmon fillets, chinook salmon from Barkley Sound had the highest mean values for PCB and PCDD/F concentrations (i.e., 13.7 ± 4.6 ng/g and 1.25 ± 0.33 pg/g, respectively). The lowest average concentrations found for PCBs and PCDD/Fs were measured respectively, in chum salmon from Johnstone St. (1.7 ± 1.0 ng/g) and coho salmon from Prince Rupert (0.47 ± 0.21 pg/g).

The overall ranking for average wet weight PCB contaminant levels found within all of the preceding sources of salmon was: F-Atlantic > W-chinook > F-chinook > F-coho > W-sockeye>W-coho > W-pink > W-chum. The ranking found for PCDD/F contaminant levels was: F-Atlantic > F-chinook > F-coho > W-sockeye > W-chinook > W-chum > W-coho > W-pink.

Although the wet weight PCB levels were generally found to be lower in wild than in farmed salmon species, it should be stressed that the highest mean concentrations of PCBs found in this study, respectively, were 147−52 fold lower than the level of concern for human consumption of fish as established by Health Canada and the US−FDA, (i.e., 2000 ng/g) (*24*). Furthermore, the highest levels of PCBs found among salmon species on Canada's Pacific Coast were well below levels of concern for PCBs in infant foods (Figure 1).

Specific comparisons of the flesh PCB concentrations found for the different wild Pacific salmon species in this study with those obtained in previous studies revealed important similarities and differences. In this study, the fillets from W chinook from Barkley Sound and the West coast of Vancouver Island (WCVI) troll fishery had mean PCB

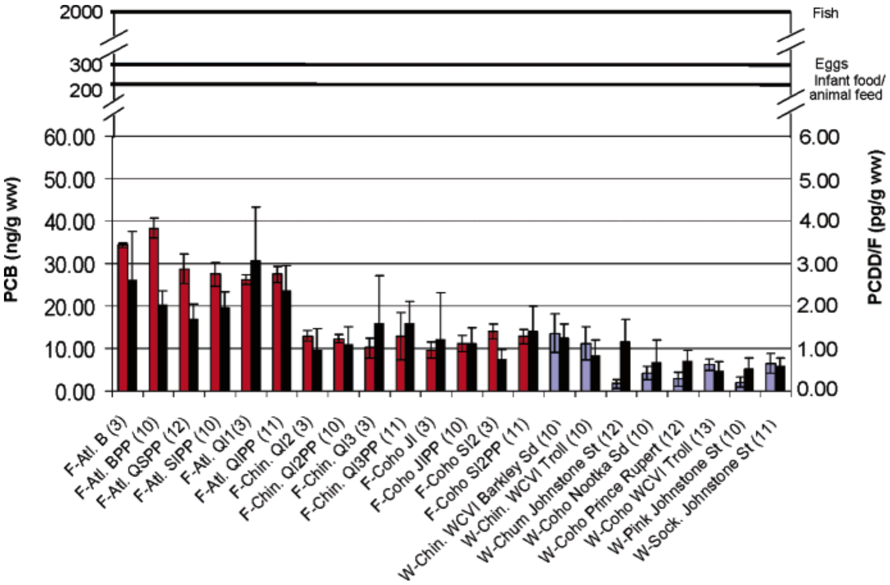

FIGURE 1. Wet weight concentrations of PCBs (colored bars) and PCDD/Fs (black bars) in various sources of farmed and wild BC salmon with 95% confidence intervals shown in relation to the USFDA tolerances for residues of PCBs in human and animal feed (*24*); PCBs in farmed and wild fish are represented by red and blue, respectively). Numbers in parentheses reflect the number of individual fish analyzed from each sampling location (see Tables S1 and S2 for additional information)

concentrations of 13.7 ± 4.6 (*n* = 10) and 11.1 ± 3.9 ng/g (*n* = 10) respectively, and the mean for all chinook samples from the two sources was 12.3 ± 3.0 ng/g. The latter overall mean for total PCBs in our wild chinook samples agreed closely with that obtained by Hites et al. (*3*) for wild BC chinook salmon, namely, 12.0 ng/g. By contrast, Jackson et al. (*25*) reported a markedly higher mean value of 1941 ± 200 ng/g (±1 SE) for 78 PCB congeners in the flesh of wild Lake Michigan chinook salmon. In the present study, wild coho salmon from Prince Rupert, Nootka Sound, and the WCVI Troll fishery had mean flesh PCB levels of 2.8 ± 1.7 (*n* = 12), 4.2 ± 1.6 (*n* = 10), and 6.2 ± 1.4 ng/g (*n* = 13), respectively, with a mean value of 4.4 ± 1.5 ng/g. Once again, our overall mean value agreed well with that found by Hites et al. (*3*) who noted a mean value of 5.0 ng/g in wild BC coho salmon fillets. The comparable value found by Jackson et al. (*25*) for wild Lake Michigan coho salmon was 1268 ± 77 ng/g. Fillets from wild Johnstone St. sockeye, pink, and chum salmon in this study, had mean PCB concentrations of 6.5 ± 2.3 (*n* = 11), 2.0 ± 1.2 (*n* = 10), and 1.7 ± 1.0 ng/g (*n* = 12), respectively, and values reported by Hites et al. (*3*) for these wild BC species were respectively, 7.0, 3.0, and 1.5 ng/g. Thus, all of our mean PCB concentration values found for the aforementioned wild BC salmon species were similar to those obtained by Hites et al. (*3*). It is noteworthy that the mean PCB level observed in wild chinook salmon from Lake Michigan was 157 times greater than that of wild BC chinook salmon and the concentration observed for wild coho salmon from Lake Michigan was 288-fold more than that found for wild BC coho salmon.

The highest mean flesh PCB concentrations found in this study (i.e., 38 ng/g) for farmed Atlantic salmon compared slightly lower than the highest levels reported by Hites et al. (*3*) (i.e., 51 ng/g, full-congeners) and was similar to levels reported by Jacobs et al. (*26*) (i.e., 32ng/g, 59 congeners).

The above-mentioned differences in flesh concentrations of contaminants between the farmed and wild BC salmon species likely reflect their respective differences in (*1*) nutritional status (ration and feed or food composition, especially the ratio of digestible protein to lipid), (*2*) fish size and age and marine residency period at the time of sexual maturation or harvesting, (*3*) innate ability to deposit lipid, and consequently, the lipophilic organohalogen compounds, into their flesh at different sizes (ages), (*4*) state of sexual maturity at the time of capture and proportions of males to females in the samples, or (*5*) a combination of these factors (*23*, *27*).

Between-species variation in wild salmon contaminant levels can be explained by several factors including differences in the marine residency periods, which for chinook, coho, sockeye, pink, and chum salmon may be as great as 4−5, 3, 3−4, 2, and 6 years, respectively (*27*, *28*). Fish size at the time of maturity is greatest for chinook salmon and least for pink salmon and this is reflected in the amount of lipid deposited into their bodies and flesh since fish size is generally directly related to lipid deposition in salmonids when food is unrestricted (*29*, *30*). Moreover, wild chinook and coho salmon, during the marine residency period, feed on small fish, higher in the trophic chain, whereas amphipods and/or euphuasiids are emphasized more in the diets of sockeye, chum, and pink salmon (*27*). The generally longer lifespan (increased size at maturity) of chinook salmon and their predominately piscivorous dietary preferences, likely account for their higher flesh concentrations of contaminants compared to other salmon species. In relation to pink, sockeye, and chum salmon, the relative importance of copepods, amphipods, euphuasiids, and other invertebrate species in their diet versus fish, likely had the most influence on their flesh contaminant levels at the time of harvesting.

Interestingly, PCB concentrations in farmed salmon fillets were less variable than in fillets from wild salmon both on a wet weight and lipid-normalized basis (see below). For instance, the mean values obtained for percent relative standard deviations (%RSD) of PCBs on a wet weight basis were 18.3% for farmed salmon and 78.6% for wild. The increased variability in the PCB data for the wild salmon species probably reflected greater variation in their dietary input of contaminants from their prey items than occurred for farmed salmon. If differences in feeding habits and lifespan are considered, the five wild Pacific salmon species can be ranked in order of their susceptibility to contaminant bioaccumulation, with chinook and coho salmon being more susceptible than sockeye, pink, and chum salmon. Both wet weight and lipid-normalized PCB contaminant trends were observed to follow this sequence, with some exceptions noted between the wild coho and sockeye salmon that probably can be ascribed to differences in the average masses of these latter species obtained for this study, their state of sexual maturity, and the proportion of females to males in the samples. Some of these points will be considered in more detail below.

The flesh concentrations of PCBs and PCDD/Fs in fish sampled at the farm sites and their respective processing plants (data not included) were not different. Therefore, our findings suggest that the marine transportation procedures used in BC had no influence on the preceding contaminant levels in farmed salmon.

Relationship Between Lipid Content and PCBs Levels in Farmed and Wild Salmon. The skin and its associated subcutaneous fatty tissue, dark muscle, contribute a substantial amount to the total lipid content of salmon. Analyses of 24 samples showed that the lipid content in the skinless homogenates was 25−89% less than noted for the homogenates that included the skin (see Figure S2). Since PCBs, PCDD/Fs, and many other organohalogen contaminants are lipophilic, the inclusion of skin with its associated subcutaneous fatty tissue, dark muscle, and belly flaps in the analysis may result in a significant overestimation of contaminant concentrations in those tissues commonly consumed. For all of the samples examined in this study, a clear linear relationship was found between their lipid content and PCB concentrations

In this regard, we noted that the PCB concentrations in both wild and farmed salmon species were generally positively correlated with their flesh lipid content and those that had the most flesh lipid deposition, namely, farmed Atlantic salmon, had the highest mean PCB concentrations (ranged from 26−38 ng/g; see Figure S3). Alternatively, the species that had the lowest lipid concentrations, namely, wild chum salmon, had the lowest PCB concentrations.

Moreover, the PCB accumulation rate, as a function of lipid content, was observed to be greater in wild salmon than in farmed salmon. In fact, farmed chinook and coho salmon followed a nearly horizontal trend in this regard, as seen in Figure S3, such that increases in their flesh lipid content due to chronic consumption of formulated diets rich in lipid content was nearly independent of any attendant rises in PCB concentration. This was not true, however, in the farmed Atlantic salmon that ingested high energy (lipid-rich) formulated diets during the culture period. Interestingly, the flesh PCB concentrations in wild coho and chinook salmon were found to increase in direct relation to their flesh lipid content. This likely can be attributed to several related factors. The increased fitness of wild stocks (feeding, predation, migration, etc.) is taxing on lipid stores when compared to the situation for pen-reared farmed salmon stocks. This, coupled with the greater age of some wild stocks (farmed stocks are harvested before sexual maturation), results in a longer time period for PCBs to accumulate in wild species even though natural prey may be lower in contaminants than formulated salmon diets where fishmeal and fish oil are the main sources of dietary protein and lipid. These foregoing factors also help to explain why there was greater variation of PCB concentrations found in the flesh of the various sources of wild salmon relative to farmed salmon, i.e., increased variations in ages, diets, and stages of sexual development most probably accounted for the variations seen in the lipid and contaminant contents in the wild fish. Conversely, the farmed salmon are harvested before energy from lipid is diverted toward reproductive development and they are fed a more uniform diet.

The aforementioned observations can be used to design future research projects aimed at reducing flesh PCB concentrations in farmed salmon to concentrations present in wild salmon. In addition to extensive replacement of fishmeal protein and fish oil in formulated diets with plant protein and lipid sources that are lower in organohalogen content (*31*, *32*), another strategy would be to raise the dietary ratio of digestible protein to lipid during the latter part of the production period before the fish are marketed since this strategy would reduce lipid deposition (*27*). Work is presently underway in our laboratory and elsewhere in the world to demonstrate the efficacy of these strategies for future production of farmed Atlantic salmon. This could also be done for farmed coho and chinook salmon, but as our findings above indicate, there is little need with these species since their flesh organohalogen concentrations were already found to be similar to those of their wild counterparts.

When PCB data are presented on a lipid-normalized basis, the PCB concentrations between the dissimilar farmed and wild BC salmon sources were less obvious than on a wet weight basis and the ranking was very different as well. The trends observed and the significance of presenting the data on a lipid-normalized basis is discussed in the corresponding Supporting Information section.

PCDD/Fs and PCBs TEQ Values and Regulatory Levels in Foods Destined for Human Consumption. The calculated wet weight TEQ values for PCBs and PCDD/Fs in the various sources of BC salmon in relation to the tolerable daily intakes of PCDD/Fs as established by various national and international agencies are presented in Figure 2.

Among the farmed salmon, Atlantic salmon from the Broughton Archipelago had the highest PCB and PCDD/F TEQ concentrations. Coho salmon from Jervis inlet, by contrast, had the lowest concentrations. With respect to the wild salmon, chinook salmon from the WCVI troll fishery exhibited the highest PCB concentration, and chinook salmon from Barkley Sound exhibited the highest PCDD/Fs concentration. By contrast, the lowest PCB and PCDD/F concentrations were found in chum and pink salmon from Johnstone Strait. Overall, the flesh wet weight PCB TEQs for the different salmon species and sources ranked as follows: F-Atlantic > F-chinook > F-coho > W-chinook > W-sockeye > W-coho > W-pink > W-chum. The ranking for the PCDD/F TEQ values was identical except for the reverse in order of W-chum and W-pink. Estimated mean values for farmed salmon feed were 2.40 ± 0.62 and 1.34 ± 0.67pg TEQ/g (n = 7) for PCBs and PCDD/Fs, respectively.

The preceding findings indicate that the combined TEQ values for PCDD/Fs and PCBs did not exceed 1.85 pg/g flesh regardless of the origin of the salmon. Since TEQ limits for PCDD/Fs are given in pg TEQ/kg bw/day, and not pg TEQ/g of food, the data in Figure 2 can be better interpreted by assuming a body weight of 70 kg for an individual consuming a 100 g fish-flesh portion (*39*). This allowed a similar comparison of the data as presented above but in relation to the recommended thresholds for the daily consumption of 100 g of fish by a 70 kg person. In this latter case, aside from the draft value set by the US−EPA, all TEQ levels found for both PCDD/Fs and PCBs were below all agency/country guidelines on a kg body weight/day basis, except for one farm that surpassed the US−ATSDR threshold for PCDD/Fs.

Hites et al. (*3*) found that the highest TEQs (for PCDD/Fs and dioxin-like PCBs) in farmed Scottish Atlantic salmon flesh were about 3 pg TEQ/g (full congener) whereas the highest TEQs in the present study were nearly half of this amount (i.e., 1.85 ± 0.27pg TEQ/g, n = 11).

Mercury and Methylmercury Levels in the Flesh Of Farmed and Wild Salmon. On average, the THg concentrations measured in farmed and wild salmon were 0.021 μg/g and 0.013−0.077 μg/g, respectively, Figure S5. The salmon samples that had the highest THg levels (n = 22) were also analyzed for MeHg to estimate the proportion of MeHg to THg. Results from the MeHg analysis indicated that, on average, 97.1% (±7.4%) of the THg was in the form of MeHg

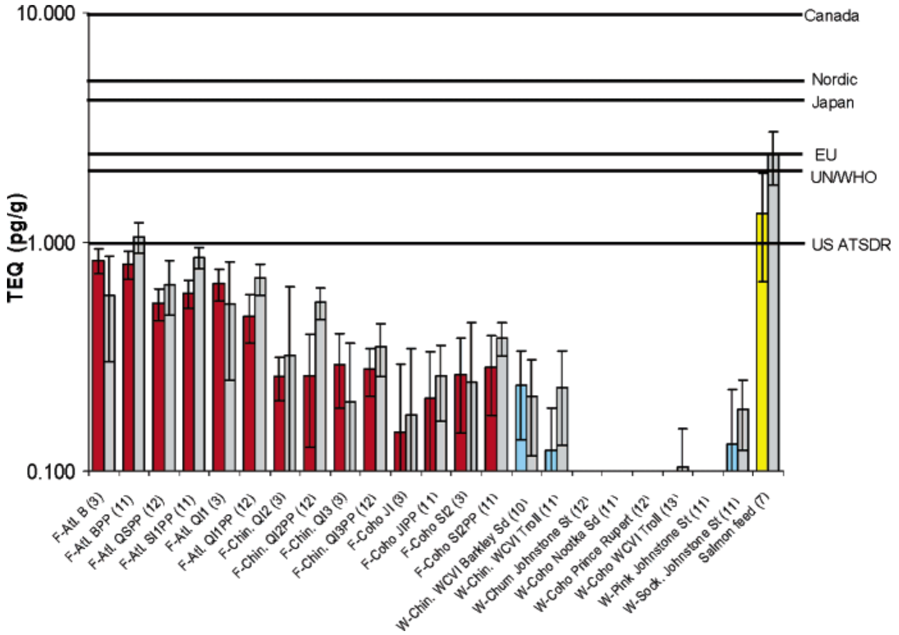

FIGURE 2. TEQs for PCBs (gray bars) and PCDD/Fs (red, blue, and yellow bars for farmed, wild, and farmed feed, respectively) in the flesh of the different sources of BC salmon (with 95% confidence intervals) in relation to the recommended tolerable daily intake for PCDD/Fs as suggested by the U.S. Agency for Toxic Substances and Disease Registry (ATSDR) (*34*), European Commission Scientific Committee on Food (*35*), UN Food and Agriculture Organization/World Health Organization Joint Expert Committee on Food Additives (UN/WHO JECFA) (*36*), Ministerial Council on Dioxin Policy of Japan (*37*), Nordic (*38*), and Health Canada (*39*). The U.S. EPA guidelines are being reviewed, but the draft value is at 0.001 pg TEQ/g (*20*). See Tables S1 and S2 for additional information.

(Figure S6) which is similar to previous studies at 93% for salmon and sea trout flesh (*40*).

Based upon the 97.1% value, average MeHg levels measured across farmed BC salmon species (0.021 μg/g ±0.004) and wild salmon species (0.038 μg/g ±0.022) were found to be well below the current Health Canada guideline of 0.5 μg/g and the US−FDA action level of 1.0 μg/g and therefore do not pose a human health concern. Relative to other, high trophic level marine fish, such as halibut (0.25 μg/g ±0.23), canned albacore tuna (0.35 μg/g ±0.13), and swordfish (0.98 μg/g ±0.51) (*18*), our data show that farmed and wild BC salmon contain very low Hg levels (Figure S5). Additionally, our study revealed that average THg concentrations in farmed BC salmon were 73% lower than W-chinook (0.077 μg/g ±0.019), 49% below that of W-sockeye (0.041 μg/g ±0.016), 45% lower than W-coho (0.038 μg/g ±0.013) and similar to W-chum and W-pink viz., 0.021 μg/g ±0.006 and 0.013 μg/g ±0.002, respectively. This distinct THg concentration difference between farmed and wild salmon has not been reported before in studies of similar scope (*21*, *41*) perhaps due to the low number of samples and/or limited species tested.

Since THg accumulates in fish over time and increases trophically (*17*), long-lived pisciverous salmon (i.e., chinook) would be expected to exhibit the highest THg levels for salmon species while smaller, shorter-lived, low trophic level salmon such as pink and chum would be anticipated to accumulate the least THg. The data of our study (Figure S5) clearly support this hypothesis.

Low THg levels measured in farmed salmon (mean, 0.021 μg/g ±0.004) can likely be attributed to the relatively low levels of THg measured in the farmed salmon diets (averaged 0.022 μg/g ±0.005 (n = 8) of which 75.1% on average was determined to be MeHg; Figures S5 and S6). Low MeHg levels in BC farmed salmon diets were likely due to their compositions containing South American origin fishmeals and oils that were based on the processing of small marine pelagic fish (*42*) with low MeHg levels as reported by the US−FDA for anchovy; THg = 0.043 μg/g (n = 40) (*18*), and plant and/or animal protein and lipid sources as partial replacements for fishmeal and oil with little or no MeHg content, e.g., canola meal and oil, soybean meal, corn gluten meal, poultry by-product meal, and poultry fat (*42*). The increased use of such products to replace fish-based ingredients will further decrease the already low MeHg levels in the feeds.

Benefits and Risks of Wild versus Farmed Salmon Consumption. The reduced flesh lipid content in wild versus farmed salmon not only depresses the concentrations of contaminants in the former fish on a wet weight basis but also their total n-3 fatty acid content/100 g portion, see Figure S7. For instance, the averages for flesh lipid and n-3 fatty acid content in wild chum salmon from Johnstone St. were, respectively, 1.6% and 0.50 ±0.08 g/100 g (n = 12), whereas those for farmed Atlantic salmon from a Quadra Island processing plant were 13.9% and 3.43 ±0.68 g/100 g (n = 12). Further, the high overall mean concentrations of selected n-3 HUFAs (i.e., EPA and DHA) that we observed in the flesh of farmed BC Atlantic salmon sources (Figure S8) are potentially of greater significance because of the many human health benefits that have been reported for these fatty acids (*44*).

In this regard, strongest evidence has been seen so far for their cardio-protective effects, but there is also mounting evidence from recent studies related to their benefits pertaining to prevention of some forms of cancer, enhancement of cognitive and visual function, and attenuation of various inflammatory indices and conditions (*4*−*11*). These benefits have been observed most consistently when the daily intake of EPA and/or DHA, particularly from oily species of fish, that have been adequately prepared (e.g., baked or broiled but not deep-fried), and/or from marine fish oil capsules, has been sufficient to exert positive effects on the aforementioned human health parameter(s), condition and/or disease under study. For instance, Mozaffarian and Rimm (*6*) recently presented evidence which shows that an intake of 250 mg of EPA and DHA per day can decrease the risk of CHD death by 36%.

Furthermore, positive outcomes have been affected by other factors such as the relative contributions of the n-6 fatty acids (i.e., linoleic acid and especially arachidonic acid), linolenic acid, saturated fatty acids, monounsaturated fatty acids, total fat, and trans fatty acids to the total daily energy intake and by other major factors that are known to influence human health such as smoking, obesity, extent of physical exercise, fruit, fiber, and alcohol intake, etc. (*12*, *13*, *23*, *41*, *43*). Foran et al. (*44*) performed a risk analysis for salmon contaminated with dioxins and dioxin-like compounds and concluded that the maximum benefit of n-3 fatty acids can be gained by choosing fish that have low concentrations of dioxins and dioxin-like compounds.

If one follows the recommended daily intake of 0.5 g of n-3 HUFAs for cardio-protective effects in adults without CHD as made by the American Heart Association (AHA) and several other agencies listed in Figure S8 for adults without documented CHD, then according to our results, only two 100 g portions of farmed Atlantic salmon would be required per week. By contrast three to five servings per week would be needed for all of the other sources of BC salmon except for wild chum salmon where nine servings would be required. The AHA recommends at least two servings of fish (especially fatty fish) per week as well as 1.5−3 g/d of alpha-linolenic acid from various sources such as flaxseed, canola, or soybean oils, or walnuts for cardio-protective effects (*45*). Moreover, the United Kingdom Foods Standards Agency (*46*) recommends consumption of at least two 140 g portions of fish per week including one of oily fish for promotion of good health. Further, the European Food Safety Authority recently concluded that one to two 130 g servings of preferably fatty fish per week would decrease the risk of CVD and stroke, and improve neurodevelopment and perinatal growth in infants.

All sources of BC salmon examined in this study had combined TEQ values for PCDD/Fs and PCBs that did not exceed 1.85 pg/g flesh. To reiterate, this level was well below the recommended tolerable daily intake for PCDD/Fs as provided by all of the world agencies shown in Figure 2, except for the U.S. Agency for Toxic Substances and Disease Registry, where the level of concern was set at 1 pg/g flesh. Hence, because of these findings and the importance of adequate intake of EPA and DHA from salmon and other fatty fish for prevention of CVD, which in 2003 accounted for almost 30% of global deaths (*13*), and possibly for other major health benefits, we concur with the aforementioned fish consumption recommendations of the AHA and UK Food Standards Agency. In support of this viewpoint, Mozaffarian and Rimm (*6*) presented convincing evidence from a quantitative risk-benefit analysis that daily intake of 250 mg of EPA and DHA from farmed or wild salmon over a 70-year lifetime would result in 7125 fewer CHD deaths per 100 000 individuals while estimated lifetime cancer risk was six and two cancer deaths per 100 000 lifetimes when ingesting farmed and wild salmon, respectively.

Finally, brief mention should be made of the increased concentrations of n-6 fatty acids noted in the flesh of farmed salmon (mostly as linoleic acid) relative to the concentrations observed in the wild salmon (Figure S8), and whether these higher levels of n-6 fatty acids could potentially reduce the beneficial effects of the EPA and DHA from these food sources. In this regard, we consider this possibility unlikely since the intake of n-6 fatty acids (mainly as linoleic acid) in a serving of farmed salmon would contribute less than 13.5% of the estimated total daily amount of linoleic acid consumed from other food sources in the North American diet (*47*).

Thus, we conclude that all of the salmon sources examined in this study had high nutritional value based upon their projected low overall contributions to the body burdens of individuals for PCDD/Fs and PCBs and Hg, and the fact that they are excellent sources of EPA and DHA as well as linolenic acid and monounsaturated fatty acids, especially in the case of farmed salmon servings.

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Supporting Information Available

More details about the sample locations, collection, and analysis. This material is available free of charge via the Internet at http://pubs.acs.org.

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