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Editor's Note: Welcome to our 100^{th} issue! I would like to thank Dr. Ikonomou for providing a wonderful overview of his group's research on fatty acid and contaminant residue levels in salmon.

We are trying to move to electronic publication and distribution of Aquaculture Update. If you would prefer to receive a PDF of the publication through e-mail, rather than a hard copy through the mail, please send me your e-mail address (see my e-mail address above). As always, I am looking for interesting aquaculture research to feature in Aquaculture Update. If you have any thoughts or suggestions, please do not hesitate to get in touch with me.

Flesh Quality of Farmed and Wild Salmon from British Columbia: Factors Affecting Fatty Acid and Contaminant Residue Levels

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Introduction

Moderate consumption of oily fish such as salmon that are high in omega-3 highly unsaturated fatty acids (*n*-3 HUFAs) – such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) – is beneficial for human health. In particular, regular weekly intake of *n*-3 HUFAs may aid in the prevention of cardiovascular disease, inflammatory responses and conditions, and certain cancers, as well as enhance brain, cognitive, and ocular development and function. However, positive health benefits of an oily fish diet may be compromised by negative effects associated with the occurrence of contaminant residues such as polychlorinated biphenyls (PCBs), polychlorinated dibenzo-p-dioxins (PCDDs), polychlorinated dibenzo furans (PCDFs), pesticides, flame retardants, as well as mercury, lead, cadmium, and other trace metals.

Several studies have shown that the benefits of moderate fish intake generally exceed the potential risks associated with contaminant exposure (Mozaffarian and Rimm, 2006; Domingo et al., 2007a). However, the fact flesh concentrations of environmental contaminants vary widely among marine fishes means that human dietary exposure is greatly dependent on selected fish species (Domingo et al., 2007a, b).

Sources of macronutrients, minerals, and essential fatty acids (EFAs) for farm-raised salmon are generally provided in the form of commercial aquafeeds which typically contain marine fish oils (MFOs) that are derived from the processing of a variety of pelagic fish species (National Research Council, 1993; Tacon, 1994). MFO-based aquafeeds generally contain meals and oils stemming from the rendering of whole fish and/or parts of small fishes (*e.g.* anchovy, jack mackerel, pilchard, menhaden, capelin, herring, sardine, *etc.*) originating from the South Pacific and/or the North Atlantic regions (National Research Council, 1993). More recently, terrestrial lipids (TLs) – derived from a variety of plants (*e.g.* oilseeds such as soybeans and canola) – and animal products (*e.g.* poultry), have been utilized as major replacements for MFOs in the production of commercial salmon feeds.

Several studies have documented the occurrence of persistent organic pollutants (POPs) such as PCBs, PCDD/Fs, pesticides, and polybrominated diphenyl ethers (PBDEs) in commercial aquafeeds and farmed fish (Jacobs et al., 2002; Hites et al., 2004; Ikonomou et al., 2007). Moreover, recent studies have shown that replacement of fish oil/meal with vegetable oils and proteins in aquafeeds can effectively reduce organohalogen contaminant levels in feeds and this, in turn, has subsequently been found to lower contaminant burdens in farm-raised fish (Bethune et al., 2006; Drew et al., 2007; Friesen et al., 2008).

In this study, we report findings of a comprehensive investigation that involved measurement of fatty acids and environmental contaminants (PCBs, dioxins, pesticides, PBDEs, mercury, and all trace elements) in commercial aquafeeds, as well as the flesh of three species of farmed salmon and five species of wild salmon from coastal British Columbia (BC). The study provides information regarding current contaminant levels in the flesh of farmed and wild BC salmon. The study also provides relevant information regarding the effects of using TLs as major sources of dietary lipid in commercial aquafeeds for BC salmon with respect to dietary and flesh concentrations of organohalogen contaminants and n-3 HUFAs.

Experimental Section

Survey of Farmed and Wild Salmon Between 2003 and 2005, a comprehensive survey of the flesh quality of farmed and wild BC salmon was conducted. This included determinations of the flesh concentrations of several key environmental contaminants (*e.g.* PCBs and PCDD/Fs, PBDEs, pesticides, mercury, and other trace elements) as well as fatty acids of importance for human health such as EPA and DHA. In particular, market-size farmed salmon (*i.e.* Atlantic, coho, and chinook; n = 110) and commercial salmon feeds (n = 8) were collected from eight BC salmon farm sites. Wild Pacific salmon (*i.e.* coho, chinook, pink, chum, and sockeye; n = 91) were sampled in 2003 and 2005 across a range of geographical locations from coastal BC waters. The survey was a blinded study in which the identities of all farmed and wild salmon samples obtained were unknown to the analysts during the analyses. Full details regarding sample collection, handling, and storage have been described by Ikonomou et al. (2007).

Alternative Diet Feeding Experiments

In 2005, a controlled laboratory study and a farm-based feeding experiment were conducted to assess the influence of various dietary TL sources in commercial salmon feeds on the fatty acid and contaminant levels in farmed salmon flesh. In particular, the studies compared traditional feeds that were based on MFO to alternative feeds that were based on blends of MFO with TLs with respect to their effects on dietary and flesh concentrations of the fatty acids EPA and DHA and organohalogens in farmed salmon. In relation to the on-farm feeding study, we examined a traditional MFO-based aquafeed and two alternative diets in which 50% of the dietary lipid stemmed from poultry fat (PF50) or 35% from canola oil (CO35) by replacement of MFO. Additional details regarding the experimental design and sampling protocols have been described elsewhere (Friesen et al., 2008).

Chemical Analysis

Samples of farmed and wild salmon and commercial feeds, collected in 2003, were analyzed for total mercury (THg) and 18 trace elements (Ag, Al, As, Ba, Cd, Co, Cr, Cu, Mg, Mn, Ni, Pb, Rb, Se, Sr, Tl, V, Zn) that were measured using inductively coupled plasma–mass spectrometry following U.S. Environmental Protection Agency (EPA) method 6020 (USEPA, 1986). Methylmercury concentrations were determined in feed samples as well as selected salmon samples using gas chromatography-electron capture detection (GC-ECD) (Stern and MacDonald, 2005). Analyses of organohalogen contaminants (PCBs and PCDD/Fs, PBDEs, pesticides) were conducted using gas chromatography-high resolution mass spectrometry (GC-HRMS) at the Institute of Ocean Sciences (IOS), Sidney, BC following previously developed multi-residue ultra trace contaminant analysis methods (Ikonomou et al., 2001).

Results and Discussion

Mean concentrations of various metals observed in the flesh of farmed and wild salmon are illustrated in Fig. 1. Concentrations of non-essential elements ranged from 0.001 μg g^{-1} (Tl, Cd, and Ag) to 1 μg g^{-1} (As, Rb, and Al). Concentrations of Pb, Ni, and THg were between 0.01 and 0.05 μg g^{-1}. Concentrations were generally comparable between wild and farmed salmon, except Hg, which exhibited concentrations in wild salmon that were significantly higher (three times) than those noted in farmed salmon. Metal concentrations in farmed and wild BC salmon were not observed to exceed Canadian and United States human consumption guidelines (U.S. Food and Drug Administration, 2001; Health Canada, 2007). For example, concentrations of Hg in all of the BC salmon that were analyzed (0.01–0.1μg g^{-1}) were below the 0.5 μg g^{-1} Hg guideline as set by Health Canada.

Mean lipid contents (%) and concentrations of 2,3,7,8 TCDD toxic equivalents (pg TEQ g^{-1} wet wt) for PCDD/Fs and dioxin-like PCBs in the flesh of farmed and wild BC salmon are shown in Fig. 2. Farmed Atlantic salmon from the Broughton Archipelago exhibited the highest PCB and PCDD/F TEQ concentrations. Farmed coho salmon from Jervis Inlet exhibited the lowest TEQ levels among the farmed species. Among wild salmon species, chinook from the west coast of Vancouver Island (WCVI) and sockeye from Johnstone Strait exhibited higher TEQ levels (0.1–0.3 pg g^{-1}) compared to wild chum, coho, and pink salmon (0.01–0.1 pg g^{-1}).

We observed significant differences in organohalogen contaminant levels between species and/or location for both farmed and wild salmon (Fig. 2). The higher organohalogen concentrations seen in the flesh of farmed Atlantic salmon, compared to other sources of farmed salmon, were primarily due to their relatively higher flesh lipid contents (12–15%) relative to those found for farmed chinook and coho salmon (8–12% lipid, Fig. 2). Wild salmon exhibited comparable flesh lipid contents (2–4%). Thus, the relatively higher organohalogen levels observed in species such as chinook were likely due to the fact chinook salmon are piscivorous rather than planktivorous (*i.e.* chum, pink). Thus chinook consume prey from a higher trophic level (*i.e.* forage fish) and these food items contain higher concentrations of bio-accumulative organohalogens than those present in zooplankton. In essence, concentrations of persistent organohalogen contaminants are biomagnified to a greater extent in relatively higher trophic level chinook salmon.

It is important to note that TEQ levels of PCDD/Fs and PCBs in the flesh of farmed and wild BC salmon were generally below current human consumption guidelines, including the United States, European Union, United Nations/World Health Organization, as well as Health Canada (Fig. 2). One exception was observed for one group of farmed Atlantic salmon from the Broughton Archipelago which exhibited PCB TEQ levels (1.1 ± 0.06) that were borderline with the US Agency for Toxic Substances and Disease Registry (US ATSDR) threshold of 1 pg g^{-1}.

Chemical analyses of the major constituents of interest in this study in the aquafeeds based on MFO (anchovy oil) and in the TL-based diets that contained either poultry fat or canola oil revealed that the TL-based diets contained dramatically reduced levels of organohalogens. ΣPCB concentrations (ng g^{-1} wet wt) in BC aquafeeds that contained 50% of the dietary lipid from poultry fat or 35% from canola oil were respectively 64% and 55% lower than noted in the traditional diet containing MFOs (Fig. 3). Further, the PCB levels found in the foregoing alternative-lipid based diets were observed to be up to 100 times lower than those reported for MFO-based commercial diets obtained from Scotland, Norway, and Eastern Canada (Fig. 3).

Concentrations of TEQs in poultry fat and canola oil were respectively 93% and 98% lower than those noted in anchovy oil (6 pg g^{-1}) (Fig. 4). This explains the preceding observations in alternative aquafeed mixtures, shown in Fig. 3.

Feeding experiments conducted using farmed Atlantic and chinook salmon showed that partial replacement of MFO in traditional diets with the less contaminated TLs resulted in dramatic reductions in the concentrations of organohalogen contaminants in the flesh of the farmed salmon. For example, farm-raised Atlantic and chinook salmon fed the alternative lipid-based diets (*i.e.* 50% poultry fat or 35% canola oil) exhibited PCB and PCDD/F TEQ flesh concentrations that were 48 to 60% lower than those found for fish fed the traditional diets (Fig. 5). Moreover, flesh TEQ levels in farm-raised salmon fed the alternative TL-based diets were found to be equivalent to or lower than those in wild Pacific salmon (Table 1, Fig. 5).

An important consequence of dietary substitution of TLs for MFOs in commercial aquafeeds is the likely reduction of *n*-3 HUFAs in the final salmon products (Drew et al., 2007). Table 1 shows that EPA and DHA levels (g per 100-g fillet) in the flesh of farmed Atlantic salmon fed the alternative TL-based diets were 32 to 58% lower than those observed in farmed Atlantic salmon fed the traditional diets. However, it should be emphasized that EPA and DHA levels in the flesh of salmon raised on the alternative TL-based diets were still higher than those found in wild Pacific salmon species (Table 1).

Conclusions

Reducing human health risks associated with contaminant exposure via consumption of seafood has become a major worldwide public health concern. Our findings indicate that current flesh levels of major contaminants that include trace metals such as Hg, As, and Cd and organohalogens (PCBs, PCDD/Fs) in farmed and wild salmon from BC are below the present recommended levels of concern for human health. Thus, weekly consumption of BC salmon products that originate from farmed and wild sources is an excellent and safe way to obtain adequate dietary intake of *n*-3 HUFAs for cardio-protective and other human health benefits. Feeding experiments that utilized TL-based diets, that contained either poultry fat or canola oil as major replacements for MFOs, also clearly showed that the introduction of these aquafeeds can reduce organohalogen contaminant levels in the flesh of farmed salmon even further while concurrently maintaining sufficient levels of *n*-3 HUFAs. Work in progress examines similar human health risk assessments for other environmental contaminants, including the flame retardants polybrominated diphenyl ethers (PBDEs), and legacy and current-use pesticides in farmed and wild salmon from BC. Also, we are currently developing mathematical models for the purpose of predicting levels and patterns of environmental contaminants and *n*-3 HUFAs in farmed salmon from known levels in aquafeed.

Acknowledgements

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Table 1 Concentrations of lipid (% lipid) as well as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) (g/100-g fillet), and PCB TEQs and PCDD/F TEQs (pg g^{-1} wet wt) in the flesh of farmed Atlantic salmon fed diets based on marine fish oil (MFO; mainly anchovy oil) or blends of MFO with terrestrial lipids (TLs, *i.e.* 35% of dietary lipid as canola oil, CO35 or 50% of lipid as poultry fat, PF50) in relation to levels of the preceding components noted in wild Pacific salmon species.

	Traditional Diet	**Alternate Diets**			**Wild Salmon**				
	Farmed Atlantic	Farmed Atlantic	Farmed Atlantic	Farmed Atlantic	Wild Chinook	Wild Sockeye	Wild Coho	Wild Chum	Wild Pink
Feed Source	MFO	CO35	PF50	PF50	-	-	-	-	-
Fork Length	77	77	77[a]	61[a]					
Fillet Lipid (%)	13.2	10.9	11.4	9.1	4.1	4.1	2.8	1.1	2.9
EPA (g /100-g fillet)	0.92	0.81	0.60	0.42	0.26	0.28	0.22	0.10	0.19
DHA (g /100-g fillet)	1.51	0.83	0.83	0.61	0.54	0.62	0.50	0.30	0.65
PCB TEQs (pg g^{-1})	0.70	0.40	0.20	0.16	0.14	0.10	0.05	0.01	0.01
Dioxins TEQs (pg g^{-1})	0.60	0.45	0.15	0.09	0.15	0.10	0.09	0.01	<0.01

[a] Two groups of fish were fed the PF50 diet. The larger typical market-sized fish had an average fork length of 77 cm. The other group was somewhat smaller with an average fork length of 61 cm. Despite the relatively small size of the second group (*i.e.* 61-cm fork length), the fish were potentially marketable products.

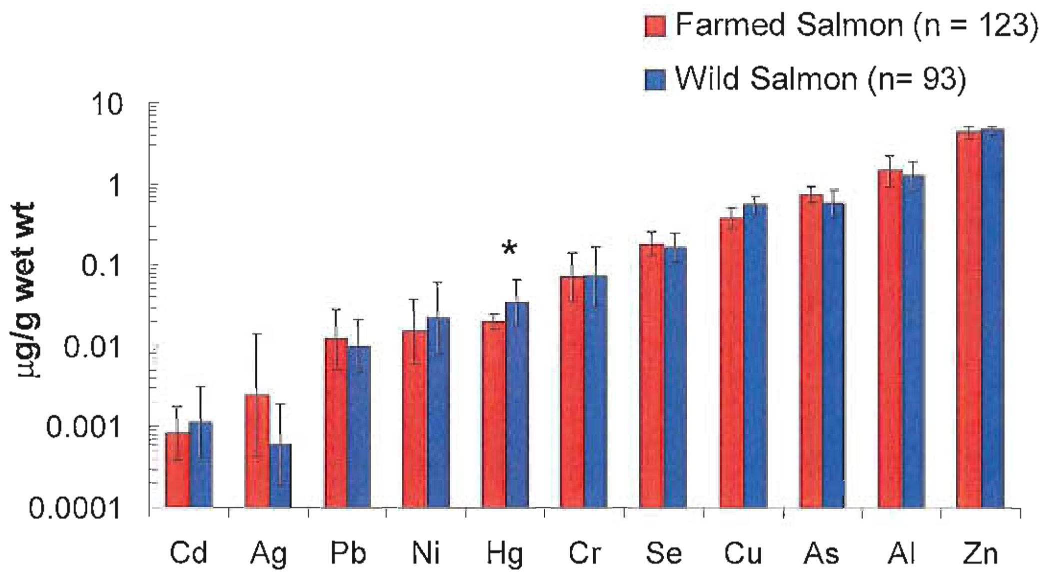

Fig. 1 Mean concentrations (μg g^{-1} wet wt) of selected trace metals in the flesh of farmed Atlantic salmon and wild Pacific salmon from British Columbia, collected in 2003. Error bars represent ± 1 standard deviation. * Significant difference (p<0.05) between farmed and wild salmon concentrations.

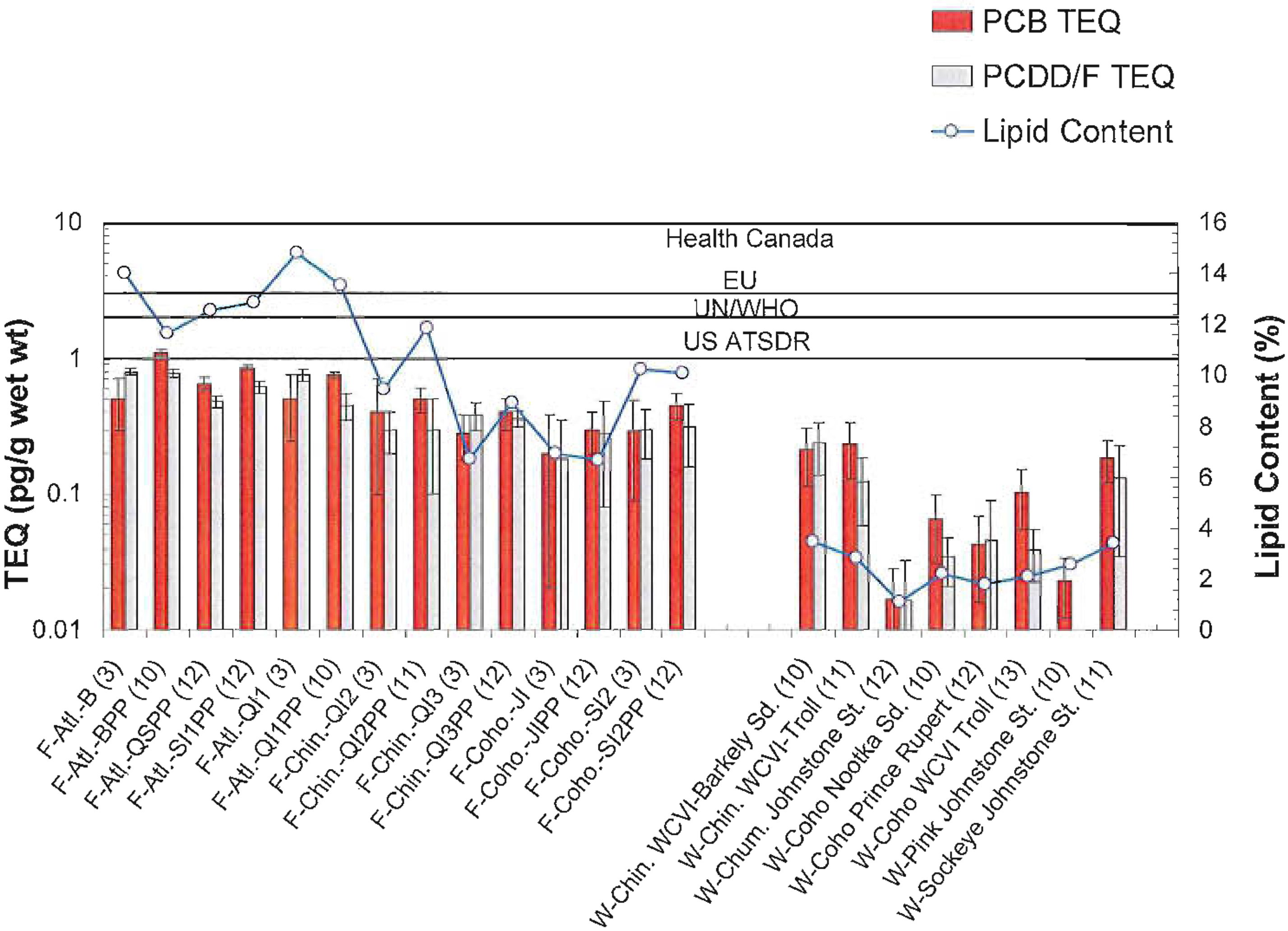

Fig. 2 Lipid contents (% lipid) and concentrations (pg g^{-1} wet wt) of toxic equivalents (TEQs) for polychlorinated biphenyls (PCBs; red bars) and polychlorinated dibenzo-p-dioxin/furans (PCDD/Fs; grey bars) in the flesh of the different sources of farmed (F; Atlantic, ATL; chinook, chin; coho) and wild (W; chin, chum, coho, pink, sockeye) BC salmon, sampled in 2003. Error bars represent 95% confidence intervals. Horizontal lines represent recommended tolerable daily intake for PCDD/Fs under the U.S. Agency for Toxic Substances and Disease Registry (ATSDR), UN Food and Agriculture Organization/World Health Organization Joint Expert Committee on Food Additives (UN/WHO JECFA), and Health Canada. Refer to Ikonomou et al. (2007) for details of fish origin.

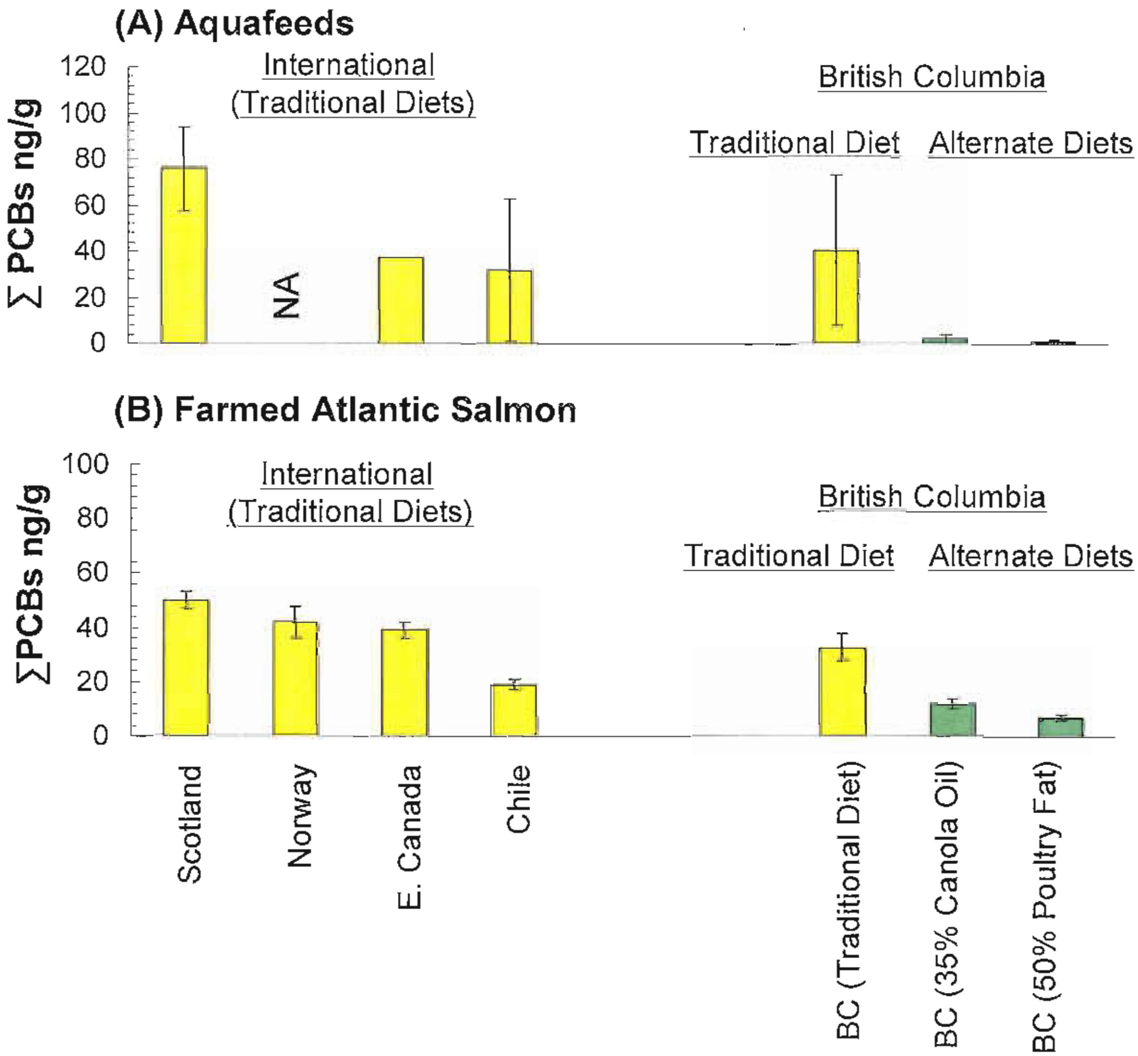

Fig. 3 Total concentrations of polychlorinated biphenyls (ΣPCBs; ng g^{-1} wet wt) in (A) aquafeeds and (B) fillets from farmed Atlantic salmon fed diets based on marine fish oils (MFOs) or terrestrial lipids (TLs). Data for BC samples are from the present study. Data for other regions in the world (*i.e.* Scotland, Norway, Eastern Canada, and Chile) are from Hites et al., 2004).

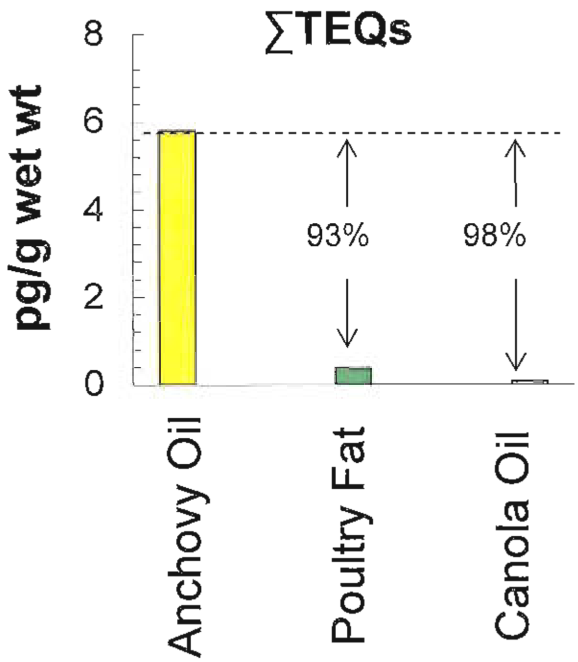

Fig. 4 Total concentrations of toxic equivalents (ΣTEQs; pg g^{-1} wet wt) measured in anchovy oil, poultry fat, and canola oil.

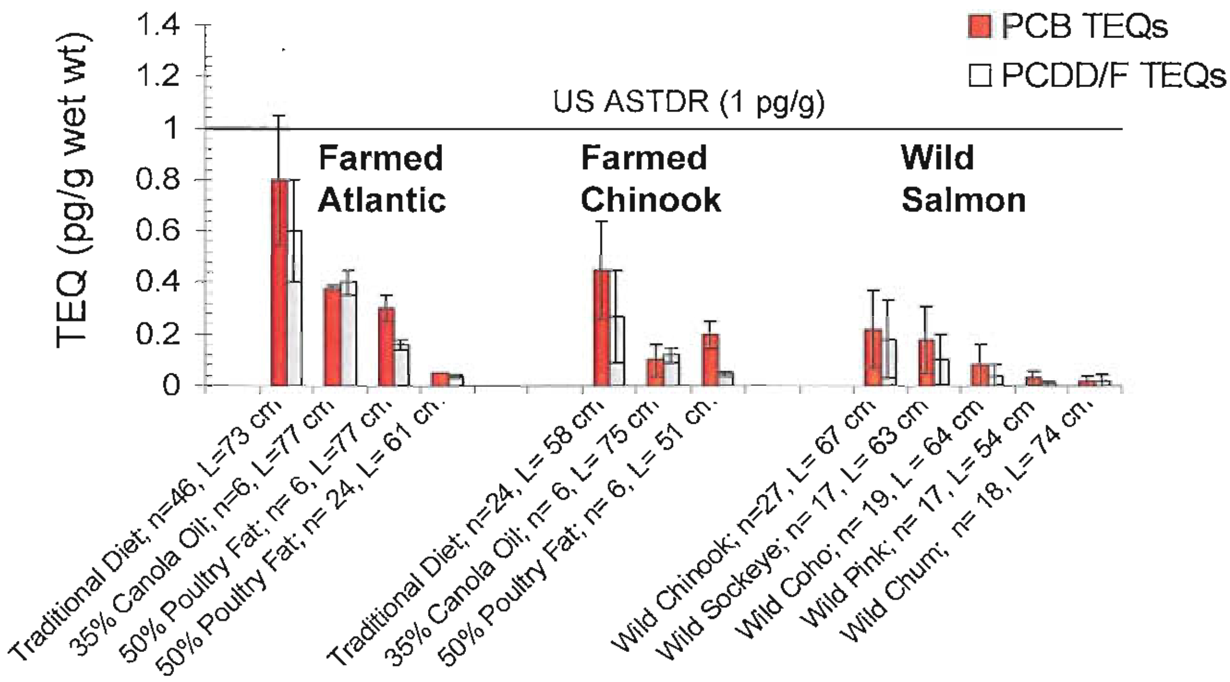

Fig. 5 Concentrations (pg g^{-1} wet wt) of polychlorinated biphenyl toxic equivalents (PCB TEQs; red bars) and polychlorinated dibenzo-p-dioxin/furan TEQs (PCDD/F TEQs; grey bars) in the flesh of farmed Atlantic salmon and farmed chinook salmon fed traditional marine fish oil (MFO)-based diets and alternative terrestrial lipid (TL)-based diets in relation to respective levels observed in the flesh of five wild Pacific salmon species (chinook, sockeye, coho, pink, chum). The TL diets contained 35% of the dietary lipid as canola oil (CO35) or 50% of the lipid as poultry fat (PF50). The number of samples (*n*) and average fork length (L, cm) of the sampled fish are also shown. Contaminant concentrations in wild salmon represent mean values of combined 2003 and 2005 samples. Error bars represent standard deviations.