

Chemical contaminants in fish feeds used in federal salmonid hatcheries in the USA

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Abstract

Recent studies have demonstrated that fish feeds contain significant concentrations of contaminants, many of which can bioaccumulate and bioconcentrate in fish. Organochlorine (OC) contaminants are present in the fish oils and fish meals used in feed manufacture, and some researchers speculate that all fish feeds contain measurable levels of some contaminants. To determine the concentration of contaminants in feeds used in US Fish and Wildlife Service's National Fish Hatcheries, we systematically collected samples of feed from 11 cold-water fish hatcheries. All samples (collected from October 2001 to October 2003) contained at least one polychlorinated dibenzo-*p*-dioxin (PCDD), polychlorinated dibenzofuran (PCDF), polychlorinated biphenyl (PCB) congener, or dichlorodiphenyltrichloroethane (DDT) metabolite. Of the 55 samples in which they were analyzed 39 contained PCDDs, 24 contained PCDFs and 24 contained DDT or its metabolites. There were 10- to 150-fold differences in concentrations of total PCBs, PCDDs, PCDFs and DDT. Although PCBs were the most commonly detected contaminant in our study, concentrations (range: 0.07–10.46 ng g⁻¹ wet weight) were low compared to those reported previously. In general, we also found lower levels of OCs than reported previously in fish feed. Perhaps most notable was the near absence of OC pesticides – except for DDT or its metabolites, and two samples containing hexachlorocyclohexane (HCH). While contaminant concentrations were generally low, the ecological impacts can not be determined without a measure of the bioaccumulation of these compounds in the fish and the fate of these compounds after the fish are released.

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1. Introduction

Fish can bioaccumulate contaminants that they ingest with their food or bioconcentrate chemicals directly from the water via diffusion across the gills and skin (Gobas et al., 1999). The rate of accumulation is based in part on the quantity and form of the contaminants (Watanabe et al., 1997; Carline et al., 2004), water quality variables, and the age, size and nutritional status of the fish (Patrick and Loutit, 1978; Sorensen, 1991). Pesticides may become

bound to the soil and enter the aquatic environment in precipitation run-off or as aeri ally transported dust (VanCuren, 2003). Other contaminants result from industrial chemicals (including byproducts of incineration), which can enter the atmosphere and be transported throughout the globe before deposition (de Wit et al., 2003; Breivik et al., 2004). Many of the contaminants entering freshwater and marine ecosystems are persistent in the environment and, because they are also lipid soluble, tend to accumulate in the lipid depots of animals, and are passed from prey to predators (Muir et al., 1992). This accumulation leads to organisms at higher trophic levels having relatively higher levels of organochlorine chemicals (OCs) and other lipophilic contaminants through the process of biomagnification. A wide range of OCs and metals have been

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documented in wild fish populations (de Wit et al., 2003), and contaminants have been found in fish in aquaculture. Hatchery diets that contain a high percentage of some pelagic, ocean fish may contain high amounts of contaminants. Hatchery salmonids might, in effect, be moved to a higher trophic level than their wild counterparts by consuming feeds derived from marine fish, as opposed to their natural food comprised in part of freshwater invertebrates. Organochlorine residues have been found in fish oil (Jacobs et al., 1997) and fish meal (Rumsey, 1980) – salmon feed can contain up to 30% fish oil and 50% fish meal (Horst et al., 1998) – while polychlorinated dibenzo-*p*-dioxins (PCDD) and polychlorinated dibenzofurans (PCDF) have been found in soybean meal (Rappe et al., 1998). Mac et al. (1979) found polychlorinated biphenyls (PCBs) and metabolites of dichlorodiphenyltrichloroethane (DDT), namely dichlorodiphenyltrichloroethylene (*p,p*-DDE), in fish feeds. Horst et al. (1998) also found OCs, specifically chlordane compounds, in farmed salmon as well as fish meal, oil and food products made from the farmed fish. Easton et al. (2002) associated the levels of OCs, polybrominated diphenyl ethers (PBDE; flame retardants) and metals in farmed salmonids with the elevated levels of contamination in commercial feeds. Several researchers concluded that there was no salmon feed free of contaminants, farmed salmon showed consistently higher levels of contaminants than did wild salmon, and that there may be safety concerns for individuals who regularly consume farmed salmonids produced with contaminated feed (Horst et al., 1998; Easton et al., 2002; Hites et al., 2004).

Thus, one of the primary concerns regarding contaminants in fish feed is the possible human health impacts. The concentrations of contaminants in the fish and feeds reported by Hites et al. (2004) were not acutely toxic based on the Code of Federal Regulations, 21 CFR 109.30, which is the Food and Drug Administration (FDA) regulation and states that the temporary tolerance for residues of PCBs in feed for food-producing animals is 0.2 ppm; tolerance levels for edible portions of fish is 2.0 ppm. However, the US Environmental Protection Agency (EPA) guidelines and assumptions used by Hites et al. (2004) are designed to manage human health risks by providing risk-based consumption advice based on a toxic equivalency quotient (TEQ) or a cumulative approach that considers compounds with similar modes of action (i.e., planar PCBs, PCDDs and PCDFs collectively). Concern for human health arises primarily over fish released for immediate catch and consumption, fish held for broodstock then released to the public, or returning adult salmonids consumed by Native Americans whose diets may contain more fish than other segments of the United States population. It is also possible that the accumulation of contaminants will reduce the quality of the fish in the hatchery and their survival after release, as exposure to certain persistent organic pollutants in urban estuaries has been linked to reduced growth rate and reduced disease resistance in juvenile salmonids (Arkoosh et al., 1998, 2001).

The objective of the current study was to determine the presence and concentrations of contaminants in fish feed used in a cross-section of cold-water US Fish and Wildlife Service (FWS) National Fish Hatcheries (NFHs). Even though it is possible that contaminants could be found in the water or physical structures of the hatcheries, feeds were chosen because they are a potential point-source and they are used universally, i.e. more than one hatchery may use the same feed. For two years we collected quarterly samples of feed from six manufacturers used at 11 NFHs and analyzed the samples for a variety of OC pesticides, metals, PCBs, PCDDs and PCDFs.

2. Materials and methods

2.1. Sample collection and handling

We collected samples of feeds from 11 NFHs in the Pacific, Great Lakes, Northeast and Mountain-Prairie FWS regions, from October 2001 to October 2003. All of the diets tested were made at commercial manufacturers except one feed that was handmade at a hatchery using shrimp paste, fish paste, beef liver, a commercial starter diet and the appropriate vitamins and minerals. This feed had higher moisture content than the other commercial diets tested. All feeds were sampled according to the Association of Official Analytical Communities (AOAC) guidelines (Horwitz, 2000). Once each quarter at each NFH, a pallet of 40 feed bags was randomly selected for sampling. Approximately 50–100 g of feed was collected from every fourth bag in the lot (i.e., 10 samples) and stored in chemically cleaned, glass jars that we provided. To sample bulk feeds, the 10 samples were collected from different parts of the load using a 99-cm (39-in.) Seedburo® chrome-plated trier. After sampling, the trier was disassembled, cleaned with soap and warm water, rinsed thoroughly and allowed to air dry. Samples of frozen fish feeds were shipped in water-tight containers on ice.

All samples were shipped to the Abernathy Fish Technology Center (Center) where the 10 samples from each NFH were pooled and ground with a mortar and pestle, which was then chemically cleaned. Each composite feed sample was then divided into four chemically cleaned glass jars coded with the identifying NFH abbreviation, sample period (i.e., 1–8), and sample weight. One of these subsample jars was given a composite, as well as, a random number code, and was sent for contaminant analyses. The three remaining jars were placed in a –20 °C freezer at the Center, where one jar of feed was used to determine proximate analysis, and two jars are being stored as archival samples.

2.2. Analytical methods

The feed samples were analyzed for protein, lipid, moisture and ash (proximate analysis) according to the AOAC methods (Horwitz, 2000). The US Geological Survey

National Water Quality Laboratory measured metals using the EPA Method 3052 microwave-assisted, nitric acid digestion procedure (Hoffman, 1996). Aluminum, barium, boron, chromium, copper, iron, magnesium, manganese, strontium and zinc were determined by inductively coupled plasma atomic emission spectrometry (ICP-OES). Arsenic, beryllium, cadmium, lead, molybdenum, nickel, selenium and vanadium were determined by inductively coupled plasma mass spectrometry (ICP-MS). Mercury was determined by cold vapor atomic fluorescence (CVAF) following US EPA Method 7474. The analysis of fish feed samples for OC pesticides was accomplished by gas chromatography with electron capture detection (GC/ECD) by USGS Laboratory Schedule 2101 (Leiker et al., 1995). Severn Trent Laboratories, Inc., Sacramento, CA (Severn) analyzed samples for PCDDs and PCDFs (EPA method 8290, US EPA, 1995). Severn Trent Laboratories, Inc., Knoxville, TN (Severn) also analyzed samples for OCs and metals using standard methods, including metals (except Hg) by US EPA method 6010B (US EPA, 1996a), mercury by method 7471A (US EPA, 1995), 14 PCB congeners by US EPA method 1668 (US EPA, 1999), and OC pesticides by EPA SW 846 (US EPA, 1996b).

2.3. Data analyses

All data were summarized by determining means (± 1 standard deviation, SD) based on the manufacturer. We also determined the total contents of PCDDs, PCDFs, PCBs and DDT metabolites by summing the values from the congener-specific analyses. Our objectives in this study were to determine the presence and concentrations of contaminants in fish feeds used at a cross-section of NFHs. We were not interested in comparing between NFHs or manufacturers; therefore, we did not conduct statistical analyses to identify differences between mean concentrations of contaminants.

Only results above detection limits were included in this report and we did not speculate as to the significance of values below the detection limits. Our data summaries contain only positive values when there were often values that may equal “0” (i.e., non-detects). We present total number of samples analyzed as well as the number of positive values (i.e., sample size, N) used in the calculations (detection limits and tabular results are presented in Supplemental data, Table S1). Severn attached qualifiers to some values when, after adjusting for the dilution factor, those values were below the estimated minimum level (EML) or above the upper calibration level (UCL); these values are estimates. We included these values in our analyses. In order to compare our results to others in the literature, we calculated TEQs for PCDD, PCDF and PCDD-like PCB congeners for which there are toxic equivalent factors (TEF), and total TEQs are based on the World Health Organization’s established TEFs for fish (Van den Berg et al., 1998).

3. Results

A total of 77 samples were collected all of which were analyzed for proximate analysis, but, because of budgetary constraints, not all were analyzed for metals or contaminants. Excluding the values for proximate analyses and the totals that were the sums of other variables, 41 compounds were detected in the samples. PCBs were found in all samples ($n = 46$; Table 1). Of the 55 samples in which they were analyzed, 39 contained PCDDs, 24 contained PCDFs and 24 contained DDT or its metabolites (Table 1). Most of the samples contained more than one of these classes of compounds. There were 10- to 150-fold differences in the range in concentrations of the additive totals for PCBs, PCDDs, PCDFs and DDT (Table 2). In addition to DDT and its metabolites, the only pesticide detected was hexachlorocyclohexane (HCH) found in two samples. Differences in the number of samples between the analyzed total values and the additive totals are the result of some samples which were positive for totals in a class of compounds, but either none of the individual congeners were above detection limits, and/or homologous congeners were detected. We calculated TEQs for PCDDs (2,3,7,8-TCDD; 1,2,3,7,8-PeCDD; 1,2,3,4,6,7,8-HpCDD; and OCDD) and PCDFs (2,3,7,8-TCDF and OCDF), and PCDD-like PCBs (Table 2). Metals were also present in all 55 samples for which they were analyzed (Table 3). Beryllium (Be) was the only metal not found in any sample, and 12 of the other 18 metals were found in all 55 samples.

Supplemental Table S2 summarizes the concentrations of components and contaminants based on the feed manufacturer. As we were not concerned with comparing manufacturers, we have coded the names (A–F). Rather than show all congeners and metabolites, we present the additive totals for PCDDs, PCDFs, PCBs, DDT metabolites and HCH, as well as mean percent composition of ash, lipids, moisture and protein, and mean concentrations of each of the metals. In general, the proximate composition of feed (protein, moisture, lipid, ash) adds up to approximately 100%. However, in some cases, the fiber and nitrogen-free extract (e.g., sugars, starches) that were not measured were in the feed at significant levels and, therefore, made up the difference seen in the proximate compositions (Supplemental Table S2). We also compared the results of our study to those reported previously by Mac et al. (1979) and Easton et al. (2002) in Table 4.

4. Discussion

4.1. OC contaminants in fish feed

In this study we found some form of chemical contaminant in all samples. In general, we found lower levels of OC contaminants than have been reported previously in fish feed. Perhaps most notable is the almost total lack of pesticides – except for DDT (and its metabolites) and just two samples contained HCH. Hites et al. (2004) reported

Table 1

Summary of polychlorinated dibenzo-*p*-dioxins (PCDD), polychlorinated dibenzofurans (PCDF) (total samples assayed = 55), PCBs (total samples assayed = 46) and organochlorine pesticides (total samples assayed = 55) detected in fish feed samples assayed by the USGS National Water Quality Lab or Severn Trent Laboratories, Inc. in fish feed samples collected from 11 National Fish Hatcheries between October 2001 and October 2003

Compound units	1,2,3,4,6,7,8-HpCDD (pg g ⁻¹)	1,2,3,7,8-PeCDD (pg g ⁻¹)	2,3,7,8-TCDD (pg g ⁻¹)	2,3,7,8-TCDF (pg g ⁻¹)	OCDD (pg g ⁻¹)	OCDF (pg g ⁻¹)	Total HpCDD (pg g ⁻¹)	Total HpCDF (pg g ⁻¹)	Total PeCDD (pg g ⁻¹)	Total TCDD (pg g ⁻¹)	Total TCDF (pg g ⁻¹)	Total PCDD (pg g ⁻¹)	Total PCDF (pg g ⁻¹)	Total PCB (ng g ⁻¹)	Total DDT (μg kg ⁻¹)	Total HCH (μg kg ⁻¹)
Mean	10.4	3.2	0.55	1.29	36.2	10.00	16.93	3.00	12.80	0.69	1.33	38.08	1.76	1.94	11.33	21.50
SD	12.6	1.0		0.82	67.5		19.25		6.30	0.19	0.82	74.25	2.40	2.42	7.97	3.54
N	10	2	1	22	38	1	10	1	3	2	23	39	24	46	24	2
SE	4.0	0.7		0.17	11.0		6.09		3.64	0.14	0.17	11.89	0.49	0.36	1.63	2.50
Max value	44.0	3.9	0.55	3.80	350.0	10.00	66.00	3.00	19.00	0.82	3.80	394.00	12.30	10.46	31.00	24.00
Min value	3.1	2.5	0.55	0.64	5.2	10.00	3.10	3.00	6.40	0.55	0.64	2.50	0.64	0.07	3.30	19.00

SD = standard deviation; N = number of samples with detectable values; SE = standard error of the mean.

DDT contains data from the two labs using different assays (see Section 2). Total DDT, Total PCDDs, Total PCDFs and Total PCBs were determined by summing across classes of compounds. All other totals were determined by independent assays. Differences in the number of samples between the assayed total values and the additive totals are the result of some samples in which assay results are positive for totals in a class compounds, but none of the individual congeners were above detection limits, and vice-versa.

Table 2

World Health Organization (WHO) toxic equivalents (TEQ; pg g⁻¹) for polychlorinated dibenzo-*p*-dioxins (PCDD; congeners: heptachlorodibenzo-*p*-dioxin, octachlorodibenzo-*p*-dioxin, pentachlorodibenzo-*p*-dioxins, tetrachlorodibenzo-*p*-dioxin), polychlorinated dibenzofurans (PCDF; congeners: tetrachlorodibenzo furan, octachlorodibenzo furan) and PCBs (congeners: PCB -77, -105, -114, -118, -123, -126, -156, -157, -167, -189) detected in 55 fish feed samples assayed by Severn Trent Laboratories, Inc. in fish feed samples collected from 11 National Fish Hatcheries between October 2001 and October 2003

	Mean	SD	N	SE	Min	Max
PCDD TEQ	0.208	0.739	39	0.1183	0.0005	3.9486
PCDF TEQ	0.064	0.041	22	0.0087	0.0320	0.1900
PCB TEQ	0.061	0.085	46	0.0125	0.0026	0.4144
PCDD + PCDF	0.227	0.708	42	0.1092	0.0005	3.9486
Total TEQs	0.237	0.647	52	0.0897	0.0006	3.9811

SD = standard deviation; N = number of samples with detectable values, each of the 52 total samples could contain 1, 2 or 3 of the classes of contaminants; SE = standard error of the mean; Min = minimum value detected above detection limits; Max = maximum value detected.

Toxic equivalent factors for fish were used in the calculations (Van den Berg et al., 1998).

detectable levels of dieldrin and toxaphene in 13 feed samples, which included six from Canada but none from the USA. Jacobs et al. (2002) found hexachlorobenzene (HCBs) and HCHs in eight feed samples of European manufacture. Hilton et al. (1983) formulated five test feeds using fish meal from several sources, and all of the resulting feeds had detectable concentrations of dieldrin, heptachlor and chlordane. Our samples contained lower concentrations of total DDTs (range: 3.3–31.0 ng g⁻¹ wet weight; Table 1) than were reported by Mac et al. (1979) for several lots from one commercial feed manufacturer (means: 80–340 ng g⁻¹ wet weight), but our samples contained about the same concentration of DDT as another feed manufacturer they examined (means: 13–51 ng g⁻¹ wet weight). Feeds manufactured in Scotland reportedly had levels of total DDT (range: 34–52 ng g⁻¹ lipid adjusted; Jacobs et al., 2002), which would be three- or fourfold greater than ours if expressed as wet weight. It appears that the concentrations of DDT metabolites we found in feeds from three manufacturers were lower than those observed by Mac et al. (1979) and Easton et al. (2002) in samples from the same manufacturers several years previous (Table 4).

Although PCBs were the most commonly detected contaminant in our study (46 of 46 samples), the additive total concentrations of 14 PCDD-like PCB congeners ranged from 0.07 to 10.46 ng g⁻¹ wet weight (Table 1). These were low compared to total PCBs reported by Hites et al. (2004; range: ~10–95 ng g⁻¹ wet weight), Carline et al. (2004; range: 69–126 ng g⁻¹ wet weight), and Mac et al. (1979; means: 54–230 ng g⁻¹ wet weight). Hilton et al. (1983) also reported high concentrations of PCBs (100–2120 ng g⁻¹) but these were expressed in dry weight of feed. It is, however, important to note that these values are probably not directly comparable as the methods used in these other studies considered more PCB congeners than the 14 in our

Table 3
Summary of metals detected in 55 fish feed samples assayed by Severn Trent Laboratories, Inc. and the National Water Quality Laboratory in fish feed samples collected from 11 National Fish Hatcheries between October 2001 and October 2003

Metal units	Al ($\mu\text{g g}^{-1}$)	As ($\mu\text{g g}^{-1}$)	Ba ($\mu\text{g g}^{-1}$)	B ($\mu\text{g g}^{-1}$)	Cd ($\mu\text{g g}^{-1}$)	Cr ($\mu\text{g g}^{-1}$)	Cu ($\mu\text{g g}^{-1}$)	Fe ($\mu\text{g g}^{-1}$)	Pb ($\mu\text{g g}^{-1}$)	Mg ($\mu\text{g g}^{-1}$)	Mn ($\mu\text{g g}^{-1}$)	Hg ($\mu\text{g g}^{-1}$)	Mo ($\mu\text{g g}^{-1}$)	Ni ($\mu\text{g g}^{-1}$)	Se ($\mu\text{g g}^{-1}$)	Sr ($\mu\text{g g}^{-1}$)	V ($\mu\text{g g}^{-1}$)	Zn ($\mu\text{g g}^{-1}$)
Mean	61.50	2.62	6.67	5.28	0.39	1.50	10.54	353.9	0.78	1763	84.31	0.03	0.76	2.35	2.48	45.94	2.07	142.76
SD	50.30	1.37	3.97	2.23	0.21	0.74	5.43	134.9	1.11	429	45.94	0.03	0.52	1.39	0.68	26.06	1.78	42.36
N	55	55	55	55	41	53	55	55	25	55	55	52	47	55	55	55	54	55
SE	6.78	0.18	0.54	0.30	0.03	0.10	0.73	18.2	0.22	58	6.19	0.00	0.08	0.19	0.09	3.51	0.24	5.71
Max value	226.00	8.17	15.30	9.80	0.89	4.70	29.83	622.0	5.82	2640	196.00	0.12	2.28	7.80	3.80	117.00	9.44	258.54
Min value	1.94	0.25	0.20	0.63	0.08	0.67	1.20	15.0	0.10	212	3.60	0.01	0.16	0.42	0.25	4.52	0.22	14.20

SD = standard deviation; N = number of samples with detectable values; SE = standard error of the mean.
The labs used different assay methods (see Section 2).

additive totals. Easton et al. (2002) presented data on the same 14 PCB congeners as our study and are thus directly comparable, as is the total PCBs reported for various feeds in the Mac et al. study (1979). The range of total PCBs in feed from manufacturer A sampled in 1999 and reported by Easton et al. (2002) is less than that reported by Mac et al. (1979) (Table 4). Easton et al. (2002) also presented the sums of 14 PCBs for the same feeds and these were greater than what we analyzed in our samples (Table 4). Furthermore, the maximum TEQ for PCBs in our samples was about one-half those in Easton et al. (2002) and from one- to two-orders of magnitude less than those reported in European fish feeds (Isosaari et al., 2004; Bell et al., 2005). In fact, the highest value from our samples ($0.44 \text{ pg TEQ g}^{-1}$) was less than the lowest value ($0.62 \text{ pg TEQ g}^{-1}$) reported in either of the European studies.

Bell et al. (2005) and Isosaari et al. (2004) combined TEQs for PCDDs and PCDFs in fish feeds and reported a range of $0.16\text{--}4.9 \text{ pg TEQ g}^{-1}$ in eight samples. In the present study, the mean PCDD plus PCDF TEQ was 0.227 and the maximum value was $3.98 \text{ pg TEQ g}^{-1}$ (Table 4). It should be noted, however, that these values are skewed by two samples (out of 42) that contained 2.5 and $3.9 \text{ pg 1,2,3,7,8-PeCDD g}^{-1}$, which has a TEF of 1.0 (fish TEF value), as compared to TEFs ≤ 0.05 (Van den Berg et al., 1998) for all other PCDD and PCDF congeners in our samples. If these two PeCDD values are excluded, the mean PCDD/PCDF TEQ is $0.077 \text{ pg TEQ g}^{-1}$ and the maximum value is $0.581 \text{ pg TEQ g}^{-1}$. Bell et al. (2005) reported that the European Union allows up to $2.25 \text{ pg TEQ g}^{-1}$ in fish feed. Hites et al. (2004) presented combined PCDD, PCDF and PCDD-like PCB TEQs in 13 fish feed samples collected from Scotland, Canada and Chile and reported TEQs of about $0.5\text{--}7.0 \text{ pg TEQ g}^{-1}$, as compared to our range of $0.0005\text{--}3.98 \text{ pg TEQ g}^{-1}$. Again, in the present study, two samples with PeCDD skew these comparisons.

4.2. Metals in fish feed

Metals found commonly in fish feed are contributed by the raw ingredients and by a mineral pack added by the manufacturer. Shearer et al. (1994) analyzed eight feeds from a Norwegian feed manufacturer for select metals. Generally, their results [Cu, $1.3\text{--}29.2 \text{ ppm}$ (i.e., $\mu\text{g g}^{-1}$); Fe, $68.7\text{--}353 \text{ ppm}$; Mg, $1860\text{--}2100 \text{ ppm}$; Mn, $5\text{--}120 \text{ ppm}$; Zn, $170\text{--}380 \text{ ppm}$] were slightly higher than the values we report here (Table 3). In addition, guidelines from the Association of Feed Control Officials (Hanks, 2000) indicate the maximum tolerable levels are for Cd, 0.5 ppm ; Hg, 2.0 ppm ; Se, 2.0 ppm ; Cu, 25 ppm ; and Pb, 30.0 ppm . These dietary levels in the feed, for a limited period, will not affect animal performance and should not produce unsafe residues in human food derived from the animal. Generally, our metal results fall below these tolerable levels. Many gaps exist in our understating of essential

Table 4

Total PCBs, 14 polychlorinated dibenzo-*p*-dioxin-like PCBs (DL-PCBs), toxic equivalents (TEQ; pg g⁻¹) for the DL-PCBs, and DDT metabolites (ng g⁻¹ wet weight) in feed from specific manufacturers (A, B and D) as reported in three studies spanning about 25 years

Manufacturer/variable	Pre-1979	1999	2001–2003
A			
Total PCBs	100–230 (<i>n</i> = 3–4)	43 and 107 (two samples)	ND
14 DL-PCBs	ND	6.7 and 4.4	1.4–4.0 (<i>n</i> = 6 of 10)
TEQ	ND	0.312 and 0.261	0.046–0.135
DDT metabolites	10–340 (<i>n</i> = 3–4)	50 and 50 (two samples)	8.4–31.0 (<i>n</i> = 7 of 10)
B			
Total PCBs	ND	90.2 (one sample)	ND
14 DL-PCBs	ND	5.2	0.4–3.0 (<i>n</i> = 7 of 14)
TEQ (mean ± SE)	ND	0.177	0.015–0.041
DDT metabolites	ND	30.7 (one sample)	4.0 (<i>n</i> = 1 of 14)
D			
Total PCBs	54–60 (<i>n</i> = 3)	ND	ND
14 DL-PCBs	ND	ND	0.6–4.8 (<i>n</i> = 14 of 19)
TEQ	ND	ND	0.004–0.125
DDT metabolites	13–51 (<i>n</i> = 3)	ND	4.4–20.0 (<i>n</i> = 6 of 19)

ND – no data available.

Values for pre-1979 are the range of means from Mac et al. (1979); values for 1999 are data from 1 or 2 assays presented in Easton et al. (2002); values for 2001–2003 are ranges of results from this report, not including those below detection levels. Sample sizes are in parentheses; for this report, we also report total number of samples examined.

minerals for fish (i.e., without them there are clinical signs of deficiency); however, it appears that B, Ca, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, P, Se, and Zn are essential. The levels of these metals required by each species of fish have not been defined.

4.3. Ecological implications

The presence of OCs and heavy metals (e.g., mercury) in fish food can have human health implications, but these compounds can also affect the survival of fish after release from hatcheries, and impact the ecosystem into which fish are released. Many of the compounds measured in this study are known to bioaccumulate and biomagnify up the food web. However, to determine the level of bioaccumulation or the effects of these feeds on the fish, we would need information about the specific amounts fed to fish throughout their life cycle and the levels of contaminants in the fish tissues. Macek (1968) reported that brook trout (*Salvelinus fontinalis*) fed DDT (2 mg kg⁻¹ body weight week⁻¹) for 31 weeks had 20-fold greater accumulated DDT than did control fish. Isosaari et al. (2004) reported that from 43% to 83% of the total mass of PCDDs, PCDFs, and PCBs fed to Atlantic salmon (*Salmo salar*) over 30 weeks accumulated in the tissue of the fish.

The majority of OCs are persistent in the environment and, because they are lipid soluble, tend to accumulate in the lipid depots of animals, and biomagnify up the food web. Because of this biomagnification, fish that are fed for months in a hatchery may accumulate OC concentrations that are significantly higher than that in the feed (Isosaari et al., 2004). Well-fed fish will accumulate these lipophilic contaminants in fat depots in muscle and viscera where the toxic effects are muted. When fish stop feeding,

however, the lipids are mobilized as an energy source and the OCs are redeposited in vital organs (Jørgensen et al., 2002). Recent work with Arctic charr (*S. alpinus*) dramatically illustrates the impacts of this mobilization of OCs. Anadromous charr normally feed for only 6–8 weeks in the ocean – where they can accumulate OCs – and fast for the remaining 10 months of the year in freshwater. In a series of experiments charr were contaminated with PCBs, fasted or fed for 5 months, and then their physiological responses were measured. Contaminated fasted charr had impaired responses to stress (Jørgensen et al., 2002), reduced immune responses leading to decreased disease resistance (Maule et al., 2005), depressed metabolic enzyme activity and liver glycogen levels (Vijayan et al., 2006) and reduced growth and survival in saltwater (Jørgensen et al., 2004) when compared to fed charr. One mechanism of PCB's effect was interference with hormonal regulation of physiological processes at the level of the brain or pituitary (Aluru et al., 2004). These results suggest strongly that PCBs – and likely other contaminants – will reduce the fitness and survival of fish in the wild.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at [doi:10.1016/j.chemosphere.2006.11.029](https://doi.org/10.1016/j.chemosphere.2006.11.029).

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