Environmental Toxicology and Chemistry, Vol. 27, No. 3, pp. 631–636, 2008

Printed in the USA
0730-7268/08 $12.00 + .00

NET TROPHIC TRANSFER EFFICIENCIES OF POLYCHLORINATED BIPHENYL CONGENERS TO LAKE WHITEFISH (*COREGONUS CLUPEAFORMIS*) FROM THEIR FOOD

CHARLES P. MADENJIAN,*† DANIEL V. O'CONNOR,† RICHARD R. REDISKE,‡ JAMES P. O'KEEFE,‡ and STEVEN A. POTHOVEN§
†U.S. Geological Survey, Great Lakes Science Center, 1451 Green Road, Ann Arbor, Michigan 48105
‡Grand Valley State University, Annis Water Resources Institute, 740 West Shoreline Drive, Muskegon, Michigan 49441, USA
§National Oceanic and Atmospheric Administration, Great Lakes Environmental Research Laboratory, 1431 Beach Street, Muskegon, Michigan 49441, USA

(*Received* 24 *April* 2007; *Accepted* 29 *August* 2007)

Abstract—Lake whitefish (*Coregonus clupeaformis*) were fed rainbow smelt (*Osmerus mordax*) in four laboratory tanks over a 133-d experiment. At the start of the experiment, 10 to 14 of the fish in each tank were sacrificed, and the concentrations of 40 polychlorinated biphenyl (PCB) congeners within these fish were determined. Polychlorinated biphenyl congener concentrations were also determined in the 15 lake whitefish remaining in each of the four tanks at the end of the experiment as well as in the rainbow smelt fed to the lake whitefish. Each lake whitefish was weighed at the start and the end of the experiment, and the amount of food eaten by the lake whitefish during the experiment was tracked. Using these measurements, net trophic transfer efficiency (γ) from the rainbow smelt to the lake whitefish in each of the four tanks was calculated for each of the 40 PCB congeners. Results showed that γ decreased exponentially as log K_{OW} for the congeners increased from 6 to 8. Further, γ averaged 0.70 for the tetrachloro congeners but averaged only 0.45 for the higher chlorinated congeners.

Keywords—Trophic transfer efficiency   Polychlorinated biphenyl congeners   Lake whitefish

INTRODUCTION

Contaminant accumulation rate in a fish is strongly influenced by the efficiency with which the fish retains contaminants from its prey [1,2]. Consequently, reliable estimates of the efficiency with which a fish retains contaminants from its prey are essential for use in risk assessment models to predict future risk to both people and wildlife eating contaminated fish under various scenarios of environmental contamination [3].

Gross trophic transfer efficiency can be defined as the efficiency with which the contaminant in the food ingested by the predator is taken up through the gut wall of the predator [4]. Once taken up through the gut wall, a portion of the quantity of the contaminant inside the body of the fish may eventually be eliminated (or excreted) from the fish's body, and a portion of this quantity may be metabolically transformed into another chemical compound. Net trophic transfer efficiency is the efficiency with which the contaminant in the food ingested by the predator is retained by the predator, including the losses due to elimination and metabolic transformation [5]. Two studies that have measured the rate of these losses of individual polychlorinated biphenyl (PCB) congeners in fish included the investigations by Niimi and Oliver [6] and Buckman et al. [7]. Some PCB congeners have been shown to be considerably more toxic than others [8,9], and therefore estimation of net trophic transfer efficiencies for individual PCB congeners would be especially valuable for risk assessment purposes.

* To whom correspondence may be addressed (cmadenjian@usgs.gov).
Published on the Web 10/29/07.

Gobas et al. [10] and Thomann [11] proposed that gross trophic transfer efficiency of organic contaminants to fish from their prey is a function of the contaminant's lipid affiliation, as measured by the octanol–water partition coefficient, K_{OW}. Thomann [11] fitted an empirical relationship to estimates of gross trophic transfer efficiencies to fish from their prey for various organic contaminants as a function of log K_{OW}. According to the fitted relationship, gross trophic transfer efficiency remained at a high level when log K_{OW} ranged from 5 to 6 but then decreased exponentially as log K_{OW} increased from 6 to 10.

However, several studies have indicated that both net and gross trophic transfer efficiencies of PCB congeners to fish from their prey either are not influenced by log K_{OW} or are influenced by log K_{OW} in a way counter to the relationship postulated by Thomann [11]. Burreau et al. [12] reported, based feeding rainbow trout (*Oncorhynchus mykiss*) contaminated with several different organochlorines to northern pike (*Esox lucius*) in the laboratory, that gross trophic transfer efficiency for PCB congeners slightly increased as log K_{OW} increased from 5.7 to 7.0. Buckman et al. [7] estimated that gross trophic transfer efficiency of PCB congeners to juvenile rainbow trout from their pelleted food slightly increased as log K_{OW} increased from 5.0 to 6.5 and then slightly decreased as log K_{OW} further increased from 6.5 to 8.0. Estimates of net trophic transfer efficiency of PCB congeners to Atlantic salmon (*Salmo salar*) from their pelleted food exhibited no significant relationship with log K_{OW} as it ranged from 5.2 to 7.8 [13]. Madenjian et al. [4] calculated that net trophic transfer efficiency of PCB congeners to Lake Michigan coho salmon (*Oncorhynchus kisutch*) from their prey increased slightly as log K_{OW} increased from 6.2 to 6.6 but did not appreciably change as log K_{OW} further increased from 6.6 to 7.9. Thus, the Thomann [11] relationship was not appropriate for describing trophic transfer efficiency of PCB congeners to northern pike, rainbow trout, Atlantic salmon, or coho salmon.

The lake whitefish (*Coregonus clupeaformis*) fishery represents one of the most important commercial fisheries in the Great Lakes [14]. During 1975–1995, an average of approximately 7,000 metric tons of lake whitefish have been harvested each year from the Great Lakes for human consumption. Given the importance of this fishery, estimates of trophic transfer efficiency of contaminants to lake whitefish from their prey would be valuable in assessing the risk to humans of consuming lake whitefish under various environmental contamination scenarios. To date, trophic transfer efficiencies for PCB congeners in lake whitefish have not been studied.

The aim of the present study was to estimate, in the laboratory, the net trophic transfer efficiencies of various PCB congeners to lake whitefish from their food. In addition, the applicability of previously mentioned relationship developed by Thomann [11] to net trophic transfer efficiencies for lake whitefish was determined. Finally, results from the present study were compared with results from previous studies.

MATERIALS AND METHODS

Laboratory experiment

The laboratory experiment was conducted from July 23 through December 5, 2003. Lake whitefish were kept in iron-filtered well water at the Great Lakes Science Center (Ann Arbor, MI, USA) in four 2,380-L circular tanks that had a water exchange rate of 15 L/min. Water temperature ranged from 11 to 13.6°C over the course of the experiment. Tanks 1, 2, 3, and 4 received lots of 25, 29, 25, and 25 lake whitefish, respectively. Each lake whitefish was weighed at the start of the experiment. In addition, 10, 14, 10, and 10 lake whitefish were sacrificed from tanks 1, 2, 3, and 4, respectively, at the start of the experiment. The sacrificed lake whitefish were frozen and stored at −30°C.

Lake whitefish in each of the four tanks were daily fed thawed rainbow smelt, which had been caught in Lake Erie during 2002, frozen and stored at −30°C. The amount of food placed in each tank was weighed to the nearest 0.1 g. All uneaten food was removed from the tanks each day, air dried for 20 min, and weighed to the nearest 0.1 g. Feeding rates ranged from 0.5 to 0.9% of the lake whitefish body weight per day. At the conclusion of the experiment, each of the 15 remaining lake whitefish in each of the four tanks was weighed and then frozen at −30°C until time of analysis. Additionally, 10 50-fish subsamples of rainbow smelt were stored at −30°C for later analysis. Refer to Madenjian et al. [15] for more details on the laboratory experiment.

PCB determinations

Lake whitefish from the laboratory experiment were grouped by tank and stage of the experiment (start or end). Each of the eight lake whitefish composites and each of the 10 rainbow smelt composites were homogenized in a blender. Polychlorinated biphenyl congener concentrations were determined in each of the composite samples using the negative chemical ionization mass spectrometry procedure outlined by Schmidt [16]. We used a slight modification to this procedure by including a multilayered anthropogenic column to remove oils and some interfering coextractables [17]. We calibrated the instrument using individual congener standards from AccuStandard (New Haven, CT, USA). Concentrations for each of 69 PCB congeners were determined. All samples were spiked with two non-Arochlor congeners (numbers 65 and 166; International Union of Pure and Applied Chemistry, Research Triangle Park, NC, USA). Calibration accuracy was based on the ability to analyze Arochlor standards and obtain the predicted amounts and ratios obtained by Frame et al. [18]. Additional calibration verification was done using the West Coast Fish Studies standard supplied by AccuStandard. Appropriate quality control samples (blanks, matrix spikes, and duplicates) were analyzed to ensure precision and accuracy. Spike recoveries ranged from 93 to 101%.

Table 1. Logarithm of the octanol–water partition coefficient (log K_{OW}) and number of chlorine atoms per molecule for the 40 polychlorinated biphenyl (PCB) congeners included in the present study. Values of log K_{OW} were taken from Hawker and Connell [22]. Numbering of congeners was according to the International Union of Pure and Applied Chemistry (Research Triangle Park, NC, USA) numbering system of PCBs

PCB congener	No. of chlorine atoms per molecule	Log K_{OW}	PCB congener	No. of chlorine atoms per molecule	Log K_{OW}
8	2	5.07	105	5	6.65
17	3	5.25	110	5	6.48
22	3	5.58	118	5	6.74
26	3	5.66	130	6	6.80
28	3	5.67	135	6	6.64
45	4	5.53	141	6	6.82
46	4	5.53	146	6	6.89
48	4	5.78	149	6	6.67
49	4	5.85	156	6	7.18
52	4	5.84	158	6	7.02
66	4	6.20	170	7	7.27
70	4	6.20	174	7	7.11
74	4	6.20	177	7	7.08
84	5	6.04	179	7	6.73
85	5	6.30	180	7	7.36
87	5	6.29	187	7	7.17
91	5	6.13	194	8	7.80
95	5	6.13	195	8	7.56
97	5	6.29	199	8	7.62
99	5	6.39	206	9	8.09

Statistical analyses

We estimated net trophic transfer efficiency, γ, of each of 40 PCB congeners from rainbow smelt to lake whitefish based on our laboratory experiment results (Table 1). Of the 69 PCB congeners examined, 29 of these PCB congeners were not in detectable quantities in either the rainbow smelt or lake whitefish samples, or they coeluted with other PCB congeners. The coelutors were not included in our statistical analyses because we wanted to restrict our investigation of relationships between γ and degree of chlorination and between γ and log K_{OW} to pure chemical compounds. For the cases of PCB congener concentrations in either the rainbow smelt samples or the lake whitefish samples below the detection limit, γ could not be estimated. The 40 congeners included in our analyses consisted of one dichloro congener (8), four trichloro congeners (17, 22, 26, and 28), eight tetrachloro congeners (congeners 45, 46, 48, 49, 52, 66, 70, and 74), 10 pentachloro congeners (congeners 84, 85, 87, 91, 95, 97, 99, 105, 110, and 118), seven hexachloro congeners (congeners 130, 135, 141, 146, 149, 156, and 158), six heptachloro congeners (congeners 170, 174, 177, 179, 180, and 187), three octochloro congeners (congeners

194, 195, and 199), and one nonachloro congener (206). The value of log K_{OW} ranged from 5.07 to 8.09 for the set of 40 PCB congeners (Table 1).

We calculated γ of each of the 40 PCB congeners for each of the four tanks using the equation

$$\gamma = \frac{([PCB_f]W_f) - ([PCB_i]W_i)}{\text{amount of the PCB congener ingested}}$$

where $[PCB_f]$ is the average PCB congener concentration of the lake whitefish in the tank at the end of the experiment, W_f is the average weight of the lake whitefish in the tank at the end of the experiment, $[PCB_i]$ is the average PCB congener concentration of the lake whitefish in the tank at the start of the experiment, W_i is the average weight of the lake whitefish in the tank at the start of the experiment, and amount of the PCB congener ingested refers to the weight of PCB congener ingested, on average, by each lake whitefish in the tank during the course of the experiment. For each PCB congener, we computed the congener's average concentration in the 10 composite samples of rainbow smelt, and we used the average concentration in calculating γ. The estimate of γ was averaged across all four tanks for each of the 40 congeners, and a standard error of the mean value was also calculated for each of the 40 congeners.

The estimate of γ was found to be significantly greater than one for three (congeners 26, 28, and 84) of the 40 PCB congeners. Because values of γ substantially exceeding one can unduly influence the results of statistical relationships between γ and degree of chlorination or log K_{OW}, we did not include congeners 26, 28, and 84 in our statistical analyses.

To determine if degree of chlorination affected γ, one-way analysis of variance (ANOVA) was used to ascertain if mean γ varied significantly with degree of chlorination [4]. We included congeners with four, five, six, seven, and eight chlorine atoms per molecule in the ANOVA; dichloro, trichloro, and nonachloro congeners were not included in the ANOVA because only one or two replicates were available in each of these categories. Each observation in the ANOVA was the value of γ averaged across all four tanks for a particular congener. The one-way ANOVA was followed by a Tukey multiple comparison procedure to determine pairwise differences between mean values of γ. In addition, a two-sample *t* test was used to determine if mean γ for tetrachloro congeners was significantly different from mean γ for congeners with more than four chlorine atoms per molecule.

To determine if log K_{OW} influenced γ, a simple linear regression of log γ as a function of log K_{OW} was performed. Significance of the slope of the regression line was assessed with a *t* test. Because the hypothesis of Thomann [11] was that γ decreased exponentially when log K_{OW} increased from 6 to 10, only congeners with log K_{OW} greater than 6 were included in this regression analysis.

To make our information on the coelutors available to the scientific community, we calculated γ for the coelutors in the same manner that we calculated γ for the 40 PCB congeners that did not coelute. The estimate of γ was averaged across all four tanks for each of the pairs of coelutors, and a standard error of the mean value was also calculated for each of the pairs of coelutors. These estimates are presented in Table S1 (http://dx.doi.org/10.1897/07-274.S1).

RESULTS

Average initial weights of the lake whitefish in the four tanks ranged from 713 to 841 g, whereas average final weights ranged from 796 to 996 g (Table 2). Average food consumption by lake whitefish over the course of the experiment in the four tanks ranged from 559 to 1,010 g. Polychlorinated biphenyl congener concentrations in the lake whitefish ranged from 0.08 to 5.40 ng/g (wet-wt basis) (Table 3). Polychlorinated biphenyl congener concentrations in the rainbow smelt ranged from 0.07 to 2.86 ng/g.

Table 2. Initial and final average weights of lake whitefish used in the 133-d laboratory experiment. Lake whitefish were fed rainbow smelt daily. Also included is the average amount of food eaten by a lake whitefish during the entire course of the experiment

	Average weight of lake whitefish (g)		
Tank no.	Initial	Final	Consumption (g)
1	713	897	1,010
2	736	886	865
3	841	996	928
4	726	796	559

Averaging across all four tanks, estimates of γ ranged from 0.046 to 2.213 (Table 4). Standard errors for these estimates of γ ranged from 0.015 to 0.461. Estimates of γ were highest for the tetrachloro congeners.

Net trophic transfer efficiency, γ, varied significantly with degree of chlorination of the PCB congeners (one-way ANOVA: $F = 3.38$; degrees of freedom [df] = 4, 28; $p = 0.0224$). The mean value of γ for tetrachloro congeners was significantly higher than the mean value of γ for heptachloro congeners (Tukey multiple comparisons; $p < 0.05$). However, no other significant differences among the homolog groups were detected (Tukey multiple comparisons; $p > 0.05$). Mean γ for the tetrachloro congeners was 0.70, whereas mean γ for the higher chlorinated congeners was only 0.45 (Table 4 and Fig. 1); this difference between means was significant (two-sample *t* test: $t = 3.07$; $df = 32$; $p = 0.0044$).

Net trophic transfer efficiency, γ, declined exponentially as log K_{OW} increased from 6 to 8 (Fig. 2). The rate of decline was significantly different from zero ($t = -2.91$; $df = 27$; $p = 0.0072$). According to the fitted curve, γ was equal to 0.60 at $K_{OW} = 6$, and γ was equal to 0.31 at $K_{OW} = 8$ (Fig. 2).

DISCUSSION

Lake whitefish appeared to be unique among fishes in their ability to retain PCB congeners from their food. Unlike other fishes studied, the efficiency with which lake whitefish retained PCB congeners from their food was strongly dependent on the log K_{OW}, with γ declining exponentially as log K_{OW} increased from 6 to 8. In fishes like northern pike, rainbow trout, Atlantic salmon, and coho salmon, trophic transfer efficiency (net or gross) either slightly increased as log K_{OW} increased from 6 to 7 or was unaffected by log K_{OW} as log K_{OW} increased from 5.2 to 7.8. The value of log K_{OW} had, by far, the greatest influence on trophic transfer efficiency of PCB congeners for lake whitefish compared with these other four species of fish. Given this substantial difference between lake whitefish and the other four fish species, a comparison of gut physiology, biochemistry, and toxicokinetics between lake whitefish and rainbow trout, for example, may provide some insights into mechanisms by which PCB congeners are transported across the gut wall in fishes.

We found that γ declined exponentially as log K_{OW} increased from 6 to 8, just as Thomann [11] postulated that gross

Table 3. Initial and final polychlorinated biphenyl (PCB) congener concentrations in lake whitefish used in the 133-d laboratory experiment. Also shown are the PCB congener concentrations in the rainbow smelt fed to the lake whitefish during the experiment

PCB congener	Initial lake whitefish PCB congener concn. (ng/g)				Final lake whitefish PCB congener concn. (ng/g)				Rainbow smelt PCB congener concn. (ng/g)
	Tank 1	Tank 2	Tank 3	Tank 4	Tank 1	Tank 2	Tank 3	Tank 4	
8	0.28	0.31	0.25	0.39	0.27	0.28	0.29	0.36	0.83
17	0.64	0.69	0.64	0.81	0.66	0.65	0.71	0.79	0.22
22	0.54	0.55	0.49	0.65	0.60	0.59	0.62	0.70	1.05
26	0.56	0.62	0.56	0.66	0.60	0.61	0.65	0.68	0.08
28	1.86	1.95	1.83	2.23	2.07	2.07	2.21	2.39	0.33
45	0.30	0.31	0.28	0.34	0.30	0.31	0.34	0.35	0.23
46	0.21	0.22	0.20	0.23	0.21	0.23	0.24	0.25	0.07
48	0.41	0.42	0.39	0.46	0.43	0.43	0.46	0.48	0.68
49	1.99	2.05	1.89	2.24	2.21	2.18	2.38	2.45	0.80
52	4.07	4.23	3.97	4.70	4.82	4.71	5.15	5.40	1.53
66	1.57	1.59	1.48	1.69	1.83	1.77	1.96	1.93	0.83
70	2.69	2.76	2.57	3.01	3.34	3.23	3.49	3.54	1.06
74	0.97	0.97	0.91	1.06	1.13	1.10	1.18	1.20	0.43
84	2.63	2.60	2.22	2.63	3.02	2.90	3.57	3.32	0.53
85	0.85	0.84	0.79	0.89	1.05	1.01	1.09	1.02	0.72
87	1.31	1.20	1.16	1.33	1.63	1.59	1.72	1.67	2.05
91	0.89	0.89	0.87	0.95	1.05	0.99	1.13	1.06	0.48
95	3.90	3.85	3.66	4.20	4.78	4.59	5.07	5.04	1.80
97	1.28	1.29	1.19	1.37	1.60	1.53	1.67	1.58	1.22
99	2.08	2.15	1.89	2.24	2.39	2.33	2.53	2.45	1.27
105	0.78	0.78	0.72	0.81	1.02	0.99	1.05	0.97	0.84
110	2.80	2.75	2.57	2.92	3.58	3.40	3.69	3.51	2.21
118	2.61	2.63	2.39	2.74	3.15	3.02	3.27	3.07	2.86
130	0.30	0.30	0.26	0.29	0.44	0.41	0.44	0.37	0.59
135	0.80	0.80	0.71	0.81	1.01	0.99	1.07	0.94	0.52
141	0.40	0.39	0.34	0.39	0.73	0.67	0.71	0.58	0.93
146	0.91	0.91	0.73	0.93	1.15	1.14	1.23	1.08	1.28
149	2.46	2.46	2.20	2.47	3.20	3.08	3.31	2.85	2.73
156	0.19	0.19	0.18	0.19	0.28	0.26	0.27	0.23	0.26
158	0.26	0.24	0.28	0.22	0.39	0.35	0.36	0.32	0.43
170	0.45	0.45	0.41	0.45	0.77	0.73	0.76	0.60	0.90
174	0.36	0.33	0.30	0.33	0.64	0.58	0.61	0.47	1.07
177	0.41	0.36	0.32	0.36	0.64	0.60	0.61	0.51	0.91
179	0.40	0.41	0.36	0.39	0.57	0.54	0.57	0.49	0.71
180	1.07	1.01	0.93	1.02	1.87	1.76	1.76	1.41	2.13
187	1.80	1.71	1.52	1.70	2.52	2.38	2.49	2.14	2.31
194	0.26	0.27	0.24	0.26	0.37	0.35	0.37	0.30	0.44
195	0.09	0.09	0.08	0.11	0.14	0.23	0.13	0.11	0.18
199	0.53	0.52	0.47	0.52	0.73	0.69	0.72	0.61	0.89
206	0.67	0.67	0.62	0.69	0.71	0.70	0.71	0.67	0.21

trophic transfer efficiency decreased exponentially as log K_{OW} increased from 6 to 10. Our estimate of rate of exponential decrease was −0.33 per unit of log K_{OW}, whereas Thomann [11] postulated that gross trophic transfer efficiency declined at a rate of −0.50 per unit of log K_{OW}. However, the two rates did not significantly differ because the 95% confidence interval for our estimate of rate of decrease, −0.33 ± 0.23, encompassed the Thomann rate of decrease.

If elimination rates of the PCB congeners were very low or did not vary greatly from congener to congener or decreased with increasing log K_{OW}, then we would expect gross trophic transfer efficiency of PCB congeners to lake whitefish from their food to decrease exponentially as log K_{OW} increased from 6 to 10. Another possibility would be that gross trophic transfer efficiencies were relatively high for all the PCB congeners, but elimination and excretion rates increased substantially with increasing log K_{OW}. However, Buckman et al. [7] showed that short-term loss rates (loss rates within 30 d of the last feeding exposure) of the PCB congeners from rainbow trout actually decreased as log K_{OW} increased from 5.2 to 6.5 but did not trend upward or downward when log K_{OW} further increased from 6.5 to 8.0. In addition, long-term loss rates (loss rates after 30 d from the last feeding exposure) were practically negligible for the bulk of the PCB congeners with three or more chlorine atoms per molecule [6,7]. Therefore, unless PCB congener loss rates for lake whitefish were influenced by log K_{OW} in a completely different manner than those observed for rainbow trout, we would expect gross trophic transfer efficiency in lake whitefish to decrease exponentially as log K_{OW} increased from 6 to 10. Perhaps gut uptake of higher chlorinated congeners is enhanced in fishes like rainbow trout, Atlantic salmon, coho salmon, and northern pike, whereas gut uptake of higher chlorinated congeners in fishes like lake whitefish is not enhanced. For a given sized fish, standard metabolic rate has been estimated to be substantially lower in lake whitefish than in fishes such as rainbow trout or coho salmon [15]. Perhaps the apparent lack of enhanced gut uptake of higher chlorinated PCB congeners in lake whitefish is somehow linked with its relatively low standard metabolic rate.

Although the energy density of the lake whitefish decreased slightly over the course of the laboratory experiment [15], this slight decrease in energy density likely had little effect on γ. Madenjian and O'Connor [19] documented a 10% decrease and a 5% increase in the energy density of lake trout (*Sal-*

Table 4. Mean estimates of net trophic transfer efficiency (γ) of polychlorinated biphenyl (PCB) congeners to lake whitefish from their food. Estimates were based on a 133-d laboratory experiment, during which rainbow smelt were fed to lake whitefish. For each congener, γ estimates from all four tanks were averaged to yield the mean estimate. Standard error of the mean is enclosed in parentheses

PCB congener	Mean estimate of γ		PCB congener	Mean estimate of γ	
8	0.046	(0.020)	105	0.448	(0.039)
17	0.540	(0.117)	110	0.584	(0.052)
22	0.155	(0.019)	118	0.347	(0.042)
26	1.707	(0.257)	130	0.312	(0.032)
28	1.684	(0.171)	135	0.697	(0.089)
45	0.300	(0.060)	141	0.399	(0.030)
46	0.785	(0.116)	146	0.345	(0.055)
48	0.143	(0.022)	149	0.419	(0.055)
49	0.773	(0.099)	156	0.425	(0.033)
52	1.001	(0.098)	158	0.363	(0.015)
66	0.690	(0.080)	170	0.399	(0.041)
70	1.079	(0.092)	174	0.293	(0.025)
74	0.813	(0.079)	177	0.336	(0.025)
84	2.213	(0.461)	179	0.316	(0.031)
85	0.483	(0.050)	180	0.418	(0.036)
87	0.314	(0.028)	187	0.440	(0.042)
91	0.660	(0.076)	194	0.309	(0.044)
95	0.939	(0.087)	195	0.402	(0.175)
97	0.444	(0.048)	199	0.304	(0.039)
99	0.551	(0.082)	206	0.657	(0.142)

velinus namaycush) fed at a low feeding rate and an intermediate feeding rate, respectively, over the course of the laboratory experiment. Yet the mean estimates of γ for total PCBs were very similar for the two different feeding rates: 0.87 for the low feeding rate and 0.91 for the intermediate feeding rate [20]. For the high feeding rate, energy density increased 28% over the course of the experiment [19], and the mean estimate of γ was 0.71 [20]. This relatively low value of γ was attributed to decreased efficiency to retain PCBs at relatively high feeding rates [20]. Similarly, laboratory and field studies have indicated that Chinook salmon (*Oncorhynchus tshawytscha*) have a reduced efficiency to retain PCBs from their food at relatively high feeding rates [21].

Reasons for our estimates of γ exceeding a value of 1.5 for three of the PCB congeners were not clear. Perhaps our subsampling of the rainbow smelt for PCB determinations was

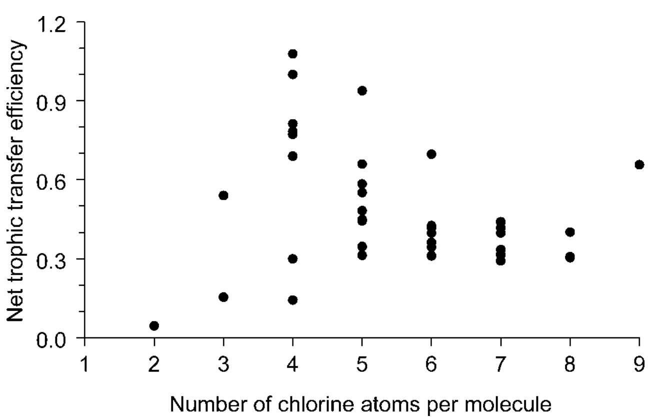

Fig. 1. Estimate of net trophic transfer efficiency (γ) of a polychlorinated biphenyl (PCB) congener to lake whitefish from their food as a function of the number of chlorine atoms per molecule of the PCB congener. Estimates were based on a 133-d laboratory experiment, during which lake whitefish were fed rainbow smelt.

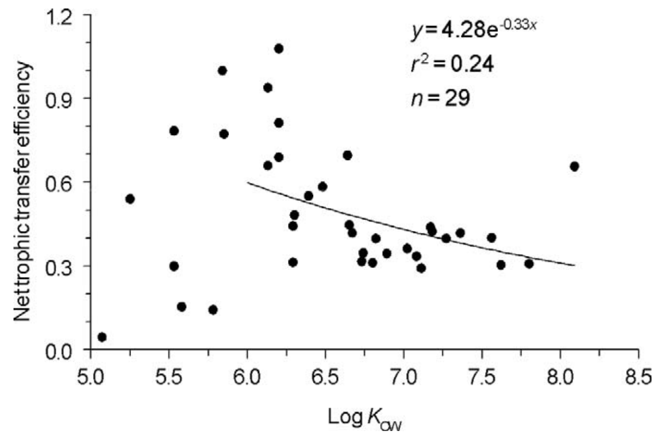

Fig. 2. Estimate of net trophic transfer efficiency (γ) of a polychlorinated biphenyl (PCB) congener to lake whitefish from their food as a function of the log K_{OW} of the PCB congener. Estimates were based on a 133-d laboratory experiment, during which lake whitefish were fed rainbow smelt. Fitted regression line for congeners with log K_{OW} greater than 6 is also displayed.

not representative of the average concentrations of these three PCB congeners in the rainbow smelt actually fed to the lake whitefish during the experiment. Perhaps the degree of matrix interference differed between the lake whitefish and rainbow smelt samples for these three PCB congeners.

CONCLUSION

Net trophic transfer efficiency, γ, of PCB congeners to lake whitefish from their food decreased exponentially as log K_{OW} increased from 6 to 8. In addition, lake whitefish were substantially more efficient at retaining the tetrachloro congeners from their food as they were at retaining the higher chlorinated congeners from their food. Our results, in conjunction with other studies, suggested that gut uptake of the pentachloro and higher chlorinated congeners was possibly more enhanced in fishes like rainbow trout than in fishes like lake whitefish.

SUPPORTING INFORMATION

Table S1. Mean estimates of net trophic transfer efficiency (γ) of pairs of polychlorinated biphenyl (PCB) coeluting congeners to lake whitefish from their food. Estimates were based on a 133-d laboratory experiment, during which rainbow smelt were fed to lake whitefish. For each pair of coeluting congeners, γ estimates from all four tanks were averaged to yield the mean estimate.

Found at DOI: 10.1897/07-274.S1 (49 KB PDF).

Acknowledgement—We thank Ian Lane for his assistance in the laboratory. Lawrence Burkhard and Jacqueline Savino provided comments for improving the manuscript. This work was funded by The Great Lakes Fishery Trust through Grant Award 2001.129. This article is Contribution 1451 of the US Geological Survey Great Lakes Science Center and is Great Lakes Environmental Research Laboratory Contribution 1447.

REFERENCES

1. Madenjian CP, Carpenter SR, Rand PS. 1994. Why are the PCB concentrations of salmonine individuals from the same lake so highly variable? *Can J Fish Aquat Sci* 51:800–807.
2. Madenjian CP, Elliott RF, Schmidt LJ, DeSorcie TJ, Hesselberg RJ, Quintal RT, Begnoche LJ, Bouchard PM, Holey ME. 1998. Net trophic transfer efficiency of PCBs to Lake Michigan coho salmon from their prey. *Environ Sci Technol* 32:3063–3067.

3. Calabrese EJ, Baldwin LA. 1993. *Performing Ecological Risk Assessments.* Lewis, Boca Raton, FL, USA.
4. Madenjian CP, Schmidt LJ, Chernyak SM, Elliott RF, DeSorcie TJ, Quintal RT, Begnoche LJ, Hesselberg RJ. 1999. Variation in net trophic transfer efficiencies among 21 PCB congeners. *Environ Sci Technol* 33:3768–3773.
5. Jackson LJ, Schindler DE. 1996. Field estimates of net trophic transfer of PCBs from prey fishes to Lake Michigan salmonids. *Environ Sci Technol* 30:1861–1865.
6. Niimi AJ, Oliver BG. 1983. Biological half-lives of polychlorinated biphenyl (PCB) congeners in whole fish and muscle of rainbow trout (*Salmo gairdneri*). *Can J Fish Aquat Sci* 40:1388–1394.
7. Buckman AH, Brown SB, Hoekstra PF, Solomon KR, Fisk AT. 2004. Toxicokinetics of three polychlorinated biphenyl technical mixtures in rainbow trout (*Oncorhynchus mykiss*). *Environ Toxicol Chem* 23:1725–1736.
8. Van den Berg M, Birnbaum L, Bosveld ATC, Brunström B, Cook P, Feeley M, Giesy JP, Hamberg A, Hasegawa R, Kennedy SW, Kubiak T, Larsen JC, van Leeuwen FXR, Liem AKD, Nolt C, Peterson RE, Poellinger L, Safe S, Schrenk D, Tillitt D, Tysklind M, Younes M, Wærn F, Zacharewski T. 1998. Toxic equivalency factors (TEFs) for PCBs, PCDDs, and PCDFs for humans and wildlife. *Environ Health Perspect* 106:775–792.
9. Ahlborg UG, Becking GC, Birnbaum LS, Brouwer A, Derks HJGM, Feeley M, Golor G, Hamberg A, Larsen JC, Liem AKD, Safe SH, Schlatter C, Wærn F, Younes M, Yrjänheikki E. 1994. Toxic equivalent factors for dioxin-like PCBs. *Chemosphere* 28:1049–1067.
10. Gobas FAPC, Muir DCG, Mackay D. 1988. Dynamics of dietary bioaccumulation and faecal elimination of hydrophobic organic chemicals in fish. *Chemosphere* 17:943–962.
11. Thomann RV. 1989. Bioaccumulation model of organic chemical distribution in aquatic food chains. *Environ Sci Technol* 23:699–707.
12. Burreau S, Axelman J, Broman D, Jakobsson E. 1997. Dietary uptake in pike (*Esox lucius*) of some polychlorinated biphenyls, polychlorinated naphthalenes, and polybrominated diphenyl ethers administered in natural diet. *Environ Toxicol Chem* 16:2508–2513.
13. Isosaarl P, Kiviranta H, Lie Ø, Lundebye AK, Ritchie G, Vartiainen T. 2004. Accumulation and distribution of polychlorinated dibenzo-*p*-dioxin, dibenzofuran, and polychlorinated biphenyl congeners in Atlantic salmon (*Salmo salar*). *Environ Toxicol Chem* 23:1672–1679.
14. Ebener MP. 1997. Recovery of lake whitefish populations in the Great Lakes. *Fisheries (Bethesda)* 22:18–22.
15. Madenjian CP, O'Connor DV, Pothoven SA, Schneeberger PJ, Rediske RR, O'Keefe JP, Bergstedt RA, Argyle RL, Brandt SB. 2006. Evaluation of a lake whitefish bioenergetics model. *Trans Am Fish Soc* 135:61–75.
16. Schmidt LJ. 1997. Method for analysis of total PCBs and PCB congeners (full suite) and transnonachlor for gas chromatography/negative chemical ionization single ion mass spectrophotometry. Vol II of Lake Michigan Mass Balance (LMMB) study methods compendium. Organic and mercury methods. EPA-905-R-97-012b. U.S. Environmental Protection Agency, Great Lakes National Program Office, Chicago, IL.
17. U.S. Environmental Protection Agency. 1999. Method 1668, revision A: Chlorinated biphenyl congeners in waters, soil, and tissue by HRGC/HRMS. EPA-821-R-00-002, Washington, DC.
18. Frame GM, Cochran JW, Boewadt SS. 1996. Complete PCB congener distributions for 17 Arochlor mixtures determined by 3 HRGC systems optimized for comprehensive, quantitative, congener specific analysis. *J High Resolut Chromatogr* 19:657–668.
19. Madenjian CP, O'Connor DV. 1999. Laboratory evaluation of a lake trout bioenergetics model. *Trans Am Fish Soc* 128:802–814.
20. Madenjian CP, O'Connor DV, Nortrup DA. 2000. A new approach toward evaluation of fish bioenergetics models. *Can J Fish Aquat Sci* 57:1025–1032.
21. Madenjian CP, O'Connor DV, Chernyak SM, Rediske RR, O'Keefe JP. 2004. Evaluation of a chinook salmon (*Oncorhynchus tshawytscha*) bioenergetics model. *Can J Fish Aquat Sci* 61:627–635.
22. Hawker DW, Connell DW. 1988. Octanol-water partition coefficients of polychlorinated biphenyl congeners. *Environ Sci Technol* 22:382–387.