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PCB Food Web Dynamics Quantify Nutrient and Energy Flow in Aquatic Ecosystems

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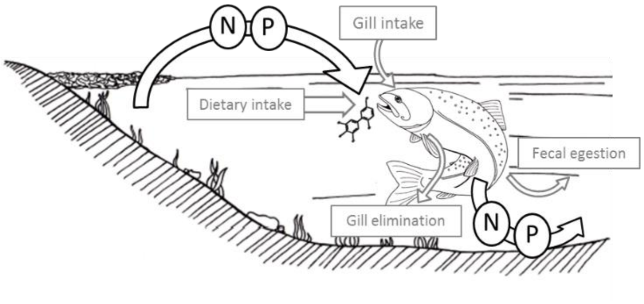

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ABSTRACT. Measuring *in situ* nutrient and energy flows in spatially and temporally complex aquatic ecosystems represents a major ecological challenge. Food web structure, energy and nutrient budgets are difficult to measure, and it is becoming more important to quantify both energy and nutrient flow to determine how food web processes and structure are being modified by multiple stressors. We propose that polychlorinated biphenyl (PCB) congeners represent an ideal tracer to quantify *in situ* energy and nutrient flow between trophic levels. Here, we demonstrate how an understanding of PCB congener bioaccumulation dynamics provides multiple direct measurements of energy and nutrient flow in aquatic food webs. To demonstrate this novel approach, we quantified nitrogen (N), phosphorus (P) and caloric turnover rates for Lake Huron lake trout, and reveal how these processes are regulated by both growth rate and fish life history. Although minimal nutrient recycling was observed in young growing fish, slow growing, older lake trout (> 5 yr) recycled an average of 482 Tonnes·yr^{-1} of N, 45 Tonnes·yr^{-1} of P and assimilated 22 TJ yr^{-1} of energy. Compared to total P loading rates of 590 Tonnes·yr^{-1}, the recycling of primarily bioavailable nutrients by fish plays an important role regulating the nutrient states of oligotrophic lakes.

Introduction:

Anthropogenic climate change, chemical pollution, nutrient loading, and habitat degradation are some of the most critical factors simultaneously affecting aquatic ecosystems. These multiple stressors can act synergistically resulting in a myriad of unpredictable responses causing aquatic food webs to be irreparably altered. These perturbations are often enhanced by invasive species[1] and can lead to declining fish abundances and condition, changes in reproductive success[2], and potentially lead to food web contractions and regime shifts[3-4]. While it is possible to estimate the effects of environmental and anthropogenic stressors on fish ecology and physiology[5-8], as well as identify changes in resource exploitation by fish through gut contents and stable isotope analyses[9-10], there are currently no methods to directly measure individual-based nutrient and energy flows in food webs[11]. To achieve such measurements it is essential to be able to quantify individual, *in situ* fish consumption rates.

Quantifying fish consumption rates is critical to understanding food web dynamics because fish have been identified as both sinks[12] and vectors of essential nutrients and energy transport[13]. Fish communities play a critical role regulating the transport and fate of nutrients in aquatic ecosystems as they are an important part of the overall nutrient pool[12]. Understanding nutrient cycling and transport in biota is vital for predicting ecosystem responses to issues such as eutrophication, species invasions and setting fisheries quotas.

The importance of quantifying fish consumption rates has long been recognized. Species-specific bioenergetics models incorporating growth, metabolic and waste processes have been developed for a suite of aquatic species, both juvenile and adult, starting with bluegills in 1974[14]. As of 2000, papers being published a year on bioenergetics modeling have increased rapidly[15]. These models rely on both laboratory and field data to estimate average consumption rates of different age cohorts of fish[16]. Validations of bioenergetics models, however, generally tend to demonstrate a poor fit between model predicted and lab or field data[15]. Thus, efforts to complete hypothesis based testing of individual model parameters will serve to improve model structure and performance[15]. Further, bioenergetics modelling efforts tend towards population based predictions of predator demand rather than assessing individual based responses to ecosystem perturbations[11,17]. Similarly, the mass-balance approach is incorporated into Ecopath, Ecosim, and Ecospace model estimates of consumption and trophic interactions[18]. Again, however, these are population-wide estimates with a Bayesian resampling approach to estimating uncertainty[18] without tracking individual responses within populations.

Chemical tracer mass balance approaches using Mercury and Cesium[19,20] have also provided alternative methods of calculating fish consumption rates. However, these approaches are limited as singular metrics of dietary consumption and do not necessarily track similar environmental processes. As food webs are temporally and spatially complex[21], there is need for a method that directly quantifies fish consumption rates and provides statistical power through multiple repeatable metrics while tracking fish bioenergetics responses to environmental change.

This study proposes the use of persistent organic pollutants (POPs) as metrics to quantify nutrient and energy flow within aquatic food webs. POPs, such as polychlorinated biphenyls (PCBs), are globally ubiquitous pollutants that span a wide range of chemical hydrophobicities[22] and many congeners are highly resistant to environmental and biological degradation[23,24]. These chemical properties regulate their bioaccumulation in fish[22], with the fraction of accumulation from dietary versus aqueous sources ranging from 70% for less hydrophobic congeners ($\log K_{OW} \leq 6.5$) to 100% for increasingly hydrophobic congeners[25]. Furthermore, elimination rates of the more hydrophobic congeners ($\log K_{OW} > 6.5$) are very low resulting in long chemical half-lives with respect to the life span of fish[26]. Therefore, the body burden of super-hydrophobic congeners (those with $\log K_{OW} > 6.5$) represents a proxy of the total amount of food a fish has consumed in its lifetime. Thus, the kinetics of PCB congeners in aquatic consumers have the potential to provide an *in-situ* repeatable method to quantify the total mass of food consumed over the duration of a fish's life. Therefore persistent hydrophobic chemicals can be used as multiple independent markers to directly measure nutrient and energy flow through the upper trophic levels of food webs.

This study investigates (1) the use of PCB bioaccumulation dynamics to develop quantitative measurements of both nutrient uptake and loss as well as the energy consumed over a fish's lifespan as compared with previous model prediction methods, and, (2) quantify the relative importance of fish for nutrient recycling in aquatic systems.

Experimental:

Sample Processing

Lake trout (*Salvelinus namayacush;* n = 195), rainbow smelt (*Osmerus mordax;* n = 34), round goby (*Neogobius melanostomus;* n = 27), alewife (*Alosa pseudoharengus;* n = 8), and whitefish species (*Coregonus artedi* and *Coregonus hoyi;* n = 54) were collected from the Canadian waters of the Main Basin, Georgian Bay, and North Channel regions of Lake Huron throughout the summers of 2010, 2011, and 2012. Fish were collected by overnight gill nets set by the Upper Great Lakes Unit of the Ontario Ministry of Natural Resources. At each site a total of 18 nets were set, and each net consisted of 15m panel of (32mm) mesh and a 25 m panel of 38 mm mesh followed by 50m panels of 51, 64, 76, 89, 102, 114 and 127 mm meshes. Length and weight measurements were taken, sex was determined, and otoliths and gut tracts removed, then samples were placed on dry ice. Frozen samples were transported back to the Great Lakes Institute for Environmental Research (GLIER) and stored at -25 ^{o}C until processing.

Sample processing included homogenization of whole fish samples and the measurement of whole body lipid contents. Moisture contents were obtained by drying approximately 0.5 g of homogenate for 24 hours. Individual PCB congener concentrations and lipid contents were determined using the microextraction method described by Daley et al.[27] In brief, 0.5 g of whole body homogenate was ground with 15 g of sodium sulfate using a glass mortar and pestle, and then wet packed into a glass chromatography column containing 15 mL of a 50 : 50 hexane(Hex):Dichloromethane(DCM) (*v*/*v*) extraction mixture, along with 35 ng of a PCB 34 extraction performance recovery standard. After solvent elution, an additional 15 mL of Hex:DCM was added to extract the homogenate. Sample extracts were then evaporated under vacuum to ~2 mL, and then diluted to 10 mL with hexane in a volumetric flask. Neutral lipid content was determined gravimetrically using 1 mL of this solution[28]. Six grams of Florisil topped with approximately 1 g of sodium sulfate was then used for sample clean up with 50 mL hexane wash. The final extract was evaporated under vacuum to <1 mL and brought to a final volume of 1 mL with iso-octane for analysis by gas chromatography-electron capture detector (GC-ECD)[29]. All samples were analyzed for the following PCB congeners (IUPAC #): 18/19, 31/28, 33, 52, 49, 44, 74, 70, 95, 101, 99, 87, 110, 151/82, 149, 118, 153, 105/132, 138, 158, 187, 183, 128, 177, 156/171, 180, 191, 170, 199, 195/208, 194, 205, 206, and 209.

A method blank and an in house reference tissue homogenate of Detroit River carp were extracted simultaneously as quality assurance for every set of 6 sample extractions. All sum PCB concentrations quantified in the reference tissue were in compliance with the Great Lakes Institute for Environmental Research organic analytical laboratory's quality assurance guidelines (mean ± 2 standard deviations (SD)). Recoveries of the internal standard averaged 89% ± 1% (Standard Error; n = 195), and sample concentrations were not recovery corrected.

Gut content analyses were performed using the Ontario Ministry of Natural Resources protocol. Contents of the gut were removed and food items were identified by using calcified structures such as otoliths that are generally resistant to digestion. Prey items were then enumerated and species proportions calculated using the number of each prey item obtained.

Consumption Estimates

One of the major assumptions of the PCB approach proposed in this paper is that biotransformation and depuration mechanisms do not contribute significantly to the whole body elimination of the super hydrophobic congeners being used as food web tracers. All metabolizable congeners were removed from the analyses to ensure no biotransformation was occurring[34]. A review of literature estimates of elimination rates of PCB congeners by fish demonstrated that congeners with a $\log K_{OW}$ greater than 6.5 did not demonstrate significant elimination (see Fig. 1.[35-40]). Furthermore, the non-significant elimination rates for these congeners resulted in a t_{95}, or time to steady state, vastly exceeding the life expectancy of the organism. Therefore, the total body burden of any one of these super-hydrophobic congeners represents an individual's lifetime of food consumption.

Amounts of nitrogen and phosphorus recycled were calculated using the concentrations of PCB congeners in the whole fish sample. First, concentration data were converted to mass values. The amount of each PCB congener ingested was then calculated according to equation (1).

$$(1)\ \textit{Amount } PCB_i \textit{ ingested [ng]} = m_{PCB_i} \times f_{PCB_i} \times \left(E_{d,PCB_i}\right)^{-1}$$

where PCB_i is the chosen PCB congener, m_{PCB_i} is the mass of PCB_i in the consumer (in ng), E_{d,PCB_i} is the chemical assimilation efficiency for PCB_i in food (prey), and f_{PCB_i} is the fraction of PCB_i mass which is accumulated through dietary uptake as opposed to gill intake (Table S1). Using the results from the gut content analyses (Figure S2), the number of smelt, round goby and other fish consumed were calculated according to equation (2)

$$(2)\ number\ of\ fish\ consumed = \left(\frac{Amount\ of\ PCB_i\ ingested}{PCB_{i,prey}}\right) \times p_{prey}$$

where amount of PCB_i ingested is calculated using equation (1), $PCB_{i,\,prey}$ is the average mass (ng) of PCB_i in the prey species (smelt, round goby, or other), and p_{prey} is the proportion of diet made up of that prey species (where proportion of smelt, round goby, and other fish consumed by lake trout were, respectively, 0.88, 0.075, and 0.045 for the Main Basin of Lake Huron, 0.77, 0.1, and 0.13 for the Georgian Bay, and 0.98, 0.015, and 0.005 for the North Channel). Consumption estimates were then compared to consumption estimates presented in Stewart et al.[16] and Pazzia et al.[20] by extrapolating their estimates to include 13 year old fish using the equations provided in their work.

Nitrogen and Phosphorus Recycling Estimates

Determination of nitrogen content was conducted in the Chemical Tracers laboratory at GLIER using a continuous-flow isotope ratio mass spectrometer (Finnigan MAT Deltaplus; Thermo

Finnigan, San Jose, California) on freeze dried homogenates (Labconco co., Kansas City Missouri) which had been ground using mortar and pestle, and then lipid extracted using chloroform-methanol[29].

Total mg of nitrogen was subsequently calculated from dry weight (g) according to equations 3 and 4.

$$(3)\ Dry\ weight[g]\ (dw) = ww - ww\left(\frac{\%moisture}{100}\right)$$

$$(4)\ N\ [mg] = \left(\left(\frac{\%N}{100}\right) \times dw\right) \times 1000$$

where ww is the wet weight of the fish. The amount of phosphorus was then estimated using the P:N ratio of 1:10.6 for wild caught fish[30]. Total calories in each diet item were calculated using fish energy densities[31].

Using the calculated mass of N, the total amount of N ingested by each lake trout was determined according to equation 5.

$$(5)\ N\ ingested\ [mg] = \sum N_{prey} \times number\ of\ fish\ consumed_{prey}$$

where N_{prey} is the average amount of nitrogen (mg) in the prey fish calculated using equation (4), and the number of fish $consumed_{prey}$ by a lake trout was estimated using equation (2). This was then summed across all prey species. Both P and calories ingested were calculated in a similar manner, where P $(mg)_{prey}$ was estimated using a P:N ratio of 1:10.6[30], and calories in prey fish were calculated using energy densities[2]. Finally, mass of N recycled was calculated according to equation 6.

$$(6)\ N\ recycled\ [mg] = N_{ingested} - N_{lake\ trout}$$

where $N_{\text{lake trout}}$ (mg) was calculated using equation (4), and N_{ingested} (mg) was calculated using equation (5). The mass of P recycled was calculated in a similar manner.

Data analysis

Growth rates of Lake Huron lake trout were calculated using the von Bertalanffy (VBL) growth rate model comparing total length and age (equation 7)

$$(7) \quad L_t = L_\infty \left(1 - e^{-k(t-t_0)}\right)$$

where t is lake trout age (yr), L_t is the total length (cm) of the fish at time t, L_∞ is the asymptotic length (cm), and k the growth coefficient (yr^{-1}). The model was calculated using a value of $t_0 = 0$, for the theoretical age at a total length of 0, an assumption validated for whitefish[32], another salmonid, and used for lake trout[33]. Calculations of the VBL growth models were done using the non-linear regression module of SYSTAT (SYSTAT 11). Multiple iterations were done to achieve optimal model fit. The square of the correlation coefficients between observed and predicted values were used to calculate the coefficient of determination (r^2) values for the VBL growth models. Individual growth rates ($\% \cdot year^{-1}$) were obtained by equation 8.

$$(8) \quad \textit{Growth rate } (\% \cdot year^{-1}) = \left(\frac{w}{w_t}\right) \times ln\left(\frac{w_t}{w_{t+1}}\right) \times 100$$

where w is the measured weight of the individual, w_t the von Bertalanffy predicted weight at age t, and w_{t+1} the von Bertalanffy predicted weight at age t+1.

Results & Discussion:

A unique aspect of using PCBs as markers of individual consumption rates is their potential to offer multiple, repeatable metrics for calculating consumption dynamics in individual fish. To demonstrate the power of the PCB approach, we used an ANOVA to compare congener-specific consumption estimates for the 15 most abundant congeners and found no significant differences among the 9 congeners with $\log K_{OW} > 6.5$ ($p > 0.15$). This lack of significant differences demonstrates that the measured consumption rates are not chemical dependent, hence any of these highly hydrophobic congeners represent tracers of prey consumption. For our purposes, we chose PCB 153, a highly recalciatrant and ubiquitous PCB congener that is commonly monitored in trophic magnification studies[41,42], as well as other contaminant ecology studies[43,44]. Moreover, the similar variability among the congeners further demonstrates that each congener is tracking common bioaccumulation processes (Figure 2). This correspondence in individual variability and bioaccumulation rates among congeners confirms that super-hydrophobic PCB congeners offer multiple, repeatable metrics for calculating consumption dynamics in fish.

Quantifying the consumption rates of top predator in aquatic ecosystems is essential for understanding pollutant and nutrient trophodynamics and multiple approaches have been developed to generate such consumption estimates. For instance, bioenergetics studies have used sub-models of physiological characteristics such as metabolism, growth, excretion, and reproduction to develop consumption estimates for age cohorts within a population[14,16,45], while more empirical approaches have used Mercury (Hg) and Cesium-137 (^{137}Cs) dynamics[19,20]. Figure 3 compares fish consumption estimates using the PCB 153 method presented here with estimates modeled by Stewart et al.[16] for Lake Michigan lake trout, and by ^{137}Cs estimates observed by Pazzia et al.[20] for Lake Ontario lake trout. Calculations of maximum consumption (C_{max}) provided in Stewart et al.[16] are also included in Figure 3 using temperature and weight data obtained from the present study. As observed in Figure 3, the PCB model developed in the current study provides consumption estimates below those of C_{max}, and similar to those obtained or estimated from the other studies or models. The PCB method, however, provides direct measurement of individual-based consumption, using concentrations observed in individual fish. As Figure 3 demonstrates, there is considerable individual variability in consumption within a population and the PCB method offers greater resolution as to the causes of these individual-level differences.

The PCB method not only provides a way of calculating individual consumption estimates, but provides a foundation for estimating nitrogen and phosphorus recycling by individual organisms. Estimates of the lifetime nitrogen (N) and phosphorus (P) recycled by lake trout (*Salvelinus namaycush*) based on PCB 153 accumulation dynamics revealed a power relationship, where the mass of N and P recycled by fish increased with age (Figure 4). As the fish reached the maximum asymptotic length predicted by the von Bertalanffy (VBL) growth model, the mass of recycled nutrients increased exponentially. Specifically, as growth rates slow to this asymptote, the majority of consumed prey energy and nutrients will be turned over via metabolic respiration rather than assimilated into new somatic growth. Therefore these older individuals become increasingly important sources of nutrient recycling. The relationship between nutrient recycling and fish age and size is further resolved by examining fish growth rates. Individual growth rates ($\% \cdot \text{year}^{-1}$) as a function of fish age (Figure 4, d), indicates that lake trout ≥ 5 years of age had individual growth rates below 50% yr^{-1}. At this time in their life history, these upper age cohorts become nutrient sources through recycling rather than net nutrient sinks. The importance of older fish regarding nutrient recycling increases exponentially as their growth rates continue to decrease with age.

In one year, a single 13 year old lake trout from Lake Huron will have consumed 65 MJ of energy and will have recycled 1441 g of N and 136 g of P. If fish population age structure estimates are made using the yearly stocking levels of 4.3×10^6 yearlings with 40% mortalities/year[46] and assuming a simple exponential decay model, then over a one year period, in total, the lake trout population between 5 and 13 years of age (estimated at 1.7×10^6 individuals; capped at 13 as that is the oldest fish captured in the study) will have recycled 482 Tonnes of N, 45 Tonnes of P, and have acquired 22 TJ of energy. This compares to zebra (*Dreissena polymorpha*) and quagga (*Dreissena bugensis*) mussels that are estimated to divert up to 20 Tonnes of P in Lake Huron's Saginaw Bay region and are also associated with the near-shore shunt in Great Lakes ecosystems[47]. Total annual P loads to Lake Huron are estimated to be 590 Tonnes and the results of our study indicate that lake trout can recycle up to 7.6% of this total load. However, it must be emphasized that much of the phosphorus recycled by fish will be in bioavailable form and thus capable of directly supporting a significant proportion of primary production in the lake[48]. Furthermore, nutrient recycling by other fish species will increase this estimate.

Although the impact of fish as a phosphorus sink has been previously documented[12], their importance as nutrient recycling sources has been highly disputed. It is recognized that anadromous species, such as Pacific salmon (*Oncorhynchus* spp), are important sources of nutrients in coastal freshwater communities, acting as biovectors, transporting nutrients accumulated in the marine environment to coastal freshwater systems[49,50]. Studies of larger, piscivorous fish have noted their importance as potential nutrient sources[51,52] whilst others examining smaller, forage fish argue to the contrary[53]. Previous nutrient studies relied on bioenergetics modeling and population density and growth estimates to estimate the relative importance of fish on nutrient recycling in aquatic ecosystems[14,17]. The PCB method developed in the current study provides a novel approach to quantify *in situ* the magnitude of nutrient recycling achieved by fish using multiple, repeatable metrics. In this capacity, top predator species such as lake trout can act as off-shore vectors of these limiting nutrients thereby reducing the impact of the near shore shunt phenomenon as associated with dreissenid mussel establishment[47].

The life history of other large piscivores, however, can prevent these top predators from acting as off-shore nutrient shunts. For instance, Lake Huron is also stocked with Pacific salmonids (*Onchorhynchus* spp) which, in contrast to lake trout, grow more rapidly, have shorter life spans and migrate to tributaries and streams at maturity where they spawn and die[54-56]. This specific reproductive ecology has garnered Pacific salmonids much attention as sources of nutrients and contaminants in spawning tributaries[57-61]. Pacific salmonid spawning migrations generally occur only when individual growth rates decline below 50% per year. These older salmon provide limited contributions to offshore nutrient recycling with the mature senescent individuals exporting a significant mass of nutrients out of the lake[61]. These observations highlight the importance of piscivore life history with respect to nutrient transportation and export in aquatic ecosystems.

While multiple factors have been identified as contributing to the regime shift in Lake Huron[62], there is general agreement the lake is showing definite signs of 'oligotrophication'. The results of this study indicate that older lake trout can play an important role in the nutrient recycling in oligotrophic lakes, systems to which they have well-adapted life histories. The stocking of fish like salmon, however, is predicted to contribute significantly to a decline in bioavailable nutrients, especially in the pelagic compartment. In Lake Huron, however, Pacific salmonid abundances have declined dramatically following the collapse of alewife stocks[46] and older (> 5 yrs) lake trout have become the predominant off-shore salmonid predator population in the lake[63]. Given the differing life-spans, growth rates and reproductive strategies of lake trout relative to stocked Pacific salmonids in the Great Lakes[54], the results of this study demonstrate that lake trout provide a critical ecosystem service by effectively recycling offshore nutrients to enhance food web stability and productivity in highly oligotrophic ecosystems.

Most importantly, this study demonstrates that PCB congeners can be used to quantify *in situ* nutrient and energy flow in aquatic systems. Through the use of this metric, we have been able to demonstrate the importance of fish growth rates and life history on the recycling of essential limiting nutrients in oligotrophic lakes. The ubiquitous nature of PCBs implies that this technique is applicable to aquatic systems across the globe. Moreover, due to the presence of different congeners, PCBs provide repeatable, independent metrics for measuring nutrient and energy flow which will allow us to quantify the effects of multiple environmental and anthropogenic stressors across different aquatic ecosystems.

FIGURES

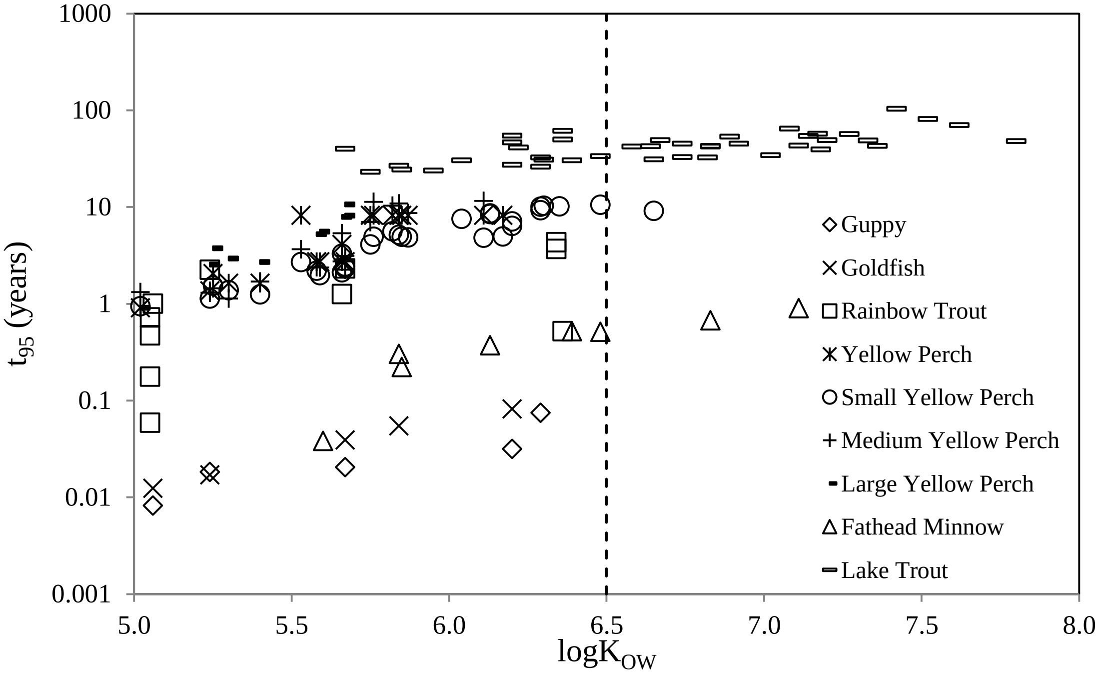

Figure 1: Literature t_{95} estimates across a range of log K_{OW}s. Only those congeners depicting significant elimination are shown[35-40]. The dashed line represents the cut off at a log K_{OW} of 6.5, after which very few studies revealed significant elimination of congeners and these congeners were only in small fish. All estimates presented here are measured t_{95} estimates, with the exception of lake trout which were modeled; hence the elimination rates may not have been significant. However, the elimination rate estimates demonstrate that it takes at least a hundred years for congeners with higher log K_{OW}s to reach steady state.

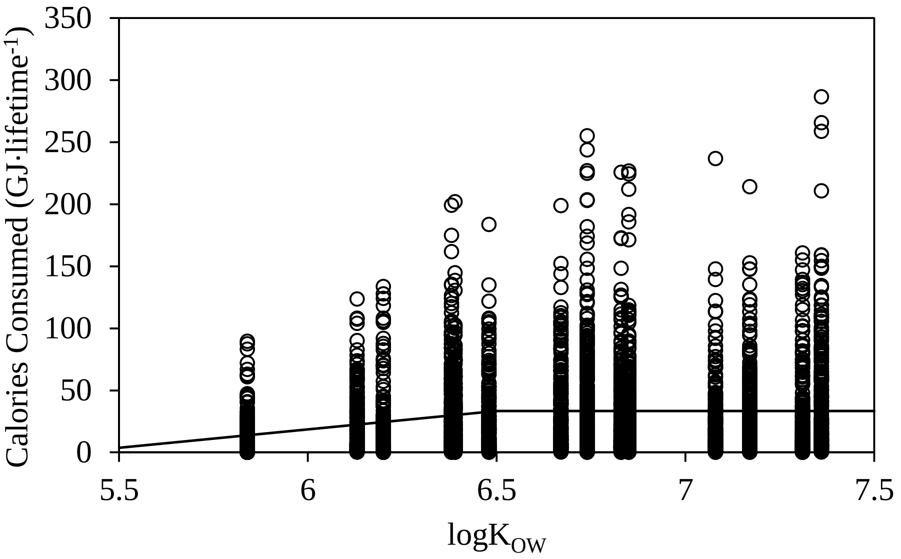

Figure 2. The relationship between calories consumed and logK$_{OW}$ for the 15 most abundant PCB congeners (PCBs 52, 70, 95, 99, 101, 110, 118, 128, 138, 149, 153, 170, 177, 180, 187). Piece-wise linear regressions were completed and no significant slope was found for congeners with logK$_{OW}$>6.5.

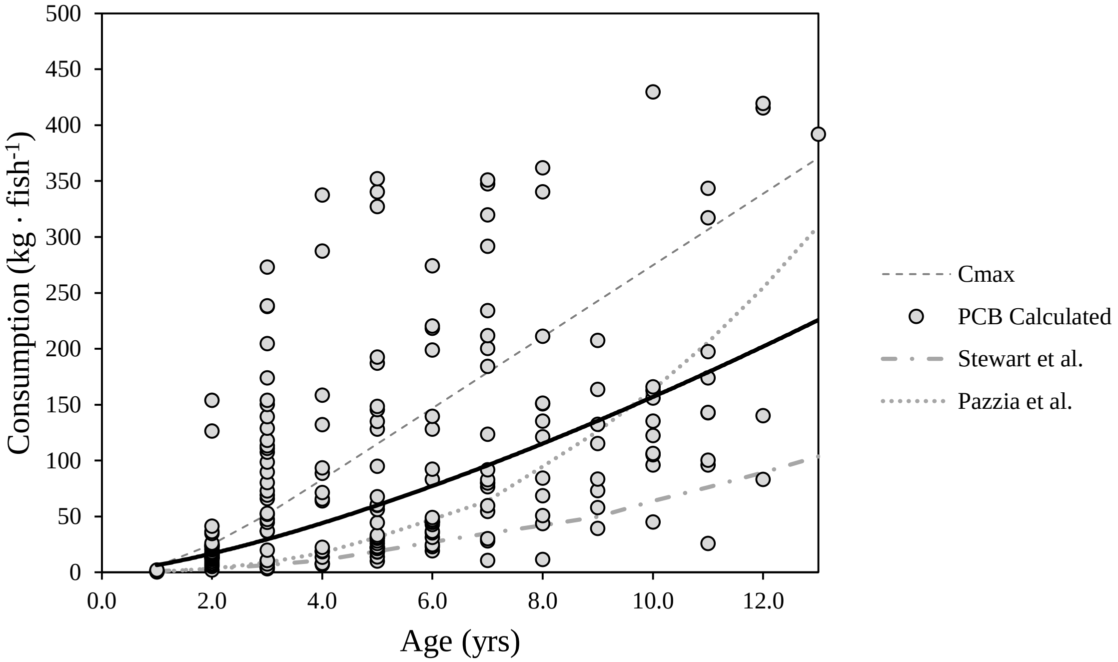

Figure 3: Lifetime prey consumption estimates (kg · fish^{-1}) for lake trout calculated using PCB 153 (grey circles, solid black line of best fit; $y = 6462.8x^{1.4}$ $R^2 = 0.4$), using C_{max} equation (dashed dark grey line) provided in Stewart et al. 1983[16], with temperature and weight values obtained from our study, from extrapolation of bioenergetics estimates by Stewart et al. 1983[16] for Lake Michigan lake trout (dashed-dotted dark grey line), and from extrapolation of ^{137}Cs estimates for Lake Ontario lake trout by Pazzia et al. 2002[20] (dotted grey line).

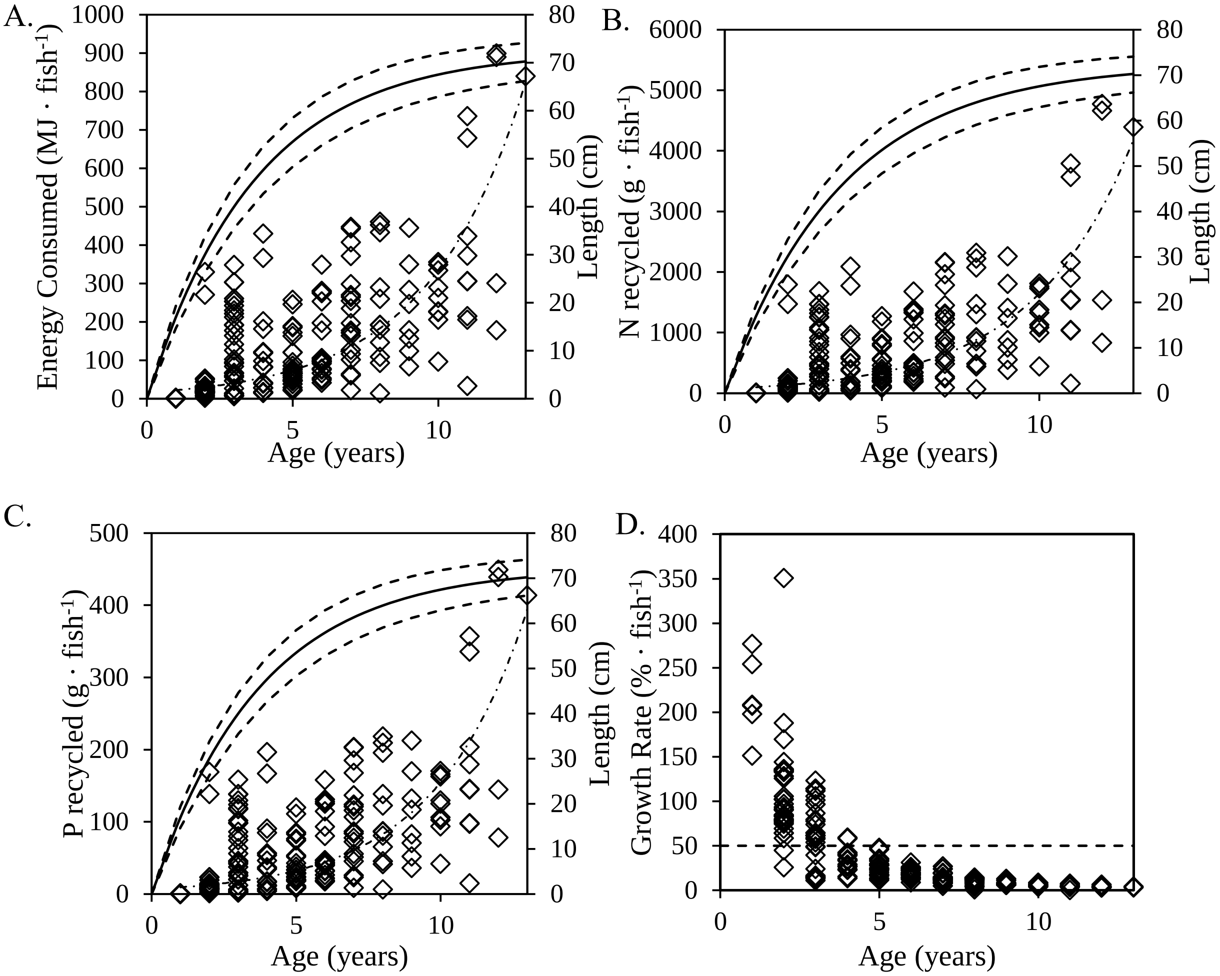

Figure 4: (A-C) Relationships between the amount of (A) energy consumed (MJ · fish) and (B) nitrogen and (C) phosphorus recycled (g · fish) by lake trout. The solid curve in panels A-C represents the von Bertalanffy growth curve for lake trout with dotted lines representing the 95% confidence intervals. The dashed line in panels A-C represent the best fit, non-linear regression ($y = 16.625e^{0.3003x}$, $R^2 = 0.42$) and N ($y = 72.339e^{0.3122x}$, $R^2 = 0.40$) and P ($y = 6.8181e^{0.3122x}$, $R^2 =$

0.40). Panel D provides the relationship between individual lake trout growth rate (% year^{-1}) and age with the dashed line indicating a growth rate of 50% year^{-1}.

ASSOCIATED CONTENT

Supporting Information.

Values for congener $\log K_{OW}$[22], $E_{d,\,PCBi}$[26] and f_{PCBi}[25] used in the calculations of the amount of PCB_i ingested by a fish, results from gut content analyses on Lake Trout. This material is available free of charge via the Internet at http://pubs.acs.org.

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Author Contributions

G.D.H., G.P., and A.M. initiated the study, while K.G.D. provided input on development of the modeling component. All authors were involved in the writing of the paper, but the main contributions were by A.M. All authors discussed the results and consulted on the paper.

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ABBREVIATIONS

PCB, polychlorinated biphenyl; N, nitrogen; P, phosphorus; POPs, persistent organic pollutants; K_{OW}, octanol-water partition coefficient; Hex, hexane; DCM, dichloromethane; VBL, von Bertalanffy Growth; dw, dry weight, m_{PCBi}, the mass of PCB_i in the fish (in ng); $E_{d,\ PCBi}$, the organism's chemical assimilation efficiency for food for PCB_i,; f_{PCBi}, the fraction of PCB_i mass which is accumulated through ingestion; *t*, lake trout age (yr); L_t, the total length (cm) of the fish at time *t*; L_∞, the asymptotic length (cm); k, the growth coefficient (yr^{-1}).

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Supporting Information: PCB Food Web Dynamics Quantify Nutrient and Energy Flow in Aquatic Ecosystems

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File consists of one supporting table and one supporting figure.

Table S1.

PCB	$\log K_{OW}$[a, 21]	$E_{d,\ PCBi}$[b, 25]	f_{PCBi}[c, 24]
18/17	5.1	0.802	0.96
31/28	5.67	0.699	0.71
48	5.85	0.667	0.86
44	5.75	0.685	0.86
70	6.2	0.604	0.88
99	6.39	0.570	0.93
87	6.29	0.588	0.91
110	6.48	0.554	0.93
118	6.74	0.507	0.96
153	6.85	0.487	0.96
105/132	6.7	0.514	0.91
138	6.83	0.491	0.96
158	7.02	0.456	0.97
187	7.17	0.429	0.98
183	7.2	0.424	0.97
128	6.74	0.507	0.96
156/171	7.2	0.424	0.97
180	7.36	0.395	0.98
170	7.31	0.404	0.98
201	7.2	0.424	0.985
195/208	7.65	0.343	0.983
194	7.8	0.316	0.98
206	8.09	0.264	0.989
209	8.18	0.248	0.99

[a] the octanol-water partition coefficient as reported in Hawker and Connell, 1988.
[b] the organism`s assimilation efficiency of PCB_i as reported in Liu et al. 2006.
[c] the fraction of PCB_i accumulated from dietary sources as reported in Arnot and Gobas 2004.

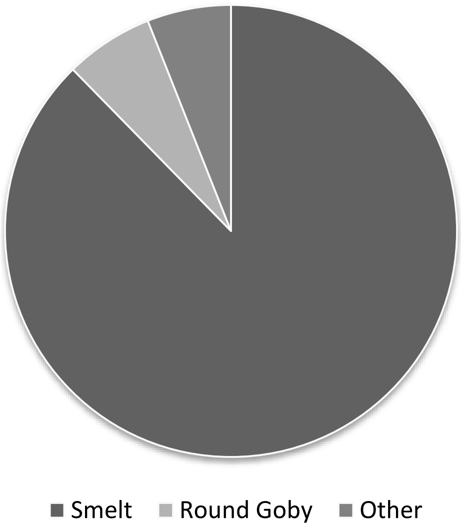

Figure S1. Results from gut content analyses on Lake Trout from Lake Huron. Proportions are based on the number of each prey item obtained.