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Influence of Chemical and Biological Factors on Trophic Transfer of Persistent Organic Pollutants in the Northwater Polynya Marine Food Web

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Persistent organic pollutants (POPs) and stable isotopes of nitrogen (δ^{15}N) were measured in zooplankton (6 species), a benthic invertebrate (*Anonyx nugax*), Arctic cod (*Boreogadus saida*), seabirds (6 species), and ringed seals (*Phoca hispida*) collected in 1998 in the Northwater Polynya to examine effects of biological and chemical factors on trophic transfer of POPs in an Arctic marine food web. Strong positive relationships were found between recalcitrant POP concentrations (lipid corrected) and trophic level based on stable isotopes of nitrogen, providing clear evidence of POP biomagnification in Arctic marine food webs. Food web magnification factors (FWMFs), derived from the slope of the POP−trophic level relationship, provided an overall magnification factor for the food web but over and underestimated biomagnification factors (BMFs) based on predator−prey concentrations in poikilotherms (fish) and homeotherms (seabirds and mammals), respectively. Greater biomagnification in homeotherms was attributed to their greater energy requirement and subsequent feeding rates. Within the homeotherms, seabirds had greater BMFs than ringed seals, consistent with greater energy demands in birds. Scavenging from marine mammal carcasses and accumulation in more contaminated winter habitats were considered important variables in seabird BMFs. Metabolic differences between species resulted in lower than expected BMFs, which would not be recognized in whole food web trophic level−POP relationships. The use of ∑POP groups, such as ∑PCB, is problematic because FWMFs and BMFs varied considerably between individual POPs. FWMFs of recalcitrant POPs had a strong positive relationship with log octanol−water partition coefficient (K_{ow}). Results of this study show the utility of using δ^{15}N to characterize trophic level and trophic transfer of POPs but highlight the effects of species and chemical differences on trophic transfer of POPs that can be overlooked when a single magnification factor is applied to an entire food web.

Introduction

Trophic transfer of persistent organic pollutants (POPs) is the movement of chemicals from one trophic level to the next. In aquatic food webs, many POPs biomagnify or increase in concentration from one trophic level to the next (*1*). Although increased lipid content with trophic level accounts in part for higher POP concentrations in upper trophic level organisms, there is clear evidence that biomagnification occurs in addition to differences associated with lipids (*2*). The relative importance of trophic transfer for exposure to POPs varies with the organism and chemical. With increasing hydrophobicity, the relative amount of chemical in the water of an aquatic system will become smaller when compared with chemical associated with particulate organic matter, resulting in reduced accumulation directly from water (*3*). Hydrophobic POPs tend to biomagnify, resulting in greater POP concentrations with increasing trophic level and subsequently greater discrepancy between food and water POP concentrations. Therefore, exposure to POPs with a log octanol−water partition coefficient (K_{ow}) of approximately 4−5 and higher by upper trophic level aquatic organisms will be predominantly through dietary accumulation (*4*). For air-breathing organisms, such as seabirds and seals, exposure to POPs via water is not an important exposure vector.

Recently, stable isotopes of nitrogen have been used to assess food web transfer of POPs in aquatic food webs. The ratio of the heavier to lighter stable isotopes of nitrogen (^{15}N/^{14}N), expressed relative to a standard (see below) as δ^{15}N, generally increases with trophic position in aquatic food webs, providing a continuous variable with which to assess both trophic level (*5, 6*) and food web transfer of POPs (*2, 7*−*9*). Stable isotopes of nitrogen provide a number of advantages in assessing trophic position because they are easily determined and incorporate diet over a longer period than stomach contents (*10*). Overall food web biomagnification factors (BMFs) can be estimated from slopes of logarithmic concentration of contaminants vs δ^{15}N values in food web components (e.g., refs *7, 11,* and *12*). Although there have been a number of POP−δ^{15}N relationships described, they have generally been used to explain differences in contaminant concentrations among species (*7, 13*) and locations (*8*). Application of these relationships to mechanisms of food web transfer is limited. For example, Kidd et al. (*2, 9*) showed that biomagnification varied with log K_{ow} in sub-Arctic and Arctic freshwater food webs, although a limited number of compounds were examined.

The Northwater (NOW) Polynya in northern Baffin Bay (Figure 1) is the largest and most productive polynya in the Canadian Arctic, supporting large populations of seabirds and marine mammals. Polynyas are areas of open water, often surrounded by sea ice, that persist throughout the winter in polar seas. They are one of the most important and least understood phenomena in polar ecology (*14*). An extensive multi-disciplinary study on the NOW afforded the opportunity to collect a large number and range of biota (zooplankton, fish, seabirds, and marine mammals) within the same area and time to assemble a comprehensive food web to examine trophic transfer of POPs. Arctic marine food

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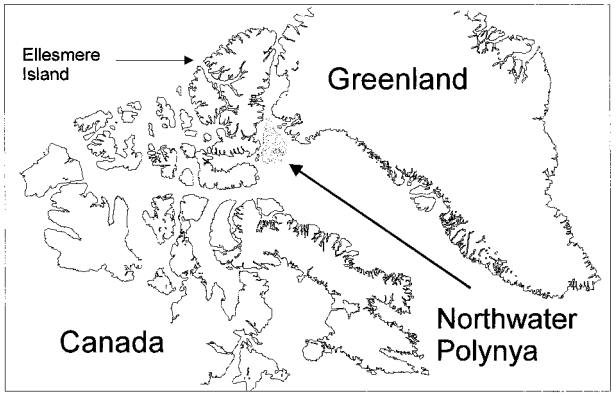

FIGURE 1. Location and approximate size of the Northwater Polynya in May/June.

webs provide an excellent opportunity to examine bioaccumulation and trophic transfer of POPs because they are relatively simple and there are very limited local point sources of pollution. The objectives of this work were to develop POP−trophic level relationships based on $\delta^{15}N$ values and to compare biomagnification factors in a number of different species, covering a large number of POPs with different physical−chemical properties. Examining a large number and diversity of species and POPs allowed us to evaluate the influence of biological and chemical properties on trophic transfer of POPs and potential limitations of using $\delta^{15}N$ to quantify trophic transfer.

Materials and Methods

Field Collection, Species, and Sample Size. Food web components were collected during the April−July 1998 voyage of the CCGV *Pierre Radisson* in the Northwater Polynya (Figure 1). Zooplankton samples were obtained from vertical tows (bottom to surface) using 1 × 1 m^2 zooplankton nets (520 μm mesh) and were sorted by species shortly after collection. Samples of the benthic amphipod (*Anonyx nugax*) were obtained using bait traps on the ocean floor. Traps contained squid or mackeral wrapped in Nilex mesh, to prevent feeding by amphipods, and were deployed for 8−12 h. Arctic cod (*Boreogadus saida*) were opportunistically sampled using hand-held nets when they were observed swimming near the surface in broken ice at one location. Seabirds were collected opportunistically by shotgun from a zodiac. A variety of body measurements were made, and the birds were sexed using dissection. Subsamples of muscle and liver were taken for stable isotope and POP analysis, respectively. Tissue samples from ringed seals (*Phoca hispida*) were obtained from Inuit hunters from Grise Fijord, Canada, and Qânâq, Greenland, during the spring of 1998. All samples were placed in Whirl Pak bags, cryo-vials, or aluminum foil and frozen until analyzed for stable isotopes (SI) and POPs.

A total of 132 samples were analyzed, including six zooplankton species [whole animal composite samples: *Calanus hyperboreus* (herbaceous copepod, $n = 20$); *Euchaeta glacialis* (omnivorous copepod, $n = 3$); *Metridia longa* (omnivorous copepod, $n = 3$); *Mysis occulata* (detritus feeding and predatory mysid, $n = 7$); *Themisto libellula* (predatory amphipod, $n = 4$); *Sagitta* sp. (predatory arrowworm, $n = 6$)], one benthic amphipod (whole animals composite samples: *A. nugax*, $n = 4$), one fish species (subsample of individual whole animals: Arctic cod, $n = 8$), one marine mammal species (blubber: males only, ringed seal, $n = 17$), and seven species of seabird (livers: DOVE (dovekie, *Alle alle*), $n = 7$; TBMU (thick-billed murre, *Uria lomvia*), $n = 9$; BLGU (black guillemot, *Cepphus grylle*), $n = 9$; BLKI (black-legged kittiwake, *Rissa tridactyla*), $n = 10$; IVGU (ivory gull, *Pagophila eburnea*), $n = 5$; GLGU (glaucous gull, *Larus hyperboreus*), $n = 10$; NOFU (Northern fulmar, *Fulmaris glacialis*), $n = 10$).

Chemicals and Standards. All solvents (pesticide grade) and sodium sulfate (Na_2SO_4) were obtained from BDH Inc. (Mississauga, ON, Canada). Pesticide grade Florisil, 60−100 mesh, was obtained from the Floridin Corp. (Berkeley Springs, WV). Biobeads SX-3 used in the GPC column were purchased from Analytical Biochemistry Laboratories Ltd. (Columbia, MO).

Extraction, Cleanup, and Analysis of Samples for POPs. Sample extraction and cleanup procedures for POPs have been published previously (*15*). Briefly, a representative sample of tissue was ground with anhydrous sodium sulfate spiked with an internal standard [2,4,6-trichlorobiphenyl (PCB 30) and octachloronaphthalene (OCN) for zooplankton and *A. nugax*; δ-hexachlorocyclohexane, TCPMe, OCN, and 2,2′,3,4,4′,5,6,6′-octachlorobiphenyl (PCB 204) for seabird livers and Arctic cod; and a series of ^{13}C-labeled chlorobenzenes and PCB congeners in ringed seal] and extracted with 100 mL (1:1) of methylene chloride (DCM)/hexane using a Dionex ASE 200 (Dionex Canada Ltd., Oakville, ON, Canada) accelerated solvent extractor (invertebrates) or glass columns. A fraction of the extract was used to determine lipids gravimetrically. Lipids were removed from the sample by gel permeation chromatography (GPC). The lipid-free eluate was evaporated to 1 mL and applied to a Florisil column (8 g, 1.2% deactivated). For the zooplankton, *A. nugax*, Arctic cod, and seabird samples, POPs were recovered by consecutive elution with 35 mL of hexane (fraction 1, F1), 38 mL of 85% hexane:15% DCM (F2), and 52 mL of DCM:hexane (F3). For seals, POPs were eluted by a single elution of 100 mL of DCM:hexane. Only one fraction was collected for seal samples because they were analyzed by MSD (see below). All fractions were rotoevaporated, transferred to 2,2,4-trimethylpentane, and evaporated to approximately 125 (zooplankton, *A. nugax*, Arctic cod, and seabird livers) or 570 μL (*P. hispida*). Aldrin (zooplankton, *A. nugax*, Arctic cod, and seabird livers) or ^{13}C-labeled PCB 138 (ringed seal blubber) was added as volume correctors.

Zooplankton, *A. nugax*, Arctic cod, and seabird samples were analyzed on a Hewlett-Packard 5890 gas chromatograph (GC) equipped with a 60 m × 0.25 mm DB-5 column (J & W Scientific, Folsom, CA) and a ^{63}Ni-electron capture detector (ECD). Ringed seal samples were analyzed on a Hewlett-Packard 5890 GC equipped with a 30 m × 0.25 mm MS column (J & W Scientific) and a mass spectrometer detector (MSD). External standards were run after every six samples. Recoveries of internal standards were 82 ± 3.8 (mean ± 1 SE) for zooplankton and benthic amphipods, 94 ± 2.1 for Arctic cod and seabirds, and 84 ± 1.4 for ringed seals. Concentrations were not corrected for recoveries of internal standards.

Stable Isotope Analysis and Trophic Level Calculations. Stable nitrogen isotope assays were performed on 1-mg subsamples of homogenized materials by loading into tin cups and combusting at 1800 °C in a Robo-Prep elemental analyzer. Resultant N_2 gas was then analyzed using an interfaced Europa 20:20 continuous-flow isotope ratio mass spectrometer (CFIRMS) with every five unknowns separated by two laboratory standards. Stable isotope abundances were expressed in δ notation as the deviation from standards in parts per thousand (‰) according to the following equation:

$$\delta^{15}N = [(^{15}N/^{14}N_{sample}/^{15}N/^{14}N_{standard}) - 1] \times 1000 \quad (1)$$

The $^{15}N/^{14}N_{standard}$ values were based on atmospheric N_2 (air). Replicate measurements of internal laboratory standards (albumen) indicate measurement errors of ±0.3 ‰ for stable nitrogen isotope measurements.

Trophic levels were determined using equations modified slightly from those reported in Hobson et al. (*6*). Trophic level was determined relative to the copepod *Calanus hyperboreus*, which we assumed occupied trophic level 2 (i.e., primary herbivore). For each individual sample of zooplankton, fish and marine mammal trophic level was determining using the following relationship:

$$TL_{consumer} = 2 + (\delta^{15}N_{consumer} - \delta^{15}N_{C.\ hyperboreus})/3.8 \quad (2)$$

where $TL_{consumer}$ is the trophic level of the organism, $\delta^{15}N_{C.\ hyperboreus}$ is equal to 7.7 ± 0.1 (mean ± 1 SE, $\delta^{15}N$ for *C. hyperboreus*), and 3.8 is the isotopic enrichment factor (*16*). Captive-rearing studies on birds suggest that the diet−tissue isotopic fractionation factor of +2.4‰ is appropriate for these taxa (*17*); therefore, we used this value. The trophic level of a seabird prey item would be $TL_{consumer}$. The relationships $TL_{bird} = TL_{consumer} + 1$ and $\delta^{15}N_{bird} = \delta^{15}N_{consumer} + 2.4$ would be used in order to modify eq 2 to

$$TL_{bird} = 3 + (\delta^{15}N_{bird} - 10.1)/3.8 \quad (3)$$

Food Web and Biomagnification Factor Calculations. Two types of trophic transfer terms were calculated for the NOW food web. The first method determined food web magnification factors (FWMFs) for the entire food web based on relationships between trophic level and concentration using simple linear regression:

$$\ln \text{POP concentration} = a + (b \times \text{trophic level}) \quad (4)$$

All concentrations were lipid corrected (concentration/lipid content) due to a large range in lipid content between species. These POP−trophic level relationships were only developed for chemicals that were found in a majority (>∼75%) of the species and samples. For each POP, samples that had nondetects were removed from the analysis. Trophic level was used in favor of $\delta^{15}N$ because seabirds have been found to have different nitrogen isotope fractionation factors (*17*). The slope *b* of eq 4 was used to calculate FWMF using

$$FWMF = e^{b} \quad (5)$$

The second method determined BMFs for individual species, corrected for trophic level, using

$$BMF_{TLC} = [\text{predator}]/[\text{prey}]/(TL_{pred}/TL_{prey}) \quad (6)$$

where [predator] is the concentration (lipid corrected) in the predator, [prey] is the concentration (lipid corrected) in the prey, and TL is the trophic level based on $\delta^{15}N$ for the predator and prey.

Results and Discussion

POP−Trophic Level Relationships and FWMFs. The trophic relationships derived from stable isotope analysis for NOW food web fell into the range expected based on stable isotope results for another Arctic polynya food web (*6*), with seabirds and ringed seal at the top and zooplankton species occupying lower trophic levels. Values of $\delta^{13}C$ were consistent through the species used in this food web (data not shown), suggesting a similar source of carbon. A more extensive study on trophic relationships among components of the NOW food web can be found in Hobson et al. (*16*).

Strong positive relationships were found between recalcitrant POP concentrations (lipid corrected) and trophic level showing the high biomagnification potential of these compounds in Arctic marine food webs (Figure 2; Table 1). This work represents the most comprehensive examination of the POP−trophic level relationship because of the large

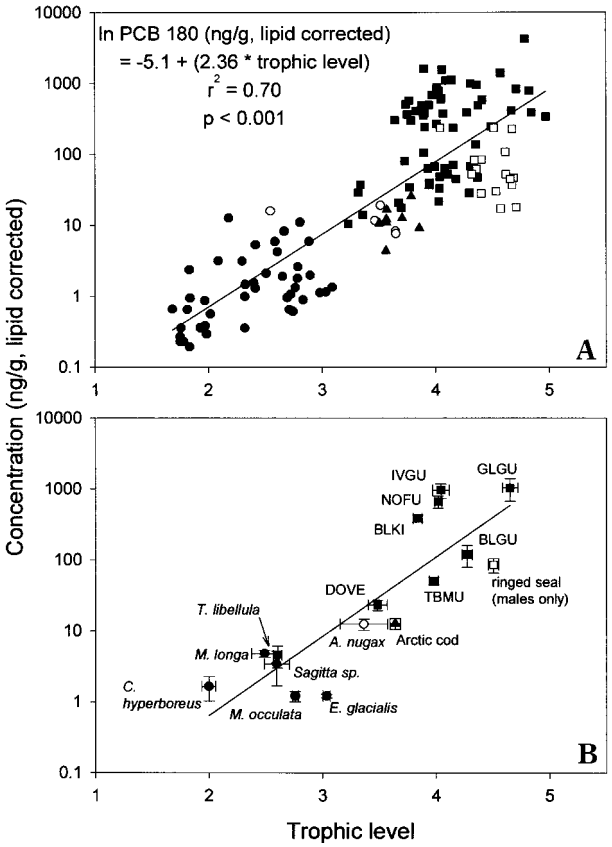

FIGURE 2. PCB 180 concentration (ng/g, lipid corrected)−trophic level relationships for the Northwater Polynya marine food web. (A) All data points. (B) Mean (±1 SE) values for each species. Lines are linear regression. Trophic level based on $\delta^{15}N$. See text for details regarding sample types analyzed and species codes. (●) Pelagic zooplankton, (○) benthic amphipods, (▲) Arctic cod, (□) ringed seals, (■) seabirds.

number of chemicals and species used and the large number of samples. Potential problems, such as establishing true predator−prey relationships, were minimized because samples were collected in the same region and time. Moreover, true predator−prey interactions were derived using stable isotope assay rather than reliance on assumed trophic relationships or by conventional dietary analyses. Stomach contents analyses were also performed on seabirds (Nina Karnovsky, unpublished data) and seals (*18*), and these tended to verify our derived trophic relationships (*16*). As well, stable isotope and POP analysis methods were kept consistent.

FWMF determined from the slope of POP−trophic level relationships in this work are in good agreement with values obtained elsewhere for food webs involving marine birds and mammals. Jarman et al. (*12*) reported POP−$\delta^{15}N$ slopes for ∑PCB and ∑DDT of 0.88 and 0.79, respectively, for a marine food web that included zooplankton, fish, seabirds, and marine mammals. Assuming that an increase in $\delta^{15}N$ value of 3.8 corresponds to one trophic level (*6*), the FWMFs of ∑PCB and ∑DDT derived for this marine food web would be 9.2 and 8.4, respectively. FWMFs from the POP−$\delta^{15}N$ slopes that were reported for an Arctic marine food web including zooplankton, fish, seabirds, and marine mammals were 3.1, 4.7, and 6.6 for ∑chlor, ∑PCBs, and PCB 153, respectively (*19*).

FWMFs determined for food webs that include only zooplankton and fish tend to be lower than those that include seabirds and/or mammals. For example, FWMFs for PCB 153 and DDE were 4.4 and 4.5, respectively, for an Arctic

TABLE 1. POP–Trophic Level Relationships and Food Web Magnification (FWMF) and Biomagnification (BMF_{TLC}) Factors for the Northwater Polynya Marine Food Web[a]

		biomagnification factors (BMF_{TLC})									
	POP–trophic level/slope[b]	FWMF[c]	*T. lib.*/ *C. hyp.*	A. cod/ *T. lib.*	TBMU/ A. cod	BLGU/ A. cod	BLKI/ A. cod	IVGU/ A. cod	GLGU/ A. cod	NOFU/ A. cod	ring seal/ A. cod
$TL_{pred}-TL_{prey}$			0.6	1.04	0.33	0.62	0.19	0.39	1	0.37	0.87
triClBz	1.22 ± 0.09 (0.57)	3.4	5.7	6.2	2.1	1.8	4.2	2.1	0.8	1.6	0.3
PClBz	1.25 ± 0.09 (0.59)	3.5	8.7	3.6	3.6	1.5	7.4	4.6	2.3	3.5	0.5
HClBz	1.41 ± 0.13 (0.48)	4.1	3.8	6.1	10.9	5.0	21.6	19.0	6.7	19.5	0.2
∑ClBz	1.40 ± 0.12 (0.53)	4.1	4.8	5.4	8.2	3.9	16.3	13.8	5.0	13.8	0.3
α-HCH	0.02 ± 0.13 (<0.01)		3.0	0.9	0.6	0.3	0.5	0.5	0.1	0.5	2.8
β-HCH	1.98 ± 0.15 (0.66)	7.2			5.5	11.1	12.1	23.6	17.2	4.1	2.1
γ-HCH	−0.08 ± 0.11 (0.04)		11.2	0.6	0.9	0.2	0.5	0.3	0.1	0.3	0.3
∑HCH	0.98 ± 0.10 (0.45)	2.7	4.5	1.1	2.1	3.5	4.2	7.4	5.2	1.6	2.0
t-chlor			30.3	1.5	0.1						0.1
c-chlor	0.50 ± 0.10 (0.18)	1.6	21.5	1.4	0.3	0.6	1.1	1.8	0.4	0.5	0.3
t-nonachlor	1.70 ± 0.12 (0.62)	5.5	35.0	1.4	0.6	3.1	4.2	14.6	3.9	3.0	2.4
c-nonachlor	1.09 ± 0.13 (0.38)	3.0	44.2	1.4	2.4	10.3	9.5	13.6	4.0	0.5	0.9
oxychlor	1.87 ± 0.35 (0.26)	6.5			5.5	6.0	37.9	64.6	27.5	153.5	8.4
HE	1.89 ± 0.13 (0.64)	6.6	12.0	0.4	17.3	39.5	162.6	208.5	79.7	203.2	12.6
∑chlor	1.94 ± 0.12 (0.68)	7.0	26.5	1.6	1.8	4.0	11.6	20.3	7.4	26.8	2.4
p,p′-DDE	2.62 ± 0.11 (0.81)	13.7	16.2	3.1	19.1	18.5	55.8	137.7	49.3	87.0	7.0
p,p′-DDD	1.30 ± 0.15 (0.43)	3.7	27.7	1.8	0.6	1.3		4.4	2.5	22.7	0.5
p,p′-DDT	1.74 ± 0.11 (0.67)	5.7	22.0	1.8	1.5	1.1	5.8	7.4	2.6	11.9	3.7
∑DDT	2.38 ± 0.11 (0.79)	10.8	20.2	2.3	10.6	10.5	31.6	76.9	27.8	54.6	4.7
OCS					2.7	2.3	9.5	4.6	1.3	29.2	0.2
dieldrin	1.28 ± 0.14 (0.46)	3.6	12.5	1.0	12.1	17.4	72.6	82.8	25.5	72.7	3.9
mirex	2.35 ± 0.19 (0.60)	10.5	6.2	18.6	4.2	7.9	55.3	63.6	24.7	44.9	1.7
CB 31			7.0	0.1	0.3				0.9		1.3
CB 28	0.73 ± 0.09 (0.32)	2.1	5.8	1.3	3.3	1.6	14.2	7.2	3.4	5.9	0.3
CB 52			7.0	0.4					5.1		4.9
CB 49			5.7	0.2	0.0	1.9					3.7
CB 47/48	0.91 ± 0.11 (0.34)	2.5	8.7	0.2	14.5	9.8	66.8	95.6	32.7	41.1	9.2
CB 64	0.92 ± 0.16 (0.24)	2.5	20.0	1.1	1.5	5.2	18.9	21.0	11.2	8.1	0.5
CB 74	1.83 ± 0.12 (0.65)	6.2	7.8	2.8	10.9	14.2	46.3	53.6	17.7	21.6	2.0
CB 70/76	0.60 ± 0.14 (0.13)	1.8	10.3	0.3	3.3	16.9	46.8	13.3	21.3	32.2	0.5
CB 95/66	0.80 ± 0.09 (0.39)	2.2	7.8	0.4	6.7	5.3	36.3	20.3	7.7	19.2	2.2
CB 56/60	0.89 ± 0.11 (0.37)	2.4	5.2	1.3	5.2	3.7	31.1	16.2	8.5	9.5	1.0
CB 101	1.28 ± 0.09 (0.61)	3.6	12.8	0.5	4.8	11.3	29.5	25.1	12.6	2.4	7.8
CB 99	2.01 ± 0.12 (0.69)	7.5	18.5	0.7	12.1	12.9	93.7	119.7	55.0	62.2	23.3
CB 97	0.52 ± 0.10 (0.17)	1.7	10.7	0.6	0.6	3.1	7.9	10.0	2.4	4.6	0.6
CB 110	0.92 ± 0.10 (0.40)	2.5	10.2	0.7	0.9	5.5	24.2	14.6	8.8	3.2	1.3
CB 151			7.2	3.9							0.5
CB 149	0.85 ± 0.10 (0.38)	2.3	9.2	0.2	4.8	16.5	29.5	56.2	17.2	11.6	7.6
CB 118	1.63 ± 0.10 (0.67)	5.1	10.0	1.0	12.4	13.4	71.6	88.2	31.2	61.6	3.3
CB 153	2.27 ± 0.11 (0.76)	9.7	10.5	1.2	20.3	20.3	152.1	198.2	79.4	120.8	17.9
CB 105[d]	1.81 ± 0.12 (0.68)	6.1	4.2	0.2							
CB 141	1.00 ± 0.09 (0.58)	2.7	12.0	1.0		3.5	5.3	2.1	3.6	2.4	1.1
CB 130/176	1.38 ± 0.14 (0.49)	4.0			2.4	7.3	19.5	24.6	14.2	12.2	1.8
CB 137	1.54 ± 0.38 (0.17)				8.5	17.3	153.2	206.9	67.1	76.8	7.0
CB 138	2.17 ± 0.10 (0.77)	8.8	8.7	1.5	15.2	13.2	121.6	139.7	49.7	63.2	11.3
CB 158	2.00 ± 0.12 (0.70)	7.4	4.5	9.1	2.1	4.0	24.7	41.3	12.0	13.0	1.6
CB 178	1.89 ± 0.13 (0.65)	6.6			16.1	56.0	144.2	193.8	91.0	20.3	22.3
CB 187	1.99 ± 0.12 (0.70)	7.3	7.0	1.2	27.9	18.1	127.4	109.7	51.1	8.9	6.7
CB 183	2.00 ± 0.14 (0.63)	7.4	5.5	1.5	12.1	15.5	164.2	197.7	72.9	108.6	6.8
CB 128	1.93 ± 0.14 (0.63)	6.9	2.2	12.4	8.8	9.4	71.6	41.3	29.6	68.6	1.8
CB 174			1.5	2.2		7.3					1.3
CB 156	2.20 ± 0.25 (0.45)	9.0			3.9	4.2	42.6	50.8	18.1	30.8	1.3
CB 180	2.36 ± 0.14 (0.70)	10.7	4.7	2.7	12.1	15.0	158.9	193.3	81.4	140.5	7.7
CB 170/190	2.31 ± 0.15 (0.66)	10.1	1.0	31.3	5.2	4.8	51.6	71.5	26.6	47.6	2.3
CB 196/203					10.0	7.6	91.6	115.4	41.2	72.4	2.1
CB 195					2.1	1.3	10.0	14.4	5.5	9.2	0.1
CB 194					6.7	3.9	39.5	56.4	24.0	35.1	2.2
CB 206					4.8	2.4	27.9	33.8	11.3	24.1	2.6
∑PCB	1.53 ± 0.09 (0.68)	4.6	7.8	0.9	8.2	8.9	60.5	69.2	27.6	40.5	5.5

[a] BMF_{TLC} for predator prey comparisons are corrected for trophic level differences between the predator and the prey (see eq 6) (predator/prey). Common and Latin names of species codes are provided in the text. A. cod is Arctic cod. [b] Slope was calculated from the model ln concentration $= a + (b \times$ trophic level). Coefficient of determination (r^2) is shown in parentheses. All concentrations were lipid corrected due to a large range in lipid content between species. [c] FWMF were determined using the equation: FWMF $= e^b$. [d] Concentrations of PCB 105 were very low in Arctic cod resulting in extremely high BMF_{TLC} for seabird and ringed seals.

freshwater food web that included only invertebrates and fish (*2*). These values are less than half those determined for the entire NOW food web (FWMFs for PCB 153 and DDE are 13.7 and 9.7; Table 1). The greater FWMFs determined for food webs that incorporate mammals and birds suggest that these animals have a greater rate of bioaccumulation (see below). When the seabird and marine mammal data are removed from the NOW food web, FWMF values for PCB 153

and DDE decreased to 6.7 and 5.5, respectively (data not shown). These values are greater than those reported for a freshwater food web described by Kidd et al. (*2*), suggesting that FWMFs may vary between marine and freshwater food webs.

POP concentrations in a number of seabird species (IVGU, NOFU, GLGU, and BLKI) were higher than expected based on the POP−trophic level relationship (Figure 2). This could be due to accumulation of high levels from occasional scavenging of marine mammals or from more polluted winter habitats. IVGU, NOFU, and GLGU are known to scavenge, including marine mammals (*20*−*22*), although the relative rate of this scavenging is unknown. An occasional meal of an upper trophic level organism, such as a dead ringed seal, would result in a high level pulse of both POPs and δ^{15}N. The whole bodies half-lives of hydrophobic POPs (such as HCBz, DDE, and mirex) in herring gulls (*Larus argentatus*) have been reported to range from approximately 100 to 400 d (*23*). These half-lives are also much longer than the turnover rate of ^{15}N in muscle, which represents the integrated diet of seabirds over the past month (*17*). Therefore, the effects of scavenging upper trophic level organisms would be observed for a longer time in POP concentrations as opposed to δ^{15}N. The long half-lives of POPs would also mean that there would be significant carry over of POPs accumulated in a more polluted winter habitat. Higher than expected POP concentrations have been observed in Lake Superior herring gulls that migrate to more polluted locations in the winter (*24*).

Integrating POP data with stable isotope data provides additional information on the feeding ecology of these seabirds. For example, the high POP concentrations provide evidence that scavenging seabirds (IVGU, GLGU, and NOFU) are likely feeding on dead marine mammals to a greater extent than suggested by stable isotopes alone. This discrepancy also suggests that in the month or so before capture there were likely few feeding events on marine mammals.

Predator/Prey Biomagnification Factors. Biomagnification factors based on predator/prey comparison (BMF_{TLC}) and corrected for trophic level differences are summarized in Table 1. BMF_{TLC} were only reported for chemicals that were found in both predator and prey. Although more predator/prey comparisons could have been made, they represent realistic relationships, and the species chosen are key and abundant components of the NOW food web. It should be noted that all of these species have varied diets and that, for many of these comparisons, the predator was not a full trophic level above the prey based on δ^{15}N values (Table 1). Therefore, to represent a full trophic level between predator and prey, all BMF_{TLC} were corrected based on the difference in trophic level between predator and prey (see eq 6) but are comparable to BMFs reported in the literature.

BMF_{TLC} for the *T. libellula*/*C. hyperboreus* are generally higher than those of Arctic cod/*T. libellula* (Table 1), but there is evidence to suggest that BMFs for zooplankton (i.e., *T. libellula*/*C. hyperboreus*) were not realistic because concentrations of POPs in zooplankton may be controlled by POP concentrations in water and not prey. The half-life of chemicals in aquatic species is positively related to the size of the organism (*25*). Zooplankton accumulate POPs from food in laboratory experiments (*26*) and are likely exposed to POPs via food in the environment and have the potential to biomagnify POPs. However, short half-lives of POPs in zooplankton may result in tissue concentrations that are near steady state with water concentrations. As well, zooplankton feed at a low trophic level, and the discrepancy between food and water POP concentrations is not as great as at higher trophic levels. The high BMF_{TLC} reported for *T. libellula* may be due to the larger size of *T. libellula* as compared to *C. hyperboreus*. *T. libellula* are approximately 6 times larger, which could result in longer half-lives, higher

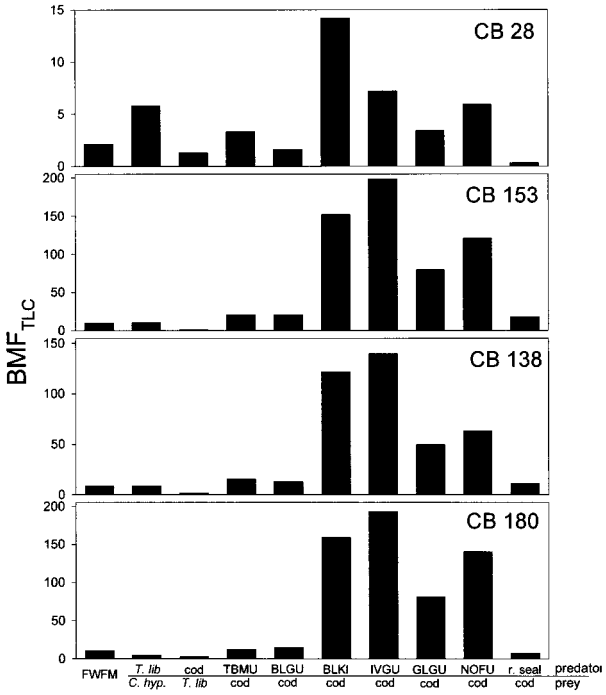

FIGURE 3. Biomagnification factors of CBs 28, 153, 138, and 180 in the Northwater Polynya marine food web. FWMFs were based on the slope of ln concentration−trophic level relationships. Predator/prey BMFs are corrected for the difference in trophic level between the predator and the prey (see eq 6), and all concentrations were lipid corrected. See text for details regarding sample types analyzed and species codes.

concentrations, and an artificially high BMF_{TLC}. Further support that size may be more important than trophic position on POP concentrations in zooplankton is found in *E. glacialis*. These predatory copepods had the highest δ^{15}N values among the zooplankton and were a full trophic level above *C. hyperboreus* but were of similar size and POP concentrations to *C. hyperboreus* (Figure 2). Further research is needed on understanding the factors controlling POP concentrations in marine zooplankton.

BMF_{TLC} for Arctic cod/*T. libellula* were slightly below and above 1 but are in the range of BMFs reported for similar sized fish in laboratory experiments (*25*) and field observations (*1*, *27*). Stomach contents of the Arctic cod contain zooplankton (Fisk, unpublished data), and the difference in trophic level between Arctic cod and *T. libellula* was very close to 1. So this was a realistic predator prey comparison. BMF_{TLC} calculated for NOW ringed seals (Table 1) were slightly lower but within the range of those reported for male ringed seals from the east central Canadian Arctic (*28*). Arctic cod was found to be the major prey item of these ringed seals, along with polar cod (*Arctogadus glacialis*) and amphipods (*18*), consistent with trophic levels derived form δ^{15}N (Table 1).

The BMF_{TLC} of the seabirds varied considerably between species (Table 1; Figure 3) and appear to be related to scavenging of marine mammals and/or migration to more contaminated regions. It should be stressed that all of these seabirds feed on a range of diet items (e.g., zooplankton and carrion) that can vary considerable over the course of the year, although Arctic cod and other similar size fish were commonly found in the stomach of these seabirds (N. Karnovsky, personal communication). The greatest BMF_{TLC}s were found in the BLKI, IVGU, GLGU, and NOFU (Table 1). Three of these species scavenge carrion (IVGU, GLGU, and NOFU) (*20*−*22*) and would be periodically exposed to high concentrations of POPs by feeding on dead marine mammals.

BLKI also had high BMF_{TLC} but are not known to scavenge marine mammals (*29*). The high BMF_{TLC} observed in the BLKI is likely due to accumulation of POPs in the winter habitat of the BLKI on the highly contaminated eastern seaboard of North America (*30*). Accumulation of POPs in their winter habitat is also an issue for GLGU and NOFU, both of which migrate (*21*, *22*). IVGU do not migrate south in winter (*20*); therefore, their high BMF_{TLC} are due solely to scavenging of marine mammals. BMF_{TLC} in the obligate fish and invertebrate feeding seabirds (BLGU and TBMU) were well below the BMF_{TLC} of scavenging and migrating species (Table 1; Figure 3). Although the TBMU migrate to more southerly areas in the winter (southern Greenland and Labrador) (*31*), they do not migrate nearly as far south as the BLKI (*29*).

BMF_{TLC} reported for NOW seabirds are in the range reported for other fishing-eating birds. Hendriks (*32*) reported persistent PCB BMFs in liver of common cormorants (*Phalacrocorax carbo*) to range from 19 to 37, slightly lower than BMFs (range 33 to >100) reported for PCBs in common cormorants collected in Japan (*33*). These cormorants are piscivorous birds, and their BMFs are in the range of BLGU from this study. Braune and Norstrom (*34*) reported whole body BMFs for a range of POPs, including organochlorines and PCBs, in Lake Ontario herring gulls (*L. argentatus*) that ranged from 18 to 59 for persistent POPs and from 1 to 9 for readily metabolized POPs. These are slightly lower than those calculated for gulls (BLKI, IVGU, and GLGU) and NOFU from the NOW. This difference could be due to additional accumulation of POPs by Arctic seabirds from scavenging highly contaminated marine mammals and/or from having a higher burden of POPs due to accumulation from more polluted winter habit as discussed above.

Homeotherm vs Poikotherm Bioaccumulation. One of the most striking differences in BMFs were between poikilotherms (fish) and homeotherms (seabirds and mammals) (Table 1; Figure 3). Zooplankon BMF_{TLC} were high, but as discussed above, BMFs may be artificial in zooplankton. BMF_{TLC} are much higher in seabirds and mammals than in fish and zooplankton. Large differences in BMFs between poikilotherms and homeotherms were first demonstrated in herring gulls and salmon for Lake Ontario (*34*). Despite similar size and POP half-lives in these species, BMFs were much higher in the herring gulls, an effect the authors attributed to the greater energy requirements and feeding rate of herring gulls and subsequently a greater exposure rate to POPs. Although hoemotherms have higher metabolic capacity than poikilotherms, the elimination and half-life of recalcitrant POPs in similar sized organisms are generally comparable (*34*). A similar observation was made for terrestrial birds and insects (*35*). Results from our study confirm the conclusions of Braune and Norstrom (*34*) and provide evidence that greater BMF_{TLC} in homeotherms applies to marine mammals. It should be noted that the fish from the NOW are much smaller than the seabirds and ringed seals, although the much larger size of the ringed seals (25−80 kg) as compared to the seabirds (0.25−2 kg) did not result in higher BMF_{TLC} for the seals.

Despite similar diets of fish and invertebrates and little dispersal out of the Arctic seasonally, ringed seal BMF_{TLC} were lower than BLGU. The energetic requirements and hence feeding rate of birds are greater than mammals (*36*). Therefore, the same processes, which result in greater bioaccumulation of POPs in homeotherm versus poikilotherm, are likely to apply to comparisons of birds and mammals, although the difference is not as large. These results suggest that birds bioaccumulate POPs more. However, it should be noted that POP concentrations were determined in seabird livers and ringed seal blubber. The dynamics of POPs can vary between tissues, and the use of liver concentrations of POPs for the ringed seals may have produced slightly different results.

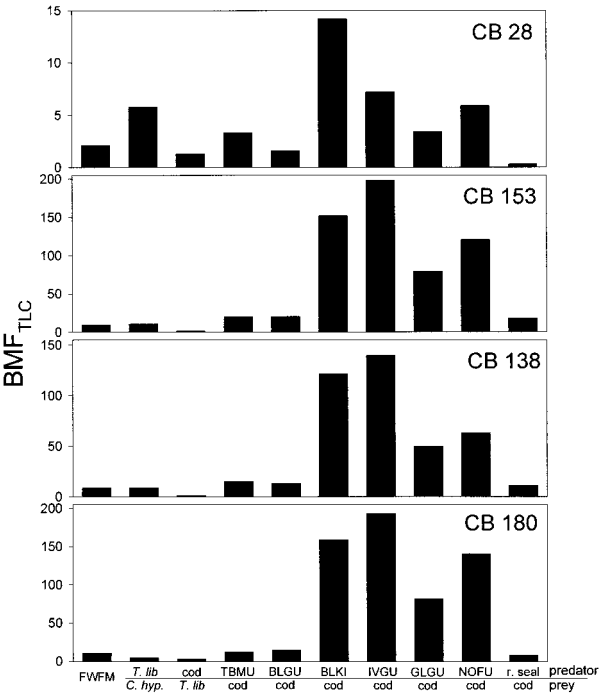

FIGURE 4. Relationship between food web magnification factors (FWMF) and log K_{ow} of recalcitrant POPs in the Northwater Polynya marine food web. FWMFs were determined from the relationship between ln concentration (lipid corrected) and trophic level. Log K_{ow} values of PCBs are from ref *39*, and for all other POPs are from ref *40*. DDE and HE were not used in the regression analysis.

Variation in contaminant bioaccumulation between poikilotherms and homeotherms has implications for the assessment of trophic transfer of POPs in food webs including both of these groups. POP−trophic level-derived FWMF fell near the middle of predator/prey calculated BMF_{TLC} and over- and underestimated biomagnification in poikilotherms and homeotherms, respectively.

Metabolic Variation between Animal Groups. Biotransformation capacity has been shown to vary between groups of organisms, with a relative ranking from highest to lowest biotransformation ability as follows: marine mammals > seabirds > fish > zooplankton (*37*). This relative ranking appears to hold for cytochrome P450 (CYP) subfamily 1A type biotransformation based on BMF_{TLC} in the NOW food web. The CYP1A enzymes are induced and are involved in the metabolism of planar POPs, such as PCB 118 (*38*). For example, the BMF_{TLC} of ClBz compounds are greatest in zooplankton, followed by Arctic cod, seabirds, and marine mammals. It also appears to hold for CYP 2B type metabolism of PCB congeners and chlordane components, although seabirds appear to have greater CYP 2B type metabolism for other POPs, such as α- and γ-HCH. CYP2B enzymes are involved in the metabolism of nonplanar POPs (*38*), although characterization of this subfamily and their role in POP metabolism is very limited. These metabolic differences result in variable BMF_{TLC} between animal groups, which can be lost when using the entire food web to assess trophic transfer. Detailed examination and discussion of metabolic differences in the species of the NOW food web is currently underway.

***K_{ow}* Effects.** A strong relationship between FWMF and log K_{ow} was determined for recalcitrant POPs (Figure 4). This relationship was limited to POPs for which a FWMF could be determined and a log K_{ow} was available in the literature. For example, there is no published log K_{ow} for *trans*-nonachlor. The FWMF−log K_{ow} relationship was stronger when confined to recalcitrant PCB congeners, those congeners that do not have hydrogen at adjacent meta and para positions on either biphenyl ring. The greater variability in

the relationship for all POPs may be due to metabolism or formation. For example, DDT is metabolized to form DDE that would decrease the FWMF for DDT and increase the FWMF for DDE. The FWMF for DDE was the highest reported. Another factor could be inaccurate log K_{ow} values. The PCB congener K_{ow} values were derived with the same method (*39*), and although they may not be completely accurate, they are consistent as a group. K_{ow} values of the other POPs are from Mackay et al. (*40*) and were chosen from many published literature values and methods and therefore may not be consistent. There is a clear need for consistent, experimentally derived K_{ow} values for a larger range of POPs.

It is clear that increasing log K_{ow} results in greater trophic transfer of recalcitrant POPs in marine food webs (Figure 4). This relationship held when examining BMF_{TLC}, although the relationships were not as strong. Kidd et al. (*2*) also noted an increase in trophic transfer with log K_{ow} for a limited number of POPs in an Arctic freshwater food web based on concentration−δ^{15}N relationships. Oliver and Niimi (*41*) noted increasing bioaccumulation with K_{ow} of PCB congeners in the Lake Ontario food web. A relationship between BMF and K_{ow} has also been found in laboratory experiments using fish (*25*).

The FWMF−log K_{ow} relationships provide insight on the behavior of a number of POPs. For example, DDE and heptachlor epoxide have values of FWMFs that are much greater than predicted based on the FWMF−log K_{ow} relationships. DDE has been well established as a metabolite of DDT formed in animals. These results suggest that a large percentage of the high concentrations of DDE in upper trophic level Arctic organisms are due to metabolic formation. Heptachlor epoxide, which is not in technical mixtures, is formed from heptachlor by photooxidation and in rat liver homogenate (*42*). Results from our work suggest that heptachlor epoxide is formed in upper trophic level Arctic organisms and may account for a large percentage of their concentrations.

Sum of Groups vs Individual Compounds. FWMFs and BMFs of ∑POP groups vary considerably from those calculated for individual components of these groups (Table 1). This is due to a combination of differential susceptibility to biotransformation and variation in kinetics due to different physical−chemical properties. For example, ∑HCH was observed to biomagnify in seabirds and throughout the entire food web, although neither α- or γ-HCH were found to biomagnify (Table 1). Variation in FWMFs and BMFs was also observed between recalcitrant chemicals within a ∑POP group. The FWMFs of PCB 28 and PCB 180 were 2.1 and 10.7, respectively, much different than for ∑PCB (FWMF = 4.6) (Table 1). Clearly, caution should be exercised when applying the sum of group FWMFs and BMFs to individual compounds.

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