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SCCPs in a western Hudson Bay food web

Measurable Levels of Short-Chain Chlorinated Paraffins (SCCPs) in Western Hudson Bay Fishes, But Limited Biomagnification from Fish to Ringed Seals

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Abstract: This study investigated short-chain ($C_{10\text{-}13}$) chlorinated paraffins (SCCP) in an Arctic marine food web. In zooplankton, fishes and ringed seals from western Hudson Bay, Canada, SCCP concentrations ranged from 38.3 to 687 ng g^{-1} lipid weight. Monte Carlo-simulated trophic-adjusted biomagnification factors of individual SCCP congeners ranged from 0.07- 0.55 for small pelagic fishes-to-seals. Despite relatively high concentrations in fishes, biomagnification of SCCPs within this food web appears limited.

Keywords: short-chain chlorinated alkanes; fish; pinnipeds; biomagnification; Arctic; GC Orbitrap MS.

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INTRODUCTION

Short-chain chlorinated paraffins (SCCPs) are chlorinated alkanes with a chain length of 10 to 13 carbons and chlorine content varying between 48% to 70%. Since the 1930s, SCCPs have been extensively used in industry (Fiedler 2010) with a global production of at least 165,000 tons/year (Glüge et al. 2016). Similar to legacy persistent organic pollutants (POPs) like polychlorinated biphenyls (PCBs), SCCPs show chemical stability and volatility leading to long-range transport, with some evidence of accumulation and toxicity in biota (Van Mourik et al. 2016). Consequently, they were listed under the Stockholm Convention on POPs in 2017, with some production exemptions (Stockholm Convention 2017). Given these properties, SCCP exposures and risks to biota should continue to be monitored.

SCCPs have received considerably less attention in Arctic contaminant monitoring studies compared to other POPs, partly because their quantification is still challenging due to lack of suitable standards, sometimes low concentrations, and chemical complexity (Van Mourik et al. 2016). Only a handful of studies on Arctic biota have reported SCCP levels in marine mammals and seabirds, and fewer still have monitored levels in marine fish (Vorkamp et al. 2019). SCCPs may biomagnify in marine food webs, similar to some of the most persistent POPs (Harju et al. 2013; Yuan et al. 2019). Although no SCCP toxicity studies have been done on Arctic biota, research on rats, mice and fish have shown effects on endocrine, reproductive, and immune functions (Wyatt et al. 1993; Cooley et al. 2001; Liu et al. 2016).

The objectives of the present study were to 1) quantify tissue SCCP concentrations in marine fish, invertebrates and ringed seals (*Pusa hispida*) from an Arctic food web, 2) compare SCCP levels with those of other legacy POPs in the same samples (Pedro et al. 2017), and 3) evaluate the SCCP biomagnification by calculating biomagnification factors (BMFs) from fishes to seals.

MATERIALS AND METHODS

Five marine fish species and amphipods were collected as previously described (Pedro et al. 2017). In brief, capelin (*Mallotus villosus*), sand lance (*Ammodytes* spp.), cisco (*Coregonus artedi*), sculpin (*Myoxocephalus spp.*), Greenland cod (*Gadus ogac*), and amphipods (*Gammarus oceanicus*) were collected by community members near Arviat (low Arctic, 61° N, 94° W), Nunavut, Canada (Figure 1) during the summer of 2014. Collection methods included rod and reel, ice fishing, and grabbing from shore (Pedro et al. 2017). Collections consisted mostly of adult fish (Table 1), except for capelin, which were likely juveniles as they were below the 130-200 mm maturity size for this species (Hop and Gjøsaeter 2013; Ogloff et al. 2020). Fish and invertebrate samples were wrapped in solvent-rinsed foil and stored at -20 °C temporarily, and then kept at -80 °C in the lab. Fish species identifications were confirmed genetically at the Canadian Center for DNA Barcoding (Guelph, Ontario).

Ringed seal blubber samples were collected by community members during subsistence hunts around Arviat in the fall of 2017, including nine females (<1 to 21-yrs old), and one male (1-yr old). Collected blubber samples were placed in Whirl-Pak® bags and stored between -15°C and -25°C within hours of sampling and then kept at -20°C (Houde et al. 2019). Age was determined by Matson's Laboratory (Milltown, MT, U.S.A) by counting the annual growth layers of longitudinal sections of teeth (Houde et al. 2019). Seals ≤1 year-old were considered young of the year and >5 were considered adults; no animals between 2 and 7 years-old were collected. Due to the environmental persistence of SCCPs, evidence that SCCPs have been successfully analyzed in a soil core between 1950 to 2004 (Iozza et al. 2008), and the storage of the fish and invertebrate samples at -80°C, substantial SCCP degradation between the two collection dates (2014 and 2017), or between collection and analysis, is unlikely.

SCCP Analysis

Fish and invertebrate contaminant extractions were carried out at the Great Lakes Institute for Environmental Research, University of Windsor. These samples were originally extracted and analyzed for PCBs, organochlorine (OC) pesticides and brominated flame retardants (Pedro et al. 2017). Briefly, muscle tissues of individual fish and whole amphipods were homogenized prior to analysis. Eight capelin and all sand lance did not have sufficient mass for individual analysis, thus individuals of each species were pooled (capelin in pairs and sand lance in quadruplets) by combining equivalent mass aliquots of each homogenate. Aliquots of 2.5 g were homogenized with anhydrous sodium sulfate and eluted with 1:1 dichloromethane:hexane. Samples were subject to gel permeation chromatography to remove lipids, and lipid content was quantified gravimetrically. Samples were further cleaned-up and fractionated on a Florisil column into three fractions, which contained different organic contaminant groups (see Pedro et al. 2017).

Seal blubber samples were extracted for SCCPs at the Québec Laboratory for Environmental Testing (Environment and Climate Change Canada) in Montreal, Québec. Samples weighing 1 g were homogenized with diatomaceous earth (J.T. Baker, Phillipsburg, NJ, USA) and spiked with 100 µL of a 200 ng/mL internal standard solution (BDE-30, BDE-156, ^{13}C-BDE-209, and ^{13}C-*anti*-DP) (Simond et al. 2017; Simond et al. 2020). Samples were extracted with 1:1 dichloromethane:hexane on a pressurized liquid extraction system. Sample clean-up was performed on an acid-basic-neutral silica column, followed by a neutral alumina column. Lipid content was quantified gravimetrically.

Fish, invertebrate and seal samples extracts were analyzed for SCCPs at the National Laboratory for Environmental Testing (Environment and Climate Change Canada, Burlington, ON). For fish and invertebrates, SCCPs were not detected in fraction 1, so fractions 2 and 3 were combined for analysis. A range of SCCP congeners were examined: $C_{10}Cl_{5-10}$, $C_{11}Cl_{5-10}$, $C_{12}Cl_{5-10}$, and $C_{13}Cl_{5-10}$. Methods were adapted from Tomy et al. (1997). SCCPs were quantified using Q Exactive GC Orbitrap GC-MS/MS (Thermo Fisher Scientific, Mississauga, ON, Canada) with a TraceGOLD TG-5SilMS GC column (30 m× 0.25mm× 0.25 μm; Thermo Fisher Scientific) operated in negative chemical ionization mode at a mass resolution of 60,000. Specific m/z values corresponding to the molecular formulas of $[M^{-}Cl]^{-}$ ions of all major C_{10}-C_{13} formula groups were monitored concurrently. Corrections were made for the fractional abundance of specific m/z values and number of Cl atoms. Quantification was performed by comparing the response of specific m/z values in the sample to that of an authentic standard, which was a C_{10}-C_{13} technical mixture containing 55.5% Cl (DRE-X23105500CY, LGC Standards, Augsburg, Germany).

For fish and invertebrates, reagent blanks were run at the start and every four to five samples. Some blanks showed concentrations (mean 0.04, range 0-0.87 ng ml^{-1}) higher than the detection limit of 0.27 ng ml^{-1}, so we blank subtracted the results on a batch-by-batch basis. Recovery of the internal standard spikes, PCB34 and BDE71 were 97 ± 10% and 99 ± 10%, as we reported previously (Pedro et al 2017). PCB and PBDE internal standards have previously been used as surrogates for SCCP recoveries (Houde et al. 2008; Ismail et al. 2009). Although no reference material exists for SCCPs, an in-house carp reference material (Table S2) was extracted alongside the fish and invertebrate samples; for legacy POPs, quantification showed concentrations within 9 ± 7% for ΣPCB and 15 ± 9% for ΣOC. For seals, $^{13}C_{10}$-1,5,5,6,6,10-hexachlorodecane surrogates were added to all samples during extraction, two blanks were run for the ten samples and standard reference material NIST 1946 was run twice for the ten samples (Table S3). All samples were blank corrected as the blanks were above the detection limit of 0.27 ng ml^{-1}. Spike recovery of $^{13}C_{10}$-1,5,5,6,6,10-hexachlorodecane ranged from 67.7 to 125%. Although the NIST 1946 was not analyzed for PCBs and OCs, for which certified concentrations are available, for the two NIST 1946 runs, the ΣSCCP concentrations were 355 ng g^{-1} and 279 ng g^{-1}, which is a percent difference of 24%. Results were corrected for weight and lipid content for all fish, invertebrate and seal samples and are presented in ng g^{-1} lipid weight (lw).

Stable isotope analyses

Extraction, quantification and quality control details for nitrogen ($\delta^{15}N$) and carbon ($\delta^{13}C$) stable isotopes analysis in fish and invertebrates were described previously (Pedro et al. 2017). Briefly, homogenized and lipid-extracted subsamples of 400-600 µg tissue were combusted in an elemental combustion system. After that, ratios of $\delta^{15}N$ and $\delta^{13}C$ were quantified with a coupled Delta V Advantage isotope ratio mass spectrometer (Thermo Scientific, Waltham, MA, USA).

For seals, stable isotopes were analyzed in non-lipid extracted muscle by the University of Waterloo’s Environmental Isotope Lab. Results have been found to be comparable to lipid-extracted analyses with differences averaging 0.28 ‰ for $\delta^{13}C$ and 0.25 ‰ for $\delta^{15}N$ (see Supplementary Material for more details) (Houde et al. 2017).

Stable isotope ratios were analyzed by continuous flow isotope ratio mass spectrometry (Finnigan MAT DeltaPlus; Thermo Finnigan).

Statistical analysis

Concentrations of lipid-corrected ΣSCCP in fish and invertebrates did not follow a normal distribution and were log-transformed to meet normality requirements of linear models. Amphipods were not included in statistical analyses due to the low sample size. We used one-way analysis of variance (ANOVA) to compare mean concentrations of ΣSCCP among species, followed by *post-hoc* Tukey's honestly significant difference tests. We also tested the effects of fish length, weight, δ^{15}N and δ^{13}C ratios on variation in SCCP concentrations among species, as these variables have been previously found to affect levels of other POPs (Pedro et al. 2017; Pedro et al. 2019). To test for among-species variation, we used mixed-effects models. Weight and length were significantly correlated ($R_s = 0.91$, $p < 0.001$), so we included length only in the models. A stepwise model selection was performed for SCCPs with δ^{15}N, δ^{13}C, fish length, and first-order interactions as fixed effects, and species as a random effect, within the R-package *nlme* (Pinheiro et al. 2015). The best relative fit models were evaluated based on lower Akaike information criterion for small sample sizes (*AICc*) within the R-package *AICcmodgav* (Mazerolle 2017), and then inspected for normality of residuals and homoscedasticity. All statistical analyses were performed using R software version 3.6.0 (R Core Team 2018). Statistical significance was considered at $p < 0.05$.

Biomagnification Factors

To test for trophic transfer of ΣSCCPs, we calculated biomagnification factors (BMFs) as the ratio of the average lipid-normalized concentration between predator and prey. Capelin and sand lance feed mostly on planktonic crustaceans, including amphipods (Danielsen et al. 2016; McNicholl et al. 2016; Ogloff et al. 2020), while Greenland cod feed mainly on forage fish, including capelin (Nielsen and Andersen 2001). Adult ringed seal in western Hudson Bay feed primarily on sand lance during the open water season and on Arctic cod and capelin when sea ice is present (Chambellant et al. 2013). BMF means and standard deviation terms were produced using a Monte Carlo simulation (Crystal Ball Oracle Inc) (see Supplemental Material for more details). The trophic adjusted BMF equation is as follows (Borgå et al. 2004):

$$Adjusted\ BMF = \frac{\frac{SCCP_{predator}}{SCCP_{prey}}}{\mathrm{TPpredator - TPprey}} \quad (1)$$

where $\mathrm{SCCP}_{\mathrm{predator}}$ and $\mathrm{SCCP}_{\mathrm{prey}}$ are specific SCCPs or ΣSCCP concentrations in ng g^{-1} lipid weight in the predator and prey species; and $\mathrm{TP}_{\mathrm{predator}}$ and $\mathrm{TP}_{\mathrm{prey}}$ represent trophic position of predator and prey. A BMF value > 1 indicates biomagnification of the compound. Trophic position (TP) was calculated based on δ^{15}N values, assuming a trophic position of 2 for calanoid copepods and respective δ^{15}N values from previous studies in the region (averaged values for *Calanus hyperboreus* and *Calanus glacialis* of 8.3 ‰ (Pomerleau et al. 2016), and a constant trophic enrichment factor of 3.8 ‰ (Hobson and Welch 1992; Fisk et al. 2003):

$$TP = \frac{2 + (\delta^{15}N_{predator} - \delta^{15}N_{copepod})}{3.8} \quad (2)$$

RESULTS AND DISCUSSION

SCCPs in Arctic marine amphipods, fish and ringed seals

Detectable levels of SCCPs were found in all amphipod and fish samples. The concentration of ΣSCCPs in the pooled sample of *G. oceanicus* amphipods was 559 ng g^{-}

^{1} lw (Table 1). When comparing on a dry weight (dw) basis, these individuals showed much lower levels compared to amphipods (*Gammarus setosus*) sampled in Svalbard from 2011-2012 (518 ± 80 ng g^{-1} dw compared to 6 ng g^{-1} dw in our samples) (Li et al. 2017). Concentrations of ΣSCCP in fish here averaged 416 ± 38 (range from 244-514) ng g^{-1} lw (Table 1). Just a few other studies have reported ΣSCCPs in marine or landlocked fish from Arctic/sub-Arctic regions. Our results in fish were two orders of magnitude higher than those reported in muscle of anadromous Arctic char (*Salvelinus alpinus*) (sampled in 2004) (Vorkamp et al. 2019). As seen with mercury, lower SCCP concentrations in anadromous Arctic char could be explained by “growth dilution”, where anadromous fish have fast growth rates, leading to lower contaminant concentrations per unit of body mass (Swanson and Kidd 2010). SCCP concentrations in our fish were also double those of landlocked (2010) Arctic char from Nunavut, and higher than those reported in Atlantic cod (*Gadus morhua*) liver in 2003-2004 from Lofoten, Norway and Iceland (mean 93 ng g^{-1} lw in cod, although SCCP levels seem to have increased in Lofoten in more recent years (Vorkamp et al. 2019)). However, our SCCP results were comparable to the means of 300 and 540 ng g^{-1} lw in Arctic char from Norwegian lakes sampled in 2001 (Reth et al. 2006; Dick et al. 2010; Muir et al. 2013) and also comparable to those reported in Icelandic Greenland shark (*Somniosus microcephalus*), an Arctic top predator, which ranged from 50-5200 ng g^{-1} lw in 2001-2003 (Strid et al. 2013). Conversely, SCCPs in fish here were two-three times lower than levels reported in cod from Svalbard (2012; ~ 1,303 ng g^{-1} lw, 41.7 ng g^{-1} ww with 3.2 lipid % or 208 ± 50 (SE ng g^{-1} dw)) (Reth et al. 2006; Li et al. 2017).

Detectable concentrations of SCCPs were also measured in all ringed seals. The young of the year seals had higher concentrations of SCCPs than the adults; mean concentrations of ΣSCCPs for the adult ringed seals were 38.3 ± 6.24 (range from 28.9-55.3) ng g^{-1} lw and young of the year were 59.9 ± 11.4 (28.9-105) ng g^{-1} lw. This is expected as marine mammals can transfer their contaminant burdens to offspring through the placenta and milk (Schweigert and Strobo 1994; Brown et al. 2016). SCCP levels in seals were 4 to 18 times lower than what we found for the fish and invertebrates (Table 1), and lower than those found in other marine mammal predators in the Canadian Arctic. Levels in ringed seal blubber near Ellesmere Island in 1994 averaged 579 ng g^{-1} lw (or 520 ± 69 (SE) ng g^{-1} ww, range 370-770 ng g^{-1} ww with 90 % lipid content) and slightly lower in more recent years, 248 (males) and 79 (females) ng g^{-1} lw in 2002, and an average of 92 ng g^{-1} lw from 1998-2004 in other Nunavut regions (Tomy et al. 2000; Muir et al. 2013). In beluga from Pangnirtung, Nunavut, blubber ΣSCCP levels ranged from non-detected to 330 ng g^{-1} lw until 2007 (Muir et al. 2013), and in the Northwest Greenland these averaged 225 ng g^{-1} lw in 1989 (or 190 ± 60 (SD) ng g^{-1} ww, range 110-250 ng g^{-1} ww) (Tomy et al. 2000). Polar bears from Hudson Bay showed SCCP levels in blubber ranging from 30 to 598 ng g^{-1} lw spanning different age classes in 2013-2014 (Letcher et al. 2018).

Variation among studies may partly be related to temporal change in environmental levels and/or production sources of SCCPs. However, measurements of SCCP levels in Arctic biota are quite limited in number and time span. For example, in blue mussels and Atlantic cod from the Norwegian Arctic, SCCPs increased from 2012-2016 at least at one station (Green et al. 2017), while belugas from the Beaufort Sea and Cumberland Sound showed a non-significant decreasing trend from the 1980s to 2010 (Muir et al. 2013). In any case, comparisons among studies remain challenging due to the array of methods used to quantify SCCPs and on-going uncertainty surrounding the reliability and comparability of results among labs and over time (Van Mourik et al. 2015). Further, our relatively low sample size of 4 to 12 specimens of each species is another potential source of uncertainty regarding SCCP levels in these species.

Variation in ΣSCCP among fish species

Of all species, Greenland cod showed the highest ΣSCCP levels, significantly higher than sand lance ($p = 0.03$), cisco ($p = 0.02$) and sculpin ($p = 0.01$); capelin also showed significantly higher levels compared to sculpin ($p = 0.04$), which in turn had the lowest ΣSCCP levels (Figure 2). The best model explaining variation of ΣSCCP in fish was the null model, suggesting that trophic position, carbon source, and fish length did not influence ΣSCCP variation in these species. However, when looking only at $C_{12}Cl_{6\text{-}8}$ (the congeners at higher concentrations), the model with $\delta^{15}N$ (but not other variables) was important (delta $AICc = 0.96$, marginal $R^2 = 0.16$, beta estimate for $\delta^{15}N = 0.19$ (more details in the Supplementary Material)). Thus, trophic position may be more important for the heavier SCCP compounds. As seen in rainbow trout, the heavier (higher chlorinated and longer carbon-chain) chlorinated paraffins showed longer half-lives and greater bioaccumulation (Fisk et al. 1998; Fisk et al. 2000). Higher $\delta^{15}N$ values in Greenland cod could explain the higher concentrations of these particular SCCPs compared to most other species. While a previous study in lake trout from the Great Lakes also did not find any correlations between SCCP levels and fish length, weight, age, lipid content or trophic level (Saborido Basconcillo et al. 2015), recent studies found biomagnification of SCCPs in fish in Liaodong Bay, in a marine food web in the South China Sea and from oysters to crabs in the Pearl River Estuary in China (Huang et al. 2017; Zeng et al. 2017; Huang et al. 2019), as well as biomagnification potential in a food web of the Baltic Sea (de Wit et al. 2020).

Congener patterns and composition within species

For fish and invertebrate species, only homologues with 6 to 9 chlorines were detected (6-8 chlorines were more prevalent), with C_{11} and C_{12} chains at higher concentrations, especially C_{12} (Figure 3a, Table S1). This is comparable to Greenland sharks in Iceland (Strid et al. 2013), Arctic char from the European Arctic (Reth et al. 2006), along with fish from the North and Baltic Seas (Reth et al. 2005), and freshwater bodies across Canada (Saborido Basconcillo et al. 2015), wherein the contribution of C_{11} and C_{12} homologues was higher compared to C_{10} and C_{11} (Reth et al. 2006; Strid et al. 2013). Among fish species, the most notable variation in congener patterns was observed in cisco, which had higher % of C_{11} (especially $C_{11}Cl_8$) and lower C_{12} congeners relative to other species (Figure S1). This could, in part, be related to the high lipid content of cisco, since longer chain homologues of SCCPs have a higher affinity for lipid rich tissues (Li et al. 2016), or their anadromous behavior could reflect congener composition of both marine and freshwater environments (Bernatchez and Dodson 1990).

In ringed seals, a broader range of homologues were detected (C_{10}-C_{13} with 5 to 10 chlorines), with C_{10} and C_{11} chains being dominant (75%) (Figure 3b). The more volatile homologue groups, C_{10} and C_{11} with 6-8 chlorines (Drouillard et al. 1998), have been prevalent in Arctic marine mammals and associated with a higher contribution from atmospheric deposition rather than local source contamination in Arctic environments

(Tomy et al. 2000; Strid et al. 2013; Li et al. 2017; Letcher et al. 2018). Compounds of C_{13} were only detected in amphipods (only the congener with 7 chlorines) and seals. Differences between fish and marine mammals could indicate different assimilation and/or metabolism of SCCP homologues. In rainbow trout, lower chlorinated and shorter chain paraffins were more susceptible to biotransformation (Fisk et al. 2000). Further, the detection of C_{13} in ringed seals but not in fish could also be associated with the type of the tissue analysed, that is lipid-rich blubber could have higher affinity for the heavier congeners (Li et al. 2016).

Levels of SCCPs compared to legacy POPs in Arctic marine fish and amphipods

Levels of ΣSCCPs were double those of ΣPCBs and ΣOCs reported previously in these same samples of capelin, sand lance and cisco; and about three times higher in Greenland cod (Table 1) (Pedro et al. 2017). Similar results were also observed in Greenland shark, with SCCPs in the same range as individual PCBs (Strid et al. 2013). The opposite was observed in seals, were the SCCPs levels were 2-4 times lower than PCB and OC levels previously reported for seals in Arviat (2014-2016) (Houde et al. 2019). In previous studies on polar bears, belugas and ringed seals, ΣSCCP levels were 2-3 times lower than those of ΣPCBs (Tomy et al. 2000; Letcher et al. 2018). Thus, the high concentrations of ΣSCCPs in fish compared to those of other legacy POPs provide evidence of a substantial burden of SCCPs at least for some marine species in the Canadian Arctic. Furthermore, little is known about the burden of medium-chain chlorinated paraffins (MCCPs; C_{14-17}) and long-chain chlorinated paraffins (LCCPs; $\geq$ 18) in Arctic marine species, despite their presence in the Arctic and bioaccumulation potential (Reth et al. 2006; de Wit et al. 2020).

Biomagnification factors

Our BMF results were not always in agreement with the few studies that have analysed food-web transfer of SCCPs in Arctic ecosystems. The ΣSCCP BMFs were 0.85 ± 0.28 for amphipod-to-capelin, 0.61 ± 0.26 for amphipod-to-sand lance, 1.72 ± 0.86 for capelin-to-Greenland cod, and 0.32 ± 0.17 for prey fish-to-ringed seal (Table 2). In Svalbard, the average BMF for SCCPs calculated from gammarid amphipods to Atlantic cod was 0.46 (Li et al. 2017), comparable to what we found here, where amphipod-to-capelin and -sand lance BMFs were below one suggesting no biomagnification. In a food web in the Baltic Sea including mussels, fish, seals and seabirds, the BMFs ranged 1.5–5.0 for SCCPs, with higher BMFs between marine mammals and fish (BMF of 3.9 for herring-to-porpoise and 5.0 for herring-to-harbour seal) (de Wit et al. 2020). This is opposite to results found here, where the majority of the BMFs were below one for the prey fish-to-ringed seal, suggesting no biomagnification; however, BMFs were mostly above one for capelin-to-Greenland cod, suggesting biomagnification. The low fish-to-seal BMFs could be related, in part, to the difference in sample collection years between ringed seal (2017) and the prey fish (2014) and possible interannual variation of SCCPs in these species. The biomagnification between fish-to-fish, but not between fish-to-seal could in part be related to differences in metabolic capacities between poikilotherms and homeotherms, differences in feeding strategies, or the higher potential capacity for seals to biotransform chlorinated contaminants as seen for OCs in harbour seals (Boon et al. 1992).

Considering all BMFs, the lower chlorinated (Cl_6) SCCPs had the highest biomagnification factors. This is contrary to what was reported in Svalbard for gammarid-to-cod BMFs, where the higher chlorinated SCCPs were associated with higher biomagnification (Li et al, 2017). The influence of carbon atoms on the BMFs was variable with the exeption of the fish-to-seal ratios, where the BMFs were highest for the C_{10} chain lengths and the lowest were found for C_{12}. This is consistent with biota in Antarctica and fish in Lake Michigan, for which SCCP BMFs decreased with increasing carbon chain length (Houde et al. 2008; Li et al. 2016). The ΣSCCP BMFs in the present study were up to two orders of magnitude lower than other legacy POPs from Arctic food webs (Hop et al. 2002; Hoekstra et al. 2003; McKinney et al. 2012; de Wit et al. 2020). Thus, SCCP biomagnification may be limited in this Arctic food web relative to biomagnification found for legacy POPs; however, more food web studies and improved analytical capabilities are needed to further evaluate SCCP biomagnification.

CONCLUSIONS

In this western Hudson Bay food web, SCCPs were detected in all amphipod, fish and seal species collected and concentrations were relatively high in fish, especially piscivorous species. Nonetheless, trophic position-adjusted BMFs suggest limited biomagnification potential of SCCPs in this pelagic marine food web. To better understand the biomagnification potential of SCCPs, a more complete representation of the food web is needed, including larger sample sizes and additional species including the apex polar bear predator. In fish, the SCCP levels were in the same range or higher than those of PCBs and OCs measured in the same specimens, while for seals the opposite was observed for individuals in the same region. The growing evidence of CP accumulation in biota in remote regions, often in the same range as legacy POPs as shown here for SCCPs, highlights the importance of continuing monitoring of Arctic ecosystems for

SCCPs. Medium and long-chain chlorinated paraffins would also be of importance to investigate.

Supporting Information—The Supporting Information are available on the Wiley Online Library at DOI: 10.1002/etc.xxxx.

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Data availability statement—Data, associated metadata, and calculation tools are available from the corresponding author (melissa.mckinney@mcgill.ca). This article has earned an Open Data/Materials badge for making publicly available the digitally-shareable data necessary to reproduce the reported results. The data is available from the provided online-only supplemental data. Learn more about the Open Practices badges from the Center for Open Science: https://osf.io/tvyxz/wiki.

Author contributions statement—M.A.M., M.H., and A.T.F. designed the study. M.A.M., S.H.F., M.H., D.C.G.M. coordinated with communities the collections of fish, invertebrate and seal samples in Western Hudson Bay, Nunavut. H.S. performed the SCCP lab analysis. S.P. and N.F. analyzed the data. S.P. and N.F. wrote the initial version of the manuscript. All authors contributed to subsequent drafts of the manuscript.

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FIGURE CAPTIONS

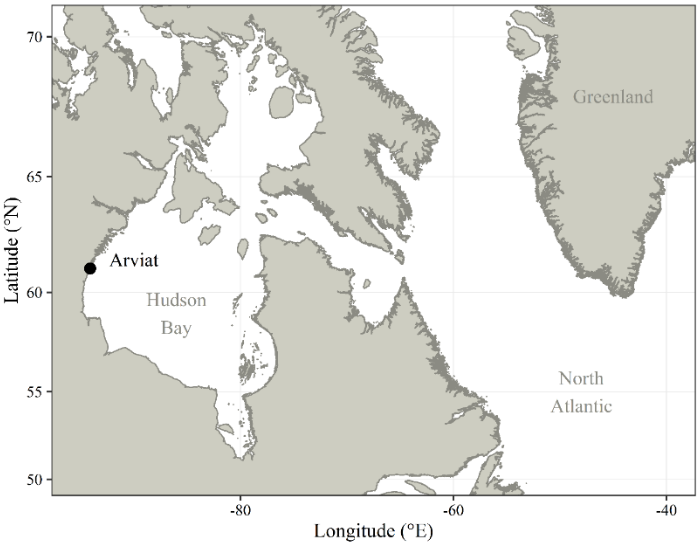

Figure 1. Sampling location of fish, and amphipods (2014) and ringed seal (2017) in Western Hudson Bay, Nunavut, Canada.

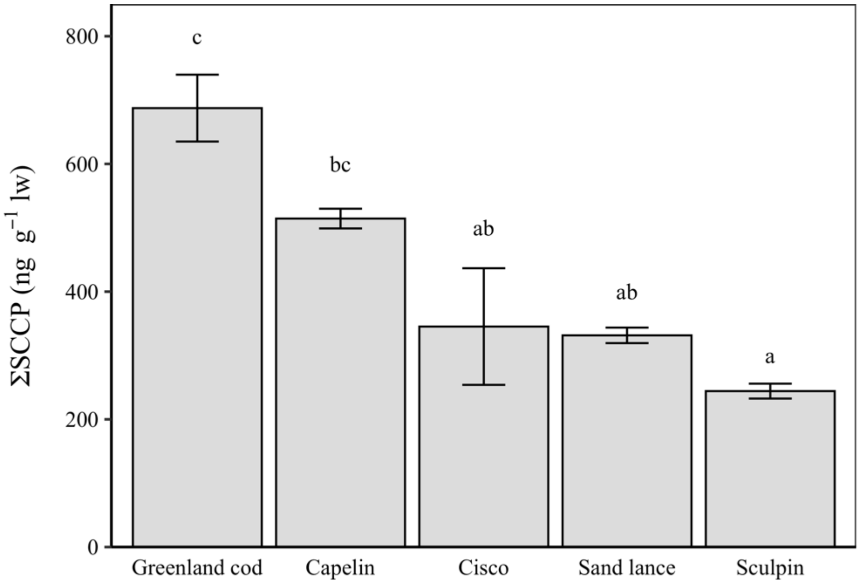

Figure 2. Mean concentrations of ΣSCCP (ng g^{-1} lipid weight (lw)) in fish from western Hudson Bay, Nunavut, sampled in 2014. Error bars represent standard errors. Significant differences in SCCP levels among species are indicated by different letters above each bar.

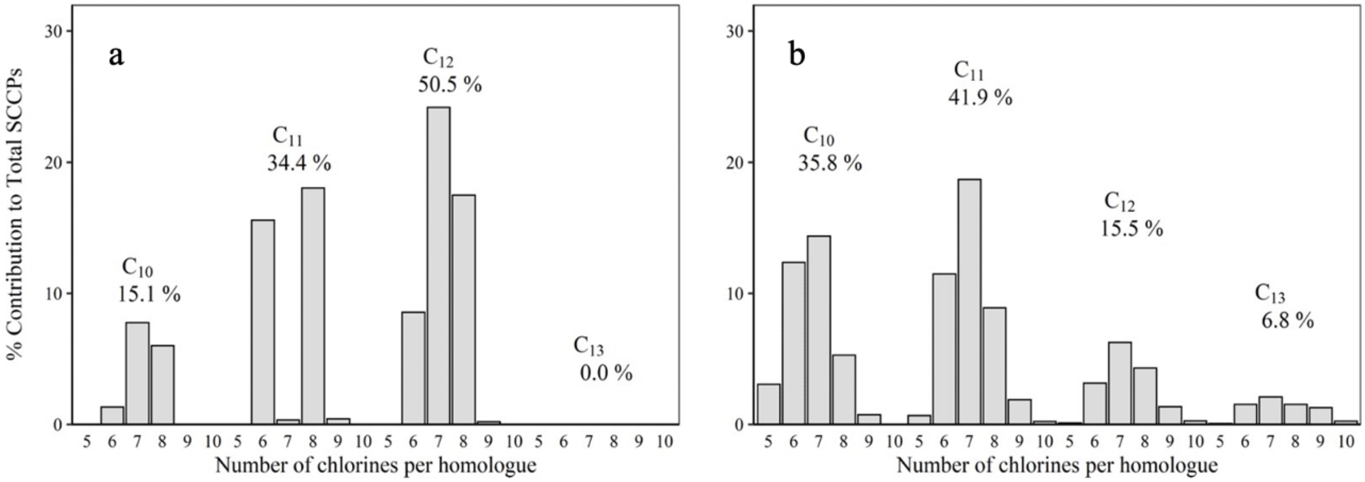

Figure 3. Average percent contribution of SCCP homologues to total % in (a) fish and invertebrates sampled in 2014 and in (b) ringed seals sampled in 2017 from western Hudson Bay, Nunavut.

Table 1. Biological, ecological, and contaminant measurements (mean (±SE) and range) in prey fish, invertebrates and ringed seals from 2014 and 2017 in Western Hudson Bay [a]

	Amphipods *Gammarus oceanicus*	Capelin *Mallotus villosus*	Sand lance *Ammodytes* spp.	Sculpin *Myoxocephalus* spp.	Cisco *Coregonus artedi*	Greenland cod *Gadus ogac*	Ringed seal *Pusa hispida*	
							Adults	*Young of the year*
n	1 pool	10	12	6	4	5	4	6
Length (mm)	NA	103 ± 3.32 (86-123)	96 ± 2.74 (84-109)	197 ± 16.6 (129-230)	352 ± 7.8 (331-378)	305 ± 24.0 (220-440)	1242.1 ± 69.5 (1160-1450)	985.0 ± 77.6 (790-1350)
Lipid %	0.75	1.8 ± 0.23 (1.3-3.2)	1.5 ± 0.06 (1.2-1.7)	0.8 ± 0.16 (0.2-1.3)	5.2 ± 1.2 (1.6-12.1)	0.6 ± 0.04 (0.5-0.8)	87 ± 1.5 (84-90)	89 ± 1.6 (83-93)
$\delta^{15}N$ ‰	10.0	14.7 ± 0.15 (13.9-15.3)	14.2 ± 0.22 (12.7-15.8)	15.7 ± 0.47 (14.4-14.5)	13.4 ± 0.35 (12.6-14.0)	18.0 ± 0.26 (17.1-19.7)	15.8 ± 0.35 (15.2-16.8)	14.5 ± 0.25 (13.9-15.6)
$\delta^{13}C$ ‰	-16.5	-21.1 ± 0.28 (-23.1--20.0)	-21.6 ± 0.26 (-23.2--19.6)	-16.6 ± 0.82 (-18.9--14.2)	-18.2 ± 1.08 (-16.6--21.7)	-18.9 ± 0.16 (-19.5--18.1)	-21.8 ± 0.55 (-23.4--21.0)	-21.6 ± 0.41 (-23.3--20.7)
Trophic position	2.46	3.67 ± 0.04 (3.48-3.85)	3.56 ± 0.05 (3.15-3.98)	3.98 ± 0.10 (3.62-4.41)	3.35 ± 0.08 (3.13-3.51)	4.53 ± 0.09 (4.34-4.70)	3.96 ± 0.09 (3.82-4.23)	3.64 ± 0.65 (3.47-3.91)
ΣSCCP	559	514 ± 49 (187-693)	332 ± 42 (220-528)	244 ± 29 (133-314)	345 ± 182 (86-885)	687 ± 117 (519-1,148)	38.3 ± 6.2 (28.1-55.3)	59.9 ± 11.4 (28.9-105)
ΣPCB	510	138 ± 14.1 (83-218)	113 ± 10.3 (70-158)	234 ± 47.4 (117-437)	80.5 ± 15.7 (50.7-140)	226 ± 21.9 (118-301)	NA	NA

ΣOC*	662	241 ± 15.7 (158-317)	166 ± 13.1 (106-216)	345 ± 77.2 (131-695)	116 ± 18.4 (60.7-173)	225 ± 31.2 (117-368)	NA	NA

[a] Concentrations (ng g^{-1} lipid weight) of short-chained chlorinated paraffins (ΣSCCP) in prey fish, invertebrates and ringed seals. Σ_{40}polychlorinated biphenyl (ΣPCB), Σorganochlorine pesticides (ΣOC) concentrations for prey fish and invertebrate species only. PCB and OC data were taken from Pedro et al. (2017). Length measurements indicated refer to standard length. Results are denoted as arithmetic mean (min-max), or NA (data not available).

*ΣOC included hexachlorocyclohexanes, chlorobenzenes, dichlorodiphenyltrichloroethanes, octachlorostyrene, Σchlordanes, mirex and dieldrin.

Ringed seal adults ranged from 8-21 years old, young of the year seals were ≤ 1 year old.

Table 2. Trophic position-adjusted biomagnification factors (±SD) using Monte Carlo simulation for SCCPs for the western Hudson Bay marine food web

Contaminant	Capelin/ amphipod	Sand lance/ amphipod	Greenland cod/ capelin	Adult Ringed seal/ prey fish[a]
ΣSCCP	0.85 ± 0.28	0.61 ± 0.26	1.72 ± 0.86	0.32 ± 0.17
$C_{10}Cl_6$*	ND	ND	1.56	2.23
$C_{10}Cl_7$	0.99 ± 0.24	0.90 ± 0.41	1.73 ± 0.93	0.55 ± 0.25
$C_{10}Cl_8$	0.79 ± 0.18	0.43 ± 0.21	1.08 ± 1.02	0.31 ±0.18
$C_{11}Cl_6$	1.11 ± 0.27	1.65 ± 0.67	3.16 ± 1.17	0.24 ± 0.13
$C_{11}Cl_8$	0.58 ± 0.25	0.35 ± 0.14	1.28 ± 1.02	0.20 ± 0.15
$C_{11}Cl_9$*	0.33	0.08	0.00	0.88
$C_{12}Cl_6$	0.97 ± 0.20	1.18 ± 0.57	2.05 ± 1.11	0.10 ± 0.06
$C_{12}Cl_7$	0.83 ± 0.32	0.46 ± 0.19	1.39 ± 0.79	0.09 ± 0.06
$C_{12}Cl_8$	0.69 ± 0.16	0.27 ± 0.11	1.57 ± 0.62	0.07 ± 0.05

[a] prey fish includes capelin and sand lance

[*] Data could not be transformed to fit any distribution offered in Crystal Ball, thus the Monte Carlo simulation was not possible for these homologues and equation (1) was used instead

ND: not determined; the SCCP concentration was below the detection limit for at least one of the species in the ratio calculation