Diet influences on growth and mercury concentrations of two salmonid species from lakes in the eastern Canadian Arctic

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ABSTRACT

Diet, age, and growth rate influences on fish mercury concentrations were investigated for Arctic char (*Salvelinus alpinus*) and brook trout (*Salvelinus fontinalis*) in lakes of the eastern Canadian Arctic. We hypothesized that faster-growing fish have lower mercury concentrations because of growth dilution, a process whereby more efficient growth dilutes a fish's mercury burden. Using datasets of 55 brook trout and 133 Arctic char, linear regression modelling showed fish age and diet indices were the dominant explanatory variables of muscle mercury concentrations for both species. Faster-growing fish (based on length-at-age) fed at a higher trophic position, and as a result, their mercury concentrations were not lower than slower-growing fish. Muscle RNA/DNA ratios were used as a physiological indicator of short-term growth rates (days to weeks). Slower growth of Arctic char, inferred from RNA/DNA ratios, was found in winter versus summer and in polar desert versus tundra lakes, but RNA/DNA ratio was (at best) a weak predictor of fish mercury concentration. Net effects of diet and age on mercury concentration were greater than any potential offset by biomass dilution in faster-growing fish. In these resource-poor Arctic lakes, faster growth was associated with feeding at a higher trophic position, likely due to greater caloric (and mercury) intake, rather than growth efficiency.

Keywords: somatic growth dilution; RNA:DNA; stable isotopes; climate change

Capsule: Age and diet, but not growth rate, are primary drivers of mercury concentrations in two salmonid fish species in Canadian Arctic lakes.

1. Introduction

Mercury contamination in fishes is a widespread environmental issue due to global emissions and long-range transport that may result in health risks to fishes (Fuchsman et al., 2016; Kidd and Batchelar, 2011) and human populations that consume them (Dellinger et al., 2012). Research since the 1990s has identified key environmental, ecological and biological processes controlling mercury concentrations in freshwater fishes including the supply of methylmercury and its uptake into aquatic food webs (Chételat et al., 2018; Pickhardt et al., 2002; Watras et al., 1998; Wu et al., 2019), biomagnification (Cabana and Rasmussen, 1994; Lavoie et al., 2013), habitat-specific trophic transfer (Eagles-Smith et al., 2008; Karimi et al., 2016; Power et al., 2002), and bioaccumulation with age due to slow elimination rates (Van Walleghem et al., 2007; Van Walleghem et al., 2013). One aspect of mercury bioaccumulation in fishes that remains uncertain (with conflicting findings in the literature and a lack of consensus) is the importance of growth rates in controlling mercury concentrations.

Bioenergetic modelling indicates that faster growth rates can reduce fish mercury concentrations through somatic growth dilution (SGD), a process where greater biomass production per unit of food (and mercury) consumed results in the dilution of a fish’s mercury burden (Carroll and Warwick, 2017; Karimi et al., 2016; Li et al., 2018; Trudel and Rasmussen, 2006). Empirical evidence for the importance of growth dilution in controlling fish mercury concentrations is more ambiguous. Some studies have concluded that the mercury concentration of a fish’s diet is more important than its growth rate (Chumchal et al., 2010; Essington and Houser, 2003; Harris and Bodaly, 1998; Marusczak et al., 2011; Stafford and Haines, 2001; Wiener et al., 1990), while other studies have found lower mercury concentrations in fish with faster growth rates (Doyon et al., 1998; Sharma et al., 2008; Simoneau et al., 2005; Verta, 1990;

Wang and Wang, 2012; Ward et al., 2010). Further refinement of theory on growth rate effects in relation to other drivers of fish mercury concentration is needed to evaluate multiple stressors currently impacting aquatic ecosystems such as climate change and eutrophication, which may alter fish growth (Eagles-Smith et al., 2018).

Climate warming is anticipated to improve growth conditions for fishes in Arctic fresh waters through warmer temperatures and increased primary production (Reist et al., 2006b). Species with Arctic distributions such as lake trout (*Salvelinus namaycush*) and Arctic char (*Salvelinus alpinus*) are typically slow-growing and long-lived, which has been reported as a contributing factor for higher contaminant concentrations (Evans et al., 2005; Schindler et al., 1995). More efficient growth could reduce mercury concentrations of Arctic fishes through somatic growth dilution (Stern et al., 2012). However, with limited information on growth-mercury dynamics of Arctic fishes and different reported findings (Braaten et al., 2014; Keva et al., 2017; Swanson and Kidd, 2010; van der Velden et al., 2013; van der Velden et al., 2012), further research is needed for Arctic ecosystems.

Divergent findings in the literature on the importance of growth rates and SGD may be influenced by different study designs. van der Velden et al. (2012) noted that SGD of mercury has been more typically found in studies of juvenile fish compared to those examining older adults. Recent growth rates, such as those measured in studies of juvenile (Ward et al., 2010) or small-bodied fish (Wang and Wang, 2018) could provide different information on growth dilution effects than growth based on length-at-age of adult fishes. There may also be seasonal effects of mercury dilution in summer relative to winter (Braaten et al., 2014; Keva et al., 2017). Growth dilution is the result of efficient growth, when more energy is allocated to biomass production for a given intake of energy (Trudel and Rasmussen, 2006; Ward et al., 2010). A faster growth rate may not lead to lower mercury concentrations if the growth is due to higher consumption rates or a diet containing more mercury (Lepak et al., 2009; Trudel and Rasmussen, 2006). Field studies on fish often lack detailed information on the mercury content of their prey, which may hamper the interpretation of growth effects.

This study examined the influence of age, diet and growth rate on mercury concentrations in two salmonid fish species, Arctic char and brook trout (*Salvelinus fontinalis*), in lakes of the eastern Canadian Arctic. Several aspects of the study design provided new insights on the relative importance of of growth, age, and diet in those Arctic fishes: (1) mercury concentrations were contrasted between short-lived, fast-growing brook trout and long-lived, slow-growing Arctic char; (2) short-term growth rates (days to weeks) were examined using a physiological indicator, the RNA/DNA ratio of fish muscle (Chícharo and Chícharo, 2008; Ciotti et al., 2010) in addition to long-term growth rates (years) estimated by length-at-age; and (3) lake-specific mercury exposure was quantified by measuring methylmercury (MMHg) concentrations near the base of the food web. We used statistical modelling to test the hypothesis that faster-growing fish have lower mercury concentrations after quantifying the influence of age and diet.

2. Materials and methods

2.1. Study Area

Fishes were investigated in 12 lakes along a latitudinal gradient in the eastern Canadian Arctic between 2012 and 2014 (Supplemental Table S1, Fig. S1). The lakes are identified by numbers (lake 1-12) because only a portion have official names. Five subarctic taiga lakes were sampled in 2012 for brook trout near the community of Kuujjuaraapik-Whapmagoustui in northern Quebec (55°N), located approximately 200 km south of the treeline boundary. In three of the five subarctic lakes, one other fish species–the small-bodied ninespine stickleback (*Pungitius*

pungitius)–was present and consumed by brook trout. Lake-dwelling Arctic char were sampled in three Arctic tundra lakes near the community of Iqaluit, Nunavut (64°N) in 2013-14 and four High Arctic polar desert lakes near the community of Resolute Bay, Nunavut (75°N) in 2014. Arctic char was the only fish species present in the lakes, with the exception of one tundra lake (near Iqaluit) which also contained nine-spine stickleback.

Cold temperatures in the Canadian Arctic result in short open-water seasons of ~1–4 months for lakes, with the majority of the year under ice cover. None of the study lakes were thermally stratified at the time of sampling, and July water temperatures were 10–17°C in the taiga lakes and ≤ 10°C in the tundra and polar desert lakes. The five taiga lakes with brook trout were small in surface area (0.01–0.39 km^2) and had shallow mean depths (0.3–1.9 m). The seven lakes containing Arctic char were larger (0.15–4.5 km^2) and deeper (3–19 m). All of the lakes were unproductive (oligotrophic) ecosystems with low water concentrations of total phosphorus (1–10 µg/L), although latitudinal gradients in water-column organic matter, measured as dissolved organic carbon (DOC) and chlorophyll, were observed among the ecoregions (Chételat et al., 2018; Richardson et al., 2020). In particular, the taiga lakes had higher water concentrations of DOC (4.4 ± 0.7 mg/L) and chlorophyll (1.2 ± 0.7 µg/L) than the tundra lakes (DOC: 1.9 ± 1.0 mg/L; chlorophyll: 0.5 ± 0.04 µg/L) and polar desert lakes (DOC: 1.6 ± 0.7 mg/L; chlorophyll: 0.3 ± 0.1 µg/L). Geographic coordinates, physical characteristics and water chemistry (measured at the time of fish sampling) for each of the study lakes are provided in Supplemental Table S1.

2.2. Field sampling

Fish were collected from each lake during one sampling period in July or August, with the exception of three tundra lakes where additional fish were collected during winter (February) under ice. Multi-panel gill nets of varying mesh size (1-5 inches) were used to capture fish of different size classes in taiga and tundra lakes. For polar desert lakes, only large-sized Arctic char were targeted by gill net as part of an annual monitoring program in those lakes (Hudelson et al., 2019). Total sample sizes per study lake ranged from 10–15 for brook trout and 7–33 for Arctic char (Table 1). Captured fish were euthanized on site according to authorized animal care protocols and measured for mass (g) and total length (cm). Three 2 mm or two 4 mm biopsy punches were immediately collected from dorsal muscle, stored in cryovials with RNAlater stabilization solution for preservation of nucleic acid content, and frozen on the same day. Muscle biopsies were not collected from some fish (e.g., if they were dead in the net upon collection), and no biopsies were obtained from Arctic char in Lake 9. In the laboratory, fish were examined qualitatively for stomach contents (brook trout only) and dissected for otoliths, scales, and a muscle sample.

Collections of sediment-dwelling benthic invertebrates (chironomid larvae: Insecta, Diptera) from the study lakes were reported previously (Chételat et al., 2014; Chételat et al., 2018). Invertebrate sampling was conducted around the same time as the fish collection for all lakes except polar desert Lake 9 (fish in 2014, invertebrates in 2011). For two other polar desert lakes, invertebrate data from 2011 were added to increase sample size (Supplemental Information, Table S2). Invertebrates were collected offshore with an Ekman grab and 500 μm sediment sieve, and occasionally from shoreline areas using a D-framed kicknet. Chironomid larvae were used as a proxy for MMHg bioaccumulation near the base of the food web, providing a consistent taxonomic comparison among lakes of food web exposure to MMHg. Previous research on the same study lakes demonstrated that chironomid MeHg concentrations were related to water MeHg concentrations and were a robust indicator of baseline MeHg bioavailability (Chételat et al., 2018). The tundra and polar desert study lakes had a low diversity of macroinvertebrate taxa, the food webs were supported by benthic carbon, and chironomids were overwhelmingly the dominant invertebrate prey item of Arctic char (Chételat et al., 2010; Gallagher and Dick, 2010; Gantner et al., 2010; Lescord et al., 2015). The food webs of the subarctic taiga lakes with brook trout had not been previously characterized, and macroinvertebrate taxa (amphipods, dragonfly nymphs, caddisflies, mayflies, and march flies) were collected at the same time as chironomids to measure MMHg concentrations in potential prey.

2.3. Laboratory analysis

Fish age was estimated with otoliths using the crack and burn method. Otoliths were not available for a small subset of brook trout and Arctic char, in which case age was estimated from scale annuli (for < 10% of fish). We found that scales slightly underestimated age (by 0–2 years) relative to otoliths for young fish, as reported elsewhere (Stolarski and Hartman, 2008). We used species-specific poisson regressions derived using scale and otolith data from a subset of study fish to estimate otolith age from scales of 6 brook trout and 9 Arctic char aged 2–6 years (Supplemental Information). Scales were not used to estimate age for fish older than 6 years.

Total mercury concentration (THg, µg/g) was measured in freeze-dried and homogenized muscle by thermal decomposition, gold trapping, and atomic absorption spectrometry at either the National Wildlife Research Centre (Ottawa, Canada; *n* = 151) or the Canada Centre for Inland Waters (Burlington, Canada; *n* = 45). For the latter samples, analytical method and quality assurance details are provided in Hudelson et al. (2019), and raw data are available from an open data portal (Environment and Climate Change Canada, 2019). For THg measurements conducted at the National Wildlife Research Centre, analytical duplicates had a relative standard deviation of 2 ± 1% (mean ± SD, *n* = 17). Recoveries of THg from certified reference materials were 109 ±

9 % (*n* = 37) for TORT-2 (lobster hepatopancreas) and 100 ± 6 % (*n* = 21) for DOLT-4 (dogfish liver) from the Natural Research Council of Canada. Muscle THg concentrations were presented on a wet weight basis assuming 80% moisture and were assumed to be representative of muscle MMHg concentrations (Lescord et al., 2015).

Methylmercury concentrations (ng/g dry weight) of benthic invertebrates were measured in freeze-dried and homogenized material by pretreatment with an alkaline then acidic digestion, extraction in dichloromethane, isolation with sodium thiosulfate and detection by capillary gas chromatography coupled with atomic fluorescence spectrometry. The results of chironomid MMHg measurements were originally reported in Chételat et al. (2014; 2018) and method and QA/QC details are found therein. MMHg concentrations for other macroinvertebrate taxa in the subarctic lakes have not been previously published although the samples were analyzed at the same time as chironomid samples reported in Chételat et al. (2018), and therefore the same method and QA/QC details apply. Lake-specific sample sizes and concentrations of invertebrate MMHg are provided in Supplemental Table S2 and S3.

Dried and homogenized fish muscle and chironomid samples were analyzed for carbon and nitrogen stable isotopes on a a DeltaPlus XP Isotope Ratio Mass Spectrometer interfaced by a Conflo II to a Vario EL III elemental analyzer. Stable isotope ratios were expressed in delta notation (δ) as the parts per thousand (‰) deviation from standards of atmospheric N_2 gas for $\delta^{15}N$ and Vienna PeeDee Belemnite for $\delta^{13}C$. Muscle C:N ratios (on a molar basis) were calculated using the %C and %N values generated by the elemental analyzer during the isotopic measurements.

Muscle plugs preserved in RNAlater (and stored frozen) were measured for RNA and DNA content. The RNA:DNA ratio of muscle is a quantitative physiological proxy for short-term growth rate of fish because RNA content increases during protein synthesis which drives growth (Chícharo and Chícharo, 2008; Ciotti et al., 2010). DNA content is used to correct for variation in muscle cell density. Muscle RNA and DNA of 157 fish were extracted from 5–10 mg of bead-milled muscle using spin column kits (miRNeasy Mini Kit or DNeasy Blood and Tissue Kit, Qiagen, Hilden, Germany), and the yields were measured by spectrophotometry on a NanoDrop (Thermoscientific, Massachusetts, USA). RNA and DNA absorbance peaks were inspected and the absorbance ratios of 260:280 nm and 260:230 nm were measured to assess the quality of extractions. RNA and DNA yields were divided by the sample mass to calculate muscle concentration (μg/mg fresh weight). Duplicate measurements of muscle samples showed good reproducibility for both RNA (RSD = 9 ± 7 %, $n = 18$) and DNA (RSD = 13 ± 11 %, $n = 20$).

2.4. Data Analysis

Fish trophic position was calculated using individual δ^{15}N values of fish and lake-specific δ^{15}N values of benthic invertebrates according to the following equation:

$$\text{Trophic position} = 2 + (\delta^{15}\text{N}_{\text{fish}} - \delta^{15}\text{N}_{\text{chironomid}})/\text{TFF}$$

where $\delta^{15}\text{N}_{\text{fish}}$ and $\delta^{15}\text{N}_{\text{chironomid}}$ are the δ^{15}N values for an individual fish and the lake-specific mean for sediment-dwelling chironomid larvae, and TFF is an assumed δ^{15}N trophic fractionation factor of 3.4 between a predator and its prey (Post, 2002). Lake-specific δ^{15}N values for chironomids are provided in supplemental Table S2.

Long-term growth rates of Arctic char and brook trout were examined in two different ways, using a continous and a categorical variable to characterize the length-at-age patterns. First, fish were pooled across lakes to generate a species-specific length-at-age distribution, which was fit with an exponential curve ($\text{Length}=a*(1-b^{\text{Age}})$) using the dynamic curve function in SigmaPlot 11.0 (Systat Software Inc., San Jose, California). A continuous variable for growth rate, termed relative length-at-age (RLAA), was calculated as the difference between total length of individual fish (L_{fish}) and the modelled total length for fish with the same age (L_{age}) determined from the exponential curve ($RLAA=L_{fish}-L_{age}$). Negative RLAA values indicated that a fish was smaller than the modelled length for a given age, while positive values indicated a fish was larger. For each species, fish were categorized as "slower", "unclassified" or "faster" growing based on the 0–25th percentiles, 26–74th percentiles, and 75–100th percentiles of RLAA values, respectively, to compare growth categories in a similar manner to van der Velden et al. (2012) Note that all Arctic char in the study lakes grew relatively slowly (e.g., median length at age 10 was 28 cm), and the term "faster" grower in this context only refers to a comparison with other Arctic char. Data for a one-year old brook trout was excluded from the analysis because it was the only fish in that age class. In addition, the influence of short-term growth rates was examined using the RNA/DNA ratio of fish muscle. Measurements of age or muscle RNA/DNA ratios were not available for all fish (4% and 20% of values missing, respectively).

Statistical models were tested with R (http://cran.r-project.org). Analysis of Covariance (ANCOVA, lm function in stats package) tested differences in log-transformed muscle THg concentration between slower- and faster-growing fish categories, after quantifying the effect of age. Separate tests were conducted for Arctic char and brook trout with fish pooled across lakes. Multiple linear regression models were tested for each species to identify the relative importance of explanatory variables (age, diet, growth) in relation to log-transformed muscle THg concentration. Regression models were tested with the lm function, and the significance of individual variables was determined using type III sums of squares (car package). The relative importance of explanatory variables in the regression models was evaluated by an "lmg" index using the relaimpo package, which calculates the average partial r^2 for all possible orderings of the explanatory variables because of the influence of variable sequence on the partial r^2 (Grömping, 2006). The lmg index (refered to here as the independent partial r^2) is equivalent to the independent contribution of each predictor variable to the variance of the response variable in a multiple regression model (Chevan and Sutherland, 1991). Comparisons between two groups were made with *t*-tests or Mann-Whitney U tests (if normality or homogeneity of variance were not satisfied), and Pearson correlations were used to test for associations among explanatory variables.

3. Results

3.1. Characteristics of the fish populations

Brook trout across the study lakes had lengths of 12.2–36.7 cm and ages of 1–6 years (Table 1). In contrast, Arctic char reached larger sizes and were longer-lived than the brook trout, with lengths of 13.5–64.5 cm and ages of 3–26 years (Table 1). Both species showed a range of trophic position estimates consistent with some individuals feeding on aquatic invertebrates while others also likely consumed fish. The lake-mean $\delta^{13}C$ values of brook trout and Arctic char ranged from -27.2 to -23.3‰ and -23.9 to -19.7‰, respectively, and there was generally little variability within a lake. While the benthic food webs supporting Arctic char have been previously characterized in the study lakes, new stomach content data of brook trout indicated they fed on a variety of macroinvertebrates (e.g., amphipods, caddisflies, chironomids, dragonfly nymphs, and snails) (Supplemental Table S4), and the $\delta^{13}C$ values of macroinvertebrates were similar to the fish (Table 1, Supplemental Table S3). The muscle C:N ratios (a proxy for lipid content) showed little variation among fish for either brook trout (3.9 ± 0.1) or Arctic char (2.8 ± 0.1). Muscle THg concentrations of brook trout varied over an order of magnitude from 0.036–0.528 μg/g (wet weight). Arctic char THg concentrations varied even more from

0.030–3.49 μg/g and 16% of the 133 char had concentrations > 0.5 μg/g. The MMHg concentrations of benthic chironomids from the brook trout lakes and Arctic char lakes ranged from 32–160 and 4–173 ng/g (dry weight), respectively, (Supplemental Table S2), indicating that MMHg exposure to the base of food webs differed among the study lakes. For the subarctic taiga lakes, MMHg concentrations of other macroinvertebrates were similar to and correlated with MMHg concentrations of chironomids in the same lakes (Supplemental Table S3, Fig. S2). Those measurements justify the use of chironomid MMHg concentrations as a proxy for among-lakes differences in food web MMHg exposure.

Table 1. Mean (range) of total length, age, trophic position (TP), muscle total mercury concentration (THg, wet weight)), and δ^{13}C values of brook trout from taiga lakes and Arctic char from tundra and polar desert lakes.

Lake	Fish *n*	Length (cm)	Age (years)	TP	THg (µg/g w.w.)	δ^{13}C (‰)
Taiga brook trout						
Lake 1	11	23.9	3	3.0	0.137	-25.9
		(17.7–29.1)	(2–5)	(2.9–3.1)	(0.072–0.176)	(-26.4 – -25.2)
Lake 2	10	18.6	4	3.2	0.294	-27.2
		(17.4–19.6)	(2–6)	(3.1–3.3)	(0.209–0.487)	(-27.6 – -26.8)
Lake 3	15	27.0	4	4.0	0.115	-23.5
		(14.8–36.6)	(2–6)	(3.7–4.4)	(0.042–0.248)	(-26.1 – -22.2)
Lake 4	15	26.4	3	3.6	0.079	-24.8
		(12.2–36.2)	(2–4)	(3.3–3.9)	(0.036–0.128)	(-25.7 – -24.1)
Lake 5	10	29.4	4	3.6	0.167	-23.3
		(20.2–36.7)	(1–6)	(3.1–4.1)	(0.074–0.528)	(-24.7 – -22.5)
Tundra Arctic char						
Lake 6	28	30.1	8	3.9	0.197	-20.2
		(14.5–58.0)	(3–20)	(3.2–4.6)	(0.043–1.17)	(-22.0 – -17.6)
Lake 7	29	31.9	11	3.2	0.481	-21.3
		(13.9–59.0)	(4–19)	(2.5–3.9)	(0.053–3.49)	(-25.7 – -18.9)
Lake 8	33	25.8	10	3.6	0.124	-19.7
		(13.5–64.5)	(5–26)	(3.1–4.5)	(0.030–1.21)	(-23.9 – -17.3)
Polar desert Arctic char						
Lake 9	11	50.5	16	4.0	1.50	-23.2
		(45.9–59.0)	(12–25)	(3.8–4.3)	(0.801–2.65)	(-23.8 – -22.7)
Lake 10	7	42.1	16	2.5	0.230	-23.9
		(39.9–53.2)	(15–17)	(2.1–2.9)	(0.139–0.386)	(-27.3 – -22.3)
Lake 11	14	42.0	17	3.2	0.130	-22.2
		(37.1–45.8)	(15–20)	(2.8–3.6)	(0.058–0.244)	(-22.9 – -21.6)
Lake 12	13	36.4	14	3.3	0.102	-23.5
		(33.5–41.5)	(12–17)	(3.0–3.7)	(0.062–0.212)	(-24.2 – -23.0)

3.2. Diet influences on long-term growth rates and mercury concentration

Growth rates based on length-at-age measurements showed large variation among Arctic char or brook trout pooled across lakes (Fig. 1). Exponential curves fit to the length-at-age data were highly significant for both species ($p < 0.001$). The length of brook trout ranged ~10–15 cm for any given age while those of Arctic char ranged even more, from ~20–30 cm for older fish. On average, brook trout categorized as faster-growing were 14 cm longer than slower-growing fish of the same age (mean ± SD: 31.9 ± 3.8 cm versus 18.3 ± 3.1 cm, *t*-test, $p < 0.001$, $n = 30$). Similarly, Arctic char categorized as faster-growing were on average 20 cm longer than slower-growing fish of the same age (46.1 ± 10.3 cm versus 25.7 ± 10.5 cm, *t*-test, $p < 0.001$, $n = 72$). Note that both fast-growing and slow-growing Arctic char were found in each of the tundra and polar desert ecoregions (Supplemental Fig. S2).

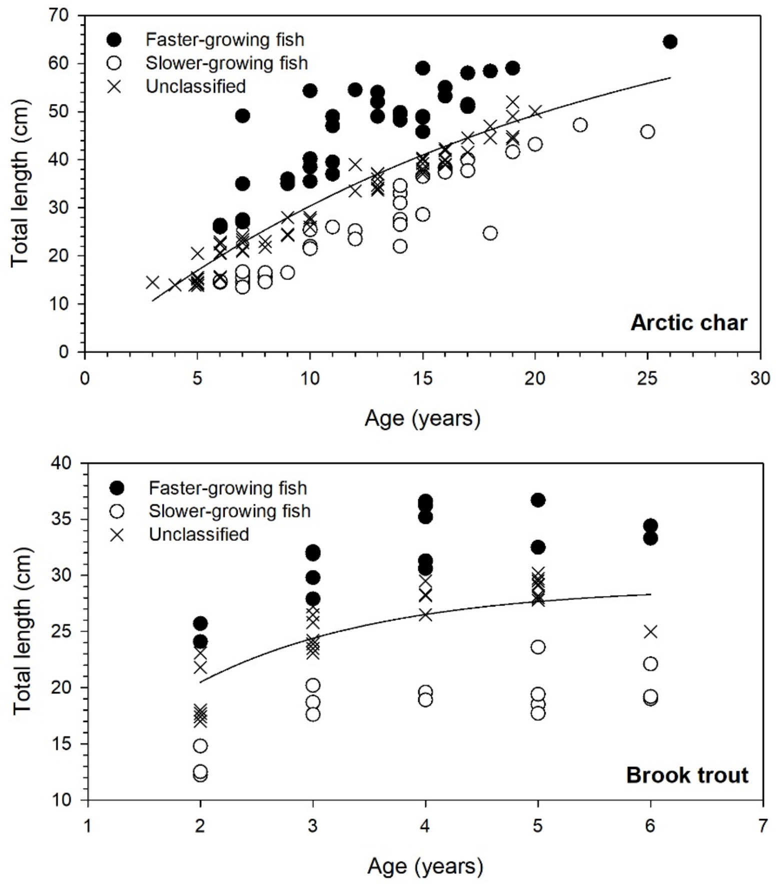

Figure 1. Length-at-age of brook trout from 5 lakes (*n* = 57) and Arctic char from 7 lakes (*n* = 133) in the eastern Canada Arctic. Individual fish were categorized as faster- or slower-growing or unclassified based their length relative to the modelled exponential growth curve (see methods).

Diet influenced the growth of brook trout and Arctic char. For both species, faster-growing fish fed at a higher trophic position than slower-growing fish (Mann-Whitney rank sum tests, $p < 0.001$, $n = 30$ or 72; Supplemental Fig. S3). The median trophic position of brook trout and Arctic char was 0.5 and 0.8 units higher, respectively, in faster-growing fish. Faster-growing brook trout had higher $\delta^{13}C$ values than slower growers (*t*-test, $p = 0.006$, $n = 30$) but that was not the case for Arctic char (*t*-test, $p = 0.26$, $n = 72$). Thus, the growth of both fish species was related to their diet, with trophic position and carbon source (for brook trout) contributing to enhanced growth.

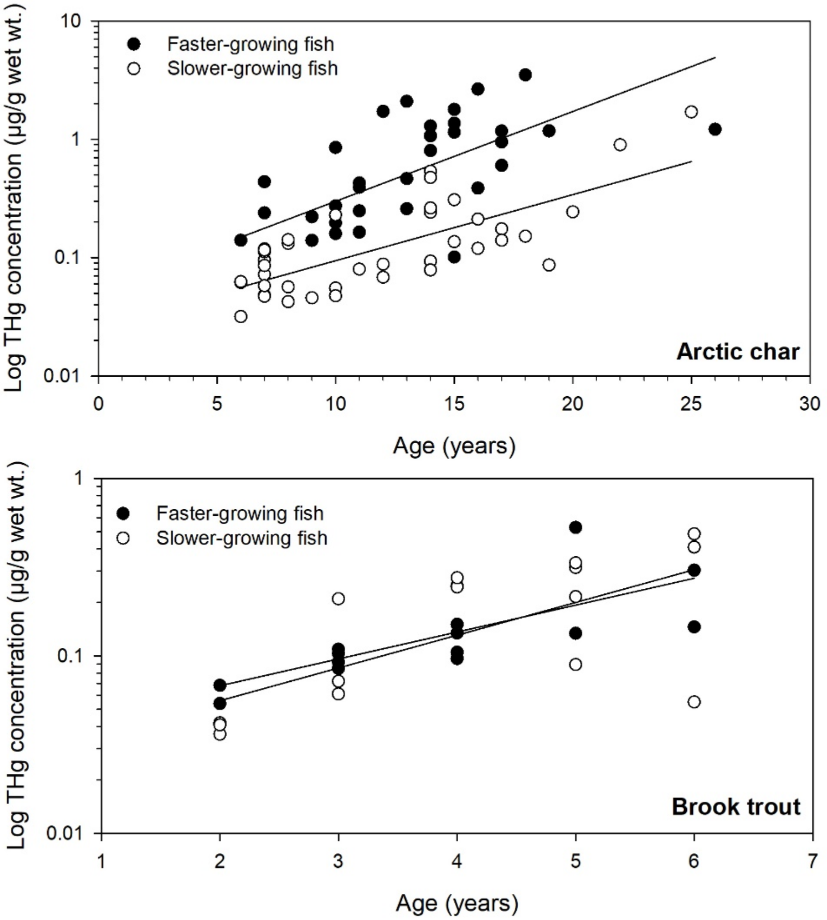

Figure 2. Comparison of log muscle THg concentration between growth categories after controlling for the effect of age for Arctic char ($n = 72$) or brook trout ($n = 30$) (see text for ANCOVA results).

Total mercury concentrations were not lower in fish categorized as faster-growing (Fig. 2). For Arctic char, log THg concentrations of fish muscle increased with age and were higher in faster than slower growing fish (ANCOVA, age $p < 0.001$, growth category $p < 0.001$, $n = 72$).

In contrast, log THg concentrations of brook trout increased with age but there was no growth effect (ANCOVA, age $p < 0.001$, growth category $p = 0.83$, $n = 30$).

Long-term growth rates estimated by a continuous variable, RLAA, showed similar patterns with diet and fish THg concentration compared to the analysis with growth categories. RLAA was positively correlated with trophic position for both Arctic char and brook trout (Fig. 3), indicating that faster-growing fish tended to have a higher trophic position. For brook trout, RLAA was also positively correlated with muscle $\delta^{13}C$ (Pearson $r = 0.50$, $p < 0.001$, $n = 57$), but that was not the case for Arctic char (Pearson $r = 0.05$, $p = 0.56$, $n = 133$). RLAA was positively correlated with the log THg concentration of Arctic char (Pearson $r = 0.52$, $p < 0.001$, $n = 133$) and there was no correlation for brook trout (Pearson $r = -0.10$, $p = 0.46$, $n = 57$). Thus, this continuous variable for growth (RLAA) similarly showed that growth rates were influenced by diet and faster-growing fish did not have lower THg concentrations.

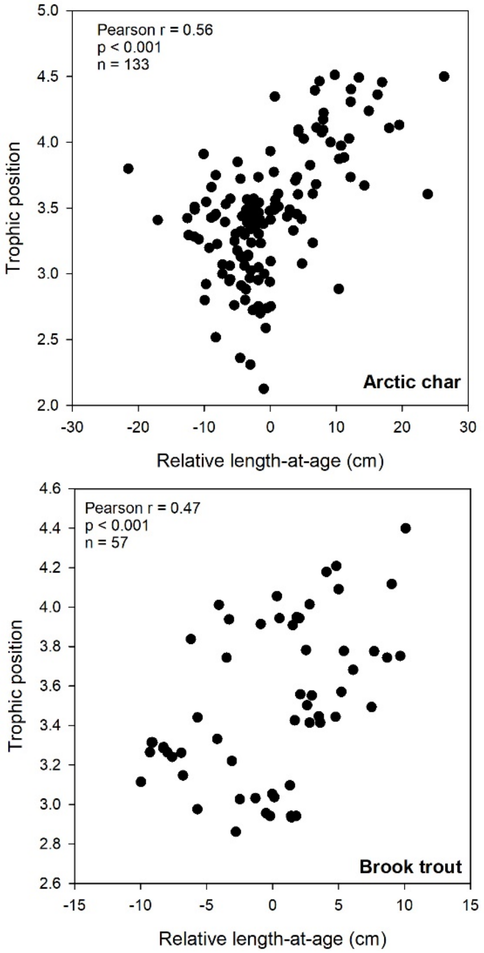

Figure 3. Correlations between trophic position and long-term growth rates (relative length-at-age) for brook trout and Arctic char.

Explanatory variables of log-transformed fish THg concentrations were tested with multiple linear regression models that included age, long-term growth rate (RLAA), trophic position, δ^{13}C, and lake-specific MMHg accumulation near the base of the food web (using chironomid MMHg concentrations). Multiple regression models were highly significant for both salmonid species, explaining almost 75% of the variation in log THg concentration of fish within and among lakes (Table 2). Age, RLAA, and diet (chironomid) MMHg concentrations were highly significant explanatory variables and had positive effects for both brook trout and Arctic char. Trophic position was also a significant positive explanatory variable in the Arctic char model. Independed partial r^2 values indicated that age and diet (trophic position and chironomid MMHg) were stronger explanatory variables, accounting more than 50% of the variance in fish THg concentration, while growth rate (RLAA) was less important (Table 2). Positive correlations between RLAA and fish THg concentrations in the models were contrary to a hypothesized negative biodilution effect.

Table 2. Results of multiple linear regression models testing the relative importance of explanatory variables of log-transformed muscle THg concentration for brook trout and Arctic char.

Explanatory variable	Brook trout Model r^2_{adj} = 0.74, p < 0.001, n = 57				Arctic char Model r^2_{adj} = 0.71, p < 0.001, n = 133			
	F	P	Independent partial r^2	Std. Co.	F	P	Independent partial r^2	Std. Co.
Age (years)	23.9	<0.001	0.21	0.36	71.3	<0.001	0.26	0.46
RLAA (cm)	31.6	<0.001	0.10	0.58	30.4	<0.001	0.16	0.33
Diet MMHg (ng/g)	34.9	<0.001	0.45	0.97	23.2	<0.001	0.19	0.30
TP	0.1	0.72	---	---	10.0	0.002	0.11	0.21
$\delta^{13}C$ (‰)	0.6	0.44	---	---	0.0	0.984	---	---

RLAA = relative length-at-age, Diet MMHg = lake-mean MMHg concentration of benthic chironomids, TP = trophic position, Std. Co. = standardized coefficient, Independent partial r^2 = contribution averaged over all possible orderings of explanatory variables (see methods)

3.3. Influence of short-term growth rates on fish mercury concentrations

Muscle RNA/DNA ratios were lower in brook trout (mean ± SD=1.8 ± 0.8, n = 57) than in Arctic char (mean ± SD = 2.9 ± 1.1, n = 100), suggesting species-specific differences for this physiological proxy of growth rate (Supplemental Fig. S4). Muscle DNA content was similar between Arctic char (1.2 ± 0.5 μg/mg) and brook trout (0.9 ± 0.3 μg/mg), and therefore, species-specific differences in RNA/DNA ratios were due to the extent of RNA expression in muscle cells. There was large (five-fold) variation in muscle RNA/DNA ratios among individual fish within a species (Supplemental Fig. S4).

The muscle RNA/DNA ratio of brook trout (n = 55–58) was not correlated with age, trophic position, or RLAA ($p > 0.05$,) but decreased with length (Pearson r = -0.35, p = 0.007) and mass (Pearson r = -0.28, p = 0.035), and increased with $\delta^{13}C$ values (Pearson r = 0.27, p = 0.037). For Arctic char (n = 98–100), muscle RNA/DNA ratio increased with $\delta^{13}C$ (Pearson r = 0.23, p = 0.022) and trophic position (Pearson r = 0.23, p = 0.022) but was not correlated with length, mass, age or RLAA ($p > 0.05$). These results showed a positive, albeit weak, correlation between diet and muscle RNA/DNA ratio for both species and a negative correlation with size for brook trout. The log-transformed THg concentration of brook trout muscle was negatively correlated with its RNA/DNA ratio (Pearson r = -0.31, p = 0.021, Supplemental Fig. S5). This pattern would be expected if biodilution from faster growth rates was resulting in lower THg concentrations. However, muscle RNA/DNA ratio was not a significant explanatory variable of THg concentration for either species in multiple regression models that included age and diet effects (Supplemental Table S3).

The muscle RNA/DNA ratio of Arctic char varied seasonally in two tundra lakes where fish were collected in both winter and summer. Winter-sampled fish had a lower RNA/DNA ratios than those sampled in summer (t-test, p = 0.013, n = 51; Fig. 4), suggesting slower short-term muscle growth of char in winter. Muscle RNA/DNA ratio was not correlated (p = 0.23) with log

THg concentration for the Arctic char in those two lakes, after including age and diet variables in a multiple regression model (Supplemental Table S4).

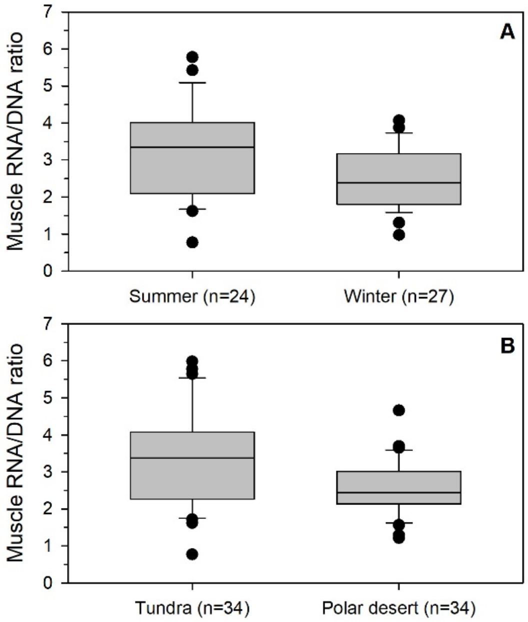

Figure 4. Comparison of RNA/DNA ratios (a physiological proxy of short-term growth rates) in Arctic char muscle between seasons (A) and ecoregions (B).

Arctic char also showed regional variation in muscle RNA/DNA ratios. The subset of fish collected in summer from more productive tundra lakes had higher ratios than those from polar desert lakes (Mann-Whitney U test, *p* = 0.003, *n* = 68; Fig. 4). Those Arctic char from tundra lakes also had higher length-at-age (RLAA) than char from polar desert lakes (Mann-Whitney U test, *p* = 0.003, *n* = 68), consistent with the interpretation of RNA/DNA results that the char from tundra lakes had faster summer growth rates. However, muscle RNA/DNA ratios of Arctic char did not correlate (*p* = 0.19) with log THg concentrations for this subset of fish in a multiple regression model with age and diet co-variates (Supplemental Table S5). Thus, inferred differences in short-term growth rates between tundra and polar desert lakes did not explain variation in muscle THg concentrations of Arctic char.

4. Discussion

4.1. Explanatory variables of fish mercury concentrations

Diet and age best explained muscle THg concentrations of two salmonid species in the Arctic study lakes. Highly significant linear regression models accounted for close to 75% of the within- and among-lake variation of THg concentration in Arctic char or brook trout, of which more than 50% was related to age and diet variables (trophic position, diet MMHg concentration). Food web exposure to MeHg differed among sites while growth rates and diet varied among fish both within and between populations. The fishes were supported by benthic-derived carbon as indicated by their carbon stable isotopes, stomach contents (of brook trout), and diet characterization in previous studies (of landlocked Arctic char; Gallagher and Dick, 2010; Gantner et al., 2010; Lescord et al., 2015). In contrast to our hypothesis, faster-growing fishes had higher THg concentrations because their long-term growth rates (RLAA) were related to trophic position. Short-term growth rates, inferred from muscle RNA/DNA ratios, did not explain or very weakly explained fish THg concentration. These findings were generated in resource-poor Arctic lakes with low fish diversity (i.e. 1 or 2 fish species) and simple, benthic-dominated food webs. Drivers of salmonid THg concentrations may be different in other Arctic lakes with more complex food webs and greater pelagic production such as in northern Europe (Eloranta et al., 2015; Kahilainen et al., 2016) or western Canada (Evans et al., 2005; Rohonczy et al., 2020).

4.2. Diet influences on growth

A major finding of this study is that diet explained why faster growth rates were not associated with lower THg concentrations in two Arctic salmonid species. Fish with faster growth for a given age fed at a higher trophic position, which was equivalent to approximately one trophic level higher in the fastest-growing fish relative to the slowest growers (Fig. 4, Supplemental Fig 3). This increase in trophic position can be explained by the consumption of fish. In resource-poor Arctic lakes, fish consumption confers an advantage for growth through greater caloric intake (Power et al., 2009). Stomach contents of the brook trout showed some fish were feeding on ninespine stickleback, which indicates fish consumption was occurring to some extent. For Arctic char, canibalism is well documented for populations in lakes of the eastern Canadian Arctic based on stomach contents, nitrogen stable isotopes, and fish parasite tracers, and the largest lacustrine morphs of char are piscivorous (Gallagher and Dick, 2010; Guiguer et al., 2002; Hobson and Welch, 1995; Power et al., 2009). In one tundra lake with Arctic char (Lake 6) where ninespine stickleback were also present, the higher trophic position of faster-growing fish may have also been supported by consumption of stickleback (Gallagher and Dick, 2010). While fish consumption allowed for greater growth by a given age, it also promoted mercury bioaccumulation because of greater mercury intake from eating higher trophic level prey. For brook trout, there was no significant difference in THg concentration between fish categorized as slower- or faster-growing (Fig. 2), nor was trophic position a significant variable in the multiple regression model (Table 2). Further, muscle RNA/DNA ratios of brook trout were negatively correlated with THg concentration (Fig. S5). Those results possibly reflect a dilution effect where greater mercury intake from feeding at a higher trophic position was somewhat offset by biomass dilution from faster growth for brook trout. Nevertheless, the multiple regression modelling indicated that the net effect of dietary exposure and age on muscle mercury concentration was greater than any potential offset by biomass dilution. In contrast with this study, faster growth rates in fish are not necessarily associated with consuming more contaminated prey, and biodilution of mercury can occur in temperate lakes from consumption of higher caloric invertebrate prey with lower mercury concentrations (Karimi et al., 2016).

Earlier research by van der Velden et al. (2012) on an Arctic char population in Heintzelman Lake (Ellesmere Island, Canada) found that muscle THg concentration did not differ between slow- and fast-growing fish. In that study, the lake-dwelling char were insectivores, and slower growth was likely due to greater energy allocation to reproduction rather than a difference in trophic position. Their research is in agreement with findings of the current study regarding the lack of growth rate influence on mercury fish concentration although the underlying drivers of growth in Arctic char were different. Lavigne et al. (2010) similarly did not find an effect of biodilution on THg concentrations of another salmonid species, lake trout, in northern Quebec (Canada) but biodilution was reported for two other fish species.

4.3. Application of RNA/DNA ratio in muscle to test short-term growth rates

To our knowledge, this study is the first to use RNA/DNA ratios in fish muscle to examine short-term growth effects on mercury concentration. On average, differences in inferred short-term growth were found for Arctic char between summer and winter, and between tundra and polar desert lakes using this physiological proxy. However, muscle RNA/DNA values varied considerably among individual fish within the same season or ecoregion, and high variability has been reported elsewhere for this measurement in fish, including Arctic char (Ferguson et al., 1990). Fish muscle RNA/DNA ratios can respond rapidly (i.e., days to weeks) to changes in food availability or environmental conditions (Chícharo and Chícharo, 2008; Stierhoff et al., 2009), and that time-scale may be shorter than rates of change in muscle mercury concentration. Additional factors such as fish age and diet, and water temperature can also influence fish muscle RNA/DNA ratios (Chícharo and Chícharo, 2008; Roberts et al., 2011). Research is recommended to further constrain the appropriate time scale and conditions for using muscle RNA/DNA ratios to track potential influences of short-term growth on mercury concentration.

4.4. Implications for somatic growth dilution theory

This theory predicts that more efficient growth will result in a lower body mercury concentration (Trudel and Rasmussen, 2006). More specifically, the prediction has been phrased as “fish that grow to a larger size for a given age and prey intake will have a lower mercury concentration” to acknowledge the influence of prey type and age (van der Velden et al., 2012; Ward et al., 2010). This study did not specifically test SGD because the theory is predicated on growth efficiency, and key variables for energy allocation (consumption rate, activity rate, reproductive effort) were not measured (Trudel and Rasmussen, 2006). Nevertheless, our findings on diet-growth influences suggest that bioenergetic assumptions of SGD are not realistic in the case of lake-dwelling salmonids in the eastern Canadian Arctic. Size variation and morphological diversity are common within populations of Arctic char, and differences in growth are probably not determined by efficiency of energy use but rather by factors such as diet, resource availability, and habitat (Guénard et al., 2010; Power et al., 2009), which also influence mercury exposure. Muscle biodilution of mercury has been reported for other Arctic fish species and regions such as lake whitefish in a Finnish subarctic lake (Keva et al., 2017), and perch, roach and northern pike in a Norwegian subarctic lake (Sharma et al., 2008). A common element of studies that found biodilution effects is the rapid onset of growth which occurred for: (1) juvenile fish (Ward et al., 2010), (2) between winter starvation and summer growth (Keva et al., 2017), (3) after the removal of predation pressure (Sharma et al., 2008), or (4) from stocking of prey fish (Lepak et al., 2012). Future research should focus on identifying the key environmental conditions where fish mercury concentrations are influenced by SGD.

4.5. Fish mercury concentrations in a changing Arctic environment

The length-at-age of lake-dwelling Arctic char declines with latitude in the Canadian Arctic (Chavarie et al., 2010), reflecting slower growth in colder, lower productivity ecosystems. Our study lakes spanned a 20° latitudinal gradient, with warmer water temperatures and greater organic matter in subarctic taiga lakes compared with tundra and polar desert lakes. Although the effects of temperature and productivity were not explicitly tested, similar modelling results were found (i.e., the importance of age and diet for fish bioaccumulation of mercury) for both a fast-growing fish species in the taiga lakes and a slower growing species in the tundra and polar desert lakes. Previous reviews of Arctic climate change have suggested altered growth conditions for fish may have a long-term impact on their contaminant concentrations (Reist et al., 2006a; Stern et al., 2012). However, this study for two salmonid species and earlier work on Arctic char (van der Velden et al., 2013; 2012) have demonstrated age (period of exposure) is a more important determinant of mercury concentration than length (growth rate). Higher mercury in fish that take longer to reach a specific length (length-adjusted concentration) is due to the older age of the fish rather than SGD. This study found MMHg concentrations near the base of the food web were a key driver of among-lake differences in fish mercury concentrations. Together, these findings suggest environmental change in the Arctic that affects food web exposure to MMHg (e.g., atmospheric mercury deposition, MMHg production, uptake at the base of the food web, food web structure) may have more of a long-term impact on mercury bioaccumulation in fish than improved growth from warmer temperatures or increased lake productivity (Reist et al., 2006b; Stern et al., 2012). Bioenergetic modelling of mercury bioaccumulation in lake-dwelling Arctic char similarly showed their mercury concentrations were highly responsive to changes in dietary mercury and not changes in water temperature (Drevnick, 2014). Since warming enhances the production of methylmercury in Arctic lake sediment (Hudelson et al., 2020), tracking future changes in MMHg exposure to food webs in Arctic lakes is warranted.

5. Conclusions

Using data on two salmonid fish species from lakes in three ecoregions of the eastern Canadian Arctic, we tested the hypothesis that faster-growing fish have lower mercury concentrations after quantifying the influence of age and diet. We found age and diet indices were the dominant explanatory variables of muscle mercury concentrations. Faster-growing fish had higher mercury concencentrations because those fish were feeding at a higher trophic position. In these resource-poor Arctic lakes, differences in growth rate were influenced by diet rather than growth efficiency. These findings contribute to the evolving science on growth rate effects in relation to other drivers of fish mercury concentration, which is needed to evaluate multiple stressors currently impacting aquatic ecosystems such as climate change in the Arctic.

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Supplemental Information

The supplemental information to this article can be found online at:

References

Braaten, H.F.V., Fjeld, E., Rognerud, S., Lund, E., Larssen, T., 2014. Seasonal and year-to-year variation of mercury concentration in perch (*Perca fluviatilis*) in boreal lakes. Environmental Toxicology and Chemistry 33, 2661-2670.

Cabana, G., Rasmussen, J.B., 1994. Modelling food chain structure and contaminant bioaccumulation using stable nitrogen isotopes. Nature 372, 255-257.

Carroll, R.W.H., Warwick, J.J., 2017. The importance of dynamic mercury water column concentrations on body burdens in a planktivorous fish: A bioenergetic and mercury mass balance perspective. Ecological Modelling 364, 66-76.

Chavarie, L., Dempson, J.B., Schwarz, C.J., Reist, J.D., Power, G., Power, M., 2010. Latitudinal variation in growth among Arctic charr in eastern North America: Evidence for countergradient variation? Hydrobiologia 650, 161-177.

Chételat, J., Cloutier, L., Amyot, M., 2010. Carbon sources for lake food webs in the Canadian High Arctic and other regions of Arctic North America. Polar Biology 33, 1111-1123.

Chételat, J., Poulain, A.J., Amyot, M., Cloutier, L., Hintelmann, H., 2014. Ecological determinants of methylmercury bioaccumulation in benthic invertebrates of polar desert lakes. Polar Biology 37, 1785-1796.

Chételat, J., Richardson, M.C., Macmillan, G.A., Amyot, M., Poulain, A.J., 2018. Ratio of Methylmercury to Dissolved Organic Carbon in Water Explains Methylmercury Bioaccumulation Across a Latitudinal Gradient from North-Temperate to Arctic Lakes. Environmental Science and Technology 52, 79-88.

Chevan, A., Sutherland, M., 1991. Hierarchical Partitioning. The American Statistician 45, 90-96.

Chícharo, M.A., Chícharo, L., 2008. RNA:DNA ratio and other nucleic acid derived indices in marine ecology. International Journal of Molecular Sciences 9, 1453-1471.

Chumchal, M.M., Drenner, R.W., Cross, D.R., Hambright, K.D., 2010. Factors influencing mercury accumulation in three species of forage fish from Caddo Lake, Texas, USA. Journal of Environmental Sciences 22, 1158-1163.

Ciotti, B.J., Targett, T.E., Nash, R.D.M., Batty, R.S., Burrows, M.T., Geffen, A.J., 2010. Development, validation and field application of an RNA-based growth index in juvenile plaice *Pleuronectes platessa*. Journal of Fish Biology 77, 2181-2209.

Dellinger, J., Dellinger, M., Yauck, J.S., 2012. Mercury exposure in vulnerable populations guidelines for fish consumption, Mercury in the Environment: Pattern and Process, pp. 289-300.

Doyon, J.F., Schetagne, R., Verdon, R., 1998. Different mercury bioaccumulation rates between sympatric populations of dwarf and normal lake whitefish (*Coregonus clupeaformis*) in the La Grande complex watershed, James Bay, Quebec. Biogeochemistry 40, 203-216.

Drevnick, P.E., 2014. Impact of Climate Warming on Mercury Dynamics in Arctic Lakes. Synopsis of Research Conducted under the 2013-2014 Northern Contaminants Program, Aboriginal Affairs and Northern Development Canada, pp. 341-350.

Eagles-Smith, C.A., Silbergeld, E.K., Basu, N., Bustamante, P., Diaz-Barriga, F., Hopkins, W.A., Kidd, K.A., Nyland, J.F., 2018. Modulators of mercury risk to wildlife and humans in the context of rapid global change. Ambio 47, 170-197.

Eagles-Smith, C.A., Suchanek, T.H., Colwell, A.E., Anderson, N.L., 2008. Mercury trophic transfer in a eutrophic lake: The importance of habitat-specific foraging. Ecological Applications 18, A196-A212.

Eloranta, A.P., Kahilainen, K.K., Amundsen, P.A., Knudsen, R., Harrod, C., Jones, R.I., 2015. Lake size and fish diversity determine resource use and trophic position of a top predator in high-latitude lakes. Ecology and Evolution 5, 1664-1675.

Environment and Climate Change Canada, 2019. Mercury in landlocked Arctic char Government of Canada Open Data Portal, available at https://open.canada.ca/data/en/dataset/90e55c10-6fef-4387-a03f-6cd1a644e8b3.

Essington, T.E., Houser, J.N., 2003. The effect of whole-lake nutrient enrichment on mercury concentration in age-1 yellow perch. Transactions of the American Fisheries Society 132, 57-68.

Evans, M.S., Lockhart, W.L., Doetzel, L., Low, G., Muir, D., Kidd, K., Stephens, G., Delaronde, J., 2005. Elevated mercury concentrations in fish in lakes in the Mackenzie River Basin: The role of physical, chemical, and biological factors. Science of the Total Environment 351-352, 479-500.

Ferguson, M.M., Noakes, D.L.G., Skúlason, S., Snorrason, S.S., 1990. Life-history styles and somatic allocation in iteroporous arctic charr and semelparous pink salmon. Environmental Biology of Fishes 28, 267-272.

Fuchsman, P.C., Henning, M.H., Sorensen, M.T., Brown, L.E., Bock, M.J., Beals, C.D., Lyndall, J.L., Magar, V.S., 2016. Critical perspectives on mercury toxicity reference values for protection of fish. Environmental Toxicology and Chemistry 35, 529-549.

Gallagher, C.P., Dick, T.A., 2010. Trophic structure of a landlocked Arctic char *Salvelinus alpinus* population from southern Baffin Island, Canada. Ecology of Freshwater Fish 19, 39-50.

Gantner, N., Muir, D.C., Power, M., Iqaluk, D., Reist, J.D., Babaluk, J.A., Meili, M., Borg, H., Hammar, J., Michaud, W., Dempson, B., Solomon, K.R., 2010. Mercury concentrations in landlocked Arctic char (*Salvelinus alpinus*) from the Canadian Arctic. Part II: Influence of lake biotic and abiotic characteristics on geographic trends in 27 populations. Environmental Toxicology and Chemistry 29, 633−643.

Grömping, U., 2006. Relative importance for linear regression in R: The package relaimpo. Journal of Statistical Software 17, 1-27.

Guénard, G., Boisclair, D., Ugedal, O., Forseth, T., Jonsson, B., Fleming, I.A., 2010. Experimental assessment of the bioenergetic and behavioural differences between two morphologically distinct populations of arctic char (*Salvelinus alpinus*). Canadian Journal of Fisheries and Aquatic Sciences 67, 580-595.

Guiguer, K.R.R.A., Reist, J.D., Power, M., Babaluk, J.A., 2002. Using stable isotopes to confirm the trophic ecology of Arctic charr morphotypes from Lake Hazen, Nunavut, Canada. Journal of Fish Biology 60, 348-362.

Harris, R.C., Bodaly, R.A., 1998. Temperature, growth and dietary effects on fish mercury dynamics in two Ontario lakes. Biogeochemistry 40, 175-187.

Hobson, K.A., Welch, H.E., 1995. Cannibalism and trophic structure in a high Arctic lake: insights from stable-isotope analysis. Canadian Journal of Fisheries and Aquatic Sciences 52, 1195-1201.

Hudelson, K.E., Drevnick, P.E., Wang, F., Armstrong, D., Fisk, A.T., 2020. Mercury methylation and demethylation potentials in Arctic lake sediments. Chemosphere 248, 126001.

Hudelson, K.E., Muir, D.C.G., Drevnick, P.E., Köck, G., Iqaluk, D., Wang, X., Kirk, J.L., Barst, B.D., Grgicak-Mannion, A., Shearon, R., Fisk, A.T., 2019. Temporal trends, lake-to-lake variation, and climate effects on Arctic char (*Salvelinus alpinus*) mercury concentrations from six High Arctic lakes in Nunavut, Canada. Science of the Total Environment 678, 801-812.

Kahilainen, K.K., Thomas, S.M., Keva, O., Hayden, B., Knudsen, R., Eloranta, A.P., Tuohiluoto, K., Amundsen, P.A., Malinen, T., Järvinen, A., 2016. Seasonal dietary shift to zooplankton influences stable isotope ratios and total mercury concentrations in Arctic charr (Salvelinus alpinus (L.)). Hydrobiologia 783, 47-63.

Karimi, R., Chen, C.Y., Folt, C.L., 2016. Comparing nearshore benthic and pelagic prey as mercury sources to lake fish: The importance of prey quality and mercury content. Science of the Total Environment 565, 211-221.

Keva, O., Hayden, B., Harrod, C., Kahilainen, K.K., 2017. Total mercury concentrations in liver and muscle of European whitefish (*Coregonus lavaretus* (L.)) in a subarctic lake - Assessing the factors driving year-round variation. Environmental Pollution 231, 1518-1528.

Kidd, K., Batchelar, K., 2011. 5 - Mercury, in: Wood, C.M., Farrell, A.P., Brauner, C.J. (Eds.), Fish Physiology. Academic Press, pp. 237-295.

Lavigne, M., Lucotte, M., Paquet, S., 2010. Relationship between mercury concentration and growth rates for walleyes, Northern Pike, and Lake Trout from Quebec lakes. North American Journal of Fisheries Management 30, 1221-1237.

Lavoie, R.A., Jardine, T.D., Chumchal, M.M., Kidd, K.A., Campbell, L.M., 2013. Biomagnification of mercury in aquatic food webs: A worldwide meta-analysis. Environmental Science and Technology 47, 13385-13394.

Lepak, J.M., Hooten, M.B., Johnson, B.M., 2012. The influence of external subsidies on diet, growth and Hg concentrations of freshwater sport fish: Implications for management and fish consumption advisories. Ecotoxicology 21, 1878-1888.

Lepak, J.M., Robinson, J.M., Kraft, C.E., Josephson, D.C., 2009. Changes in mercury bioaccumulation in an apex predator in response to removal of an introduced competitor. Ecotoxicology 18, 488-498.

Lescord, G.L., Kidd, K.A., Kirk, J.L., O'Driscoll, N.J., Wang, X., Muir, D.C.G., 2015. Factors affecting biotic mercury concentrations and biomagnification through lake food webs in the Canadian high Arctic. Science of the Total Environment 509-510, 195-205.

Li, J., Haffner, G.D., Paterson, G., Walters, D.M., Burtnyk, M.D., Drouillard, K.G., 2018. Importance of growth rate on mercury and polychlorinated biphenyl bioaccumulation in fish. Environmental Toxicology and Chemistry 37, 1655-1667.

Marusczak, N., Larose, C., Dommergue, A., Paquet, S., Beaulne, J.S., Maury-Brachet, R., Lucotte, M., Nedjai, R., Ferrari, C.P., 2011. Mercury and methylmercury concentrations in high altitude lakes and fish (Arctic charr) from the French Alps related to watershed characteristics. Science of the Total Environment 409, 1909-1915.

Pickhardt, P.C., Folt, C.L., Chen, C.Y., Klaue, B., Blum, J.D., 2002. Algal blooms reduce the uptake of toxic methylmercury in freshwater food webs. Proceedings of the National Academy of Sciences of the United States of America 99, 4419−4423.

Post, D.M., 2002. Using stable isotopes to estimate trophic position: Models, methods, and assumptions. Ecology 83, 703-718.

Power, M., Klein, M., Guiguer, K.R.R.A., Kwan, M.K.H., 2002. Mercury accumulation in the fish community of a sub-Arctic lake in relation to trophic position and carbon sources. Journal of Applied Ecology 39, 819−830.

Power, M., Reist, J.D., Dempson, J.B., 2009. Fish in high-latitude Arctic lakes, Polar Lakes and Rivers: Limnology of Arctic and Antarctic Aquatic Ecosystems.

Reist, J.D., Wrona, F.J., Prowse, T.D., Dempson, J.B., Power, M., Köck, G., Carmichael, T.J., Sawatzky, C.D., Lehtonen, H., Tallman, R.F., 2006a. Effects of Climate Change and UV Radiation on Fisheries for Arctic Freshwater and Anadromous Species. AMBIO: A Journal of the Human Environment 35, 402-410, 409.

Reist, J.D., Wrona, F.J., Prowse, T.D., Power, M., Dempson, J.B., Beamish, R.J., King, J.R., Carmichael, T.J., Sawatzky, C.D., 2006b. General effects of climate change on arctic fishes and fish populations. Ambio 35, 370-380.

Richardson, M.C., Chételat, J., Macmillan, G.A., Amyot, M., 2020. Mercury concentrations and associations with dissolved organic matter are modified by water residence time in eastern Canadian lakes along a 30o latitudinal gradient. Limnology and Oceanography In press.

Roberts, J.J., Brandt, S.B., Fanslow, D., Ludsin, S.A., Pothoven, S.A., Scavia, D., Höök, T.O., 2011. Effects of Hypoxia on Consumption, Growth, and RNA:DNA Ratios of Young Yellow Perch. Transactions of the American Fisheries Society 140, 1574-1586.

Rohonczy, J., Cott, P.A., Benwell, A., Forbes, M.R., Robinson, S.A., Rosabal, M., Amyot, M., Chételat, J., 2020. Trophic structure and mercury transfer in the subarctic fish community of Great Slave Lake, Northwest Territories, Canada. Journal of Great Lakes Research 46, 402-413.

Schindler, D.W., Kidd, K.A., Muir, D.C.G., Lockhart, W.L., 1995. The effects of ecosystem characteristics on contaminant distribution in northern freshwater lakes. Science of the Total Environment 160-161, 1-17.

Sharma, C.M., Borgstrøm, R., Huitfeldt, J.S., Rosseland, B.O., 2008. Selective exploitation of large pike Esox lucius-Effects on mercury concentrations in fish populations. Science of the Total Environment 399, 33-40.

Simoneau, M., Lucotte, M., Garceau, S., Laliberté, D., 2005. Fish growth rates modulate mercury concentrations in walleye (*Sander vitreus*) from eastern Canadian lakes. Environmental Research 98, 73-82.

Stafford, C.P., Haines, T.A., 2001. Mercury contamination and growth rate in two piscivore populations. Environmental Toxicology and Chemistry 20, 2099-2101.

Stern, G.A., Macdonald, R.W., Outridge, P.M., Wilson, S., Chételat, J., Cole, A., Hintelmann, H., Loseto, L.L., Steffen, A., Wang, F., Zdanowicz, C., 2012. How does climate change influence arctic mercury? Science of the Total Environment 414, 22-42.

Stierhoff, K.L., Targett, T.E., Power, J.H., 2009. Hypoxia-induced growth limitation of juvenile fishes in an estuarine nursery: Assessment of small-scale temporal dynamics using RNA:DNA. Canadian Journal of Fisheries and Aquatic Sciences 66, 1033-1047.

Stolarski, J.T., Hartman, K.J., 2008. An evaluation of the precision of fin ray, otolith, and scale age determinations for brook trout. North American Journal of Fisheries Management 28, 1790-1795.

Swanson, H.K., Kidd, K.A., 2010. Mercury Concentrations in Arctic Food Fishes Reflect the Presence of Anadromous Arctic Charr (Salvelinus alpinus), Species, and Life History. Environmental Science & Technology 44, 3286-3292.

Trudel, M., Rasmussen, J.B., 2006. Bioenergetics and mercury dynamics in fish: A modelling perspective. Canadian Journal of Fisheries and Aquatic Sciences 63, 1890-1902.

van der Velden, S., Evans, M.S., Dempson, J.B., Muir, D.C.G., Power, M., 2013. Comparative analysis of total mercury concentrations in anadromous and non-anadromous Arctic charr (*Salvelinus alpinus*) from eastern Canada. Science of the Total Environment 447, 438-449.

van der Velden, S., Reist, J.D., Babaluk, J.A., Power, M., 2012. Biological and life-history factors affecting total mercury concentrations in Arctic charr from Heintzelman Lake, Ellesmere Island, Nunavut. Science of the Total Environment 433, 309-317.

Van Walleghem, J.L.A., Blanchfield, P.J., Hintelmann, H., 2007. Elimination of mercury by yellow perch in the wild. Environmental Science & Technology 41, 5895−5901.

Van Walleghem, J.L.A., Blanchfield, P.J., Hrenchuk, L.E., Hintelmann, H., 2013. Mercury elimination by a top predator, *Esox lucius*. Environmental Science and Technology 47, 4147-4154.

Verta, M., 1990. Changes in fish mercury concentrations in an intensively fished lake. Canadian Journal of Fisheries and Aquatic Sciences 47, 1888-1897.

Wang, R., Wang, W.X., 2012. Contrasting mercury accumulation patterns in tilapia (*Oreochromis niloticus*) and implications on somatic growth dilution. Aquatic Toxicology 114-115, 23-30.

Wang, R., Wang, W.X., 2018. Diet-specific trophic transfer of mercury in tilapia (*Oreochromis niloticus*): Biodynamic perspective. Environmental Pollution 234, 288-296.

Ward, D.M., Nislow, K.H., Chen, C.Y., Folt, C.L., 2010. Rapid, efficient growth reduces mercury concentrations in stream-dwelling Atlantic salmon. Transactions of the American Fisheries Society 139, 1-10.

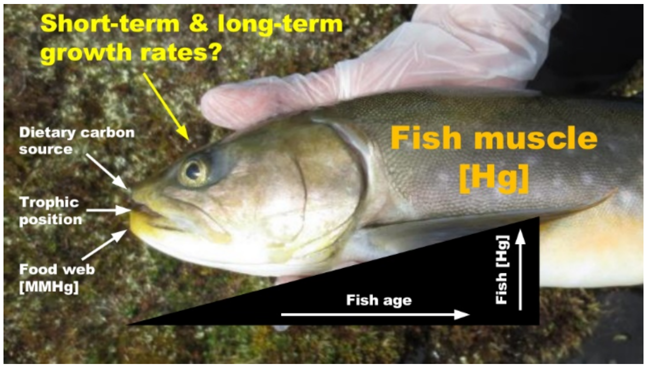
Watras, C.J., Back, R.C., Halvorsen, S., Hudson, R.J.M., Morrison, K.A., Wente, S.P., 1998. Bioaccumulation of mercury in pelagic freshwater food webs. Science of the Total Environment 219, 183−208.

Wiener, J.G., Cope, W.G., Rada, R.G., 1990. Mercury accumulation in yellow perch in wisconsin seepage lakes: Relation to lake characteristics. Environmental Toxicology and Chemistry 9, 931-940.

Wu, P., Kainz, M., Åkerblom, S., Bravo, A.G., Sonesten, L., Branfireun, B., Deininger, A., Bergström, A.K., Bishop, K., 2019. Terrestrial diet influences mercury bioaccumulation in zooplankton and macroinvertebrates in lakes with differing dissolved organic carbon concentrations. Science of the Total Environment 669, 821-832.

Highlights

- Age and diet best explained mercury concentrations of fishes in Arctic lakes.
- Long-term growth rates (length-at-age) were related to fish trophic position.
- Faster-growing fish had a higher trophic position and mercury concentration.
- Muscle RNA/DNA ratios indicated differences in short-term growth rates of fishes.
- Muscle RNA/DNA ratios were a poor predictor of fish mercury concentrations.


Short-term & long-term growth rates?
Dietary carbon source
Trophic position
Food web [MMHg]
Fish muscle [Hg]
Fish age
Fish [Hg]

Supplementary Information for:

Diet influences on growth and mercury concentrations of two salmonid fish species from lakes in the eastern Canadian Arctic

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Table S1. Ecoregion, location, physical characteristics and water chemistry of the study lakes in the eastern Canadian Arctic.

Ecoregion	**Nearest community**	**Lake ID**	**Local lake name**	**Latitude (°N)**	**Longitude (°W)**	**Lake area (km2)**	**Mean depth (m)**	**Water DOC (mg/L)**	**Water Chl (µg/L)**
Subarctic taiga	Kuujjuaraapik-Whapmagoustui	Lake 1	Christmas Lake	55°22’10”	77°37’04”	0.11	1.0	4.2	0.9
Subarctic taiga	Kuujjuaraapik-Whapmagoustui	Lake 2		55°18’16”	77°42’56”	0.01	0.3	4.1	0.8
Subarctic taiga	Kuujjuaraapik-Whapmagoustui	Lake 3	Kachishayoot Lake	55°20’03”	77°37’31”	0.29	1.9	4.0	1.7
Subarctic taiga	Kuujjuaraapik-Whapmagoustui	Lake 4		55°20’01”	77°35’48”	0.39	0.9	5.8	2.5
Subarctic taiga	Kuujjuaraapik-Whapmagoustui	Lake 5		55°20’14”	77°36’42”	0.10	1.2	3.9	2.1
Arctic tundra	Iqaluit	Lake 6	Iqalugaajuruluit Lake	63°41’06”	68°22’34”	0.54	8	3.0	0.4
Arctic tundra	Iqaluit	Lake 7		63°49’30”	68°36’14”	0.56	12	1.6	0.4
Arctic tundra	Iqaluit	Lake 8	Tasirluk (Crazy) Lake	63°52'29"	68°28'40"	4.5	7.5	1.0	0.5
High Arctic polar desert	Resolute Bay	Lake 9	Amituk Lake	75°02’44”	93°47’15”	0.38	19	1.7	0.3
High Arctic polar desert	Resolute Bay	Lake 10	North Lake	74°46’37”	95°05’47”	0.63	7	0.9	0.3
High Arctic polar desert	Resolute Bay	Lake 11	Resolute Lake	74°41’15”	94°56’33”	1.21	9	1.4	0.2
High Arctic polar desert	Resolute Bay	Lake 12	Small Lake	74°45’33”	95°03’37”	0.15	3	2.5	0.4

DOC = dissolved organic carbon, Chl = chlorophyll; water chemistry data are from Chételat et al. (2018), except for Lake 9 (Amituk) for which water chemistry data were collected earlier by Gantner et al. 2010)

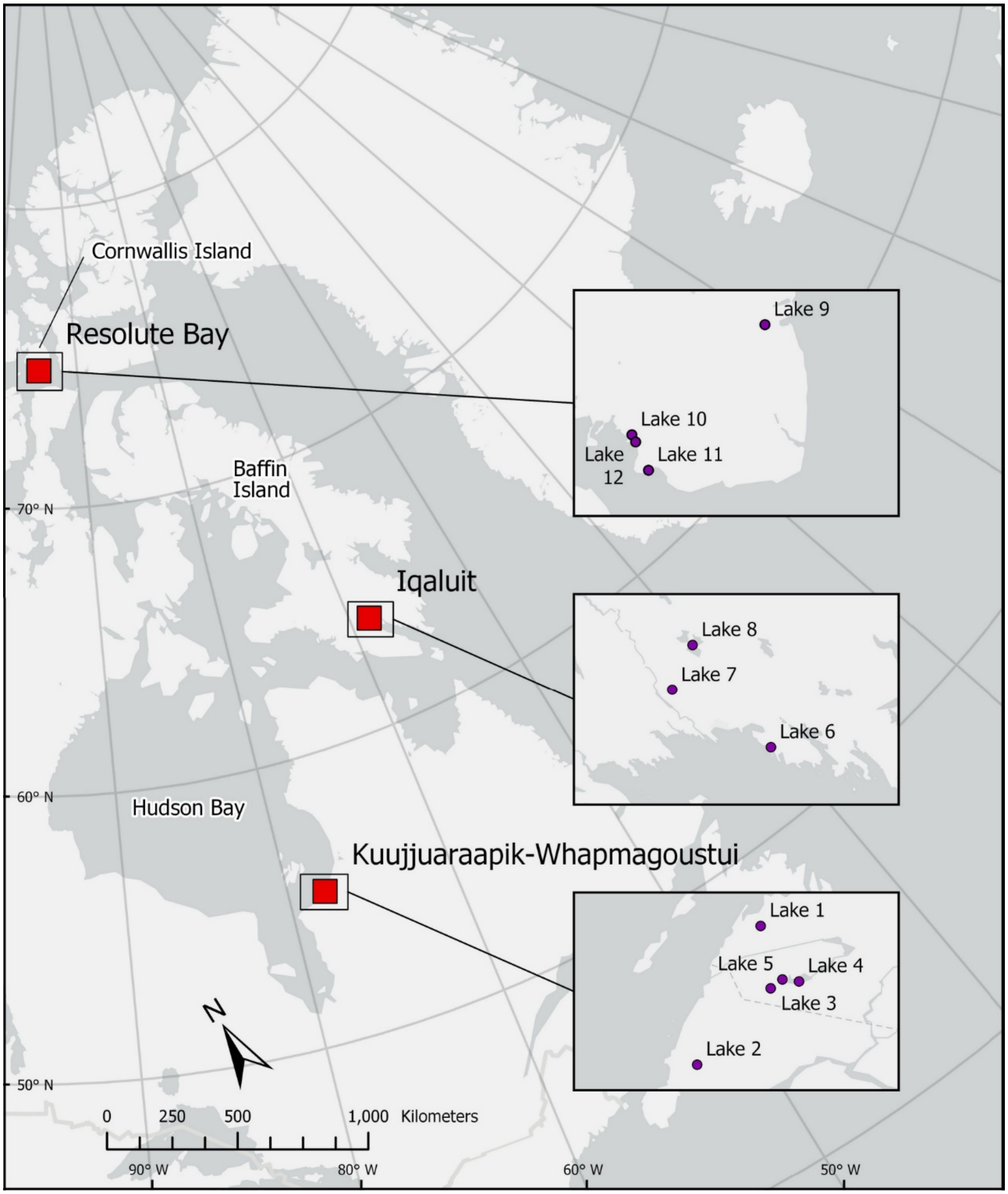

Figure S1. Map of lake locations at the subarctic taiga (Kuujjuaraapik-Whapmagoustui), Arctic tundra (Iqaluit) and High Arctic polar desert (Resolute Bay) study sites.

Age estimations using scales

Fish age was estimated with otoliths using the crack and burn method. Otoliths were not available for a small subset of brook trout and Arctic char (<10%), in which case fish age was estimated from scale annuli. We found that scales gave similar age estimates to otoliths for young fish (<6 years) although slightly underestimated (by 0-2 years) relative to otoliths, as reported elsewhere (Stolarski et al. 2008). We therefore used species-specific poisson regressions derived using scale and otolith data from our study fish to estimate otolith age from scales for young fish (6 brook trout and 9 Arctic char).

Comparison of age estimates from scales and otoliths for brook trout (n=13) and Arctic char (n=32) from study fish.

Fish species	**Scale Age**	**Otolith Age**
Brook trout	2	2
Brook trout	2	2
Brook trout	3	3
Brook trout	3	5
Brook trout	3	5
Brook trout	3	3
Brook trout	3	4
Brook trout	3	3
Brook trout	3	3
Brook trout	3	3
Brook trout	3	3
Brook trout	4	6
Brook trout	4	4
Arctic char	3	3
Arctic char	3	5
Arctic char	3	4
Arctic char	3	5
Arctic char	4	7
Arctic char	4	7
Arctic char	4	6
Arctic char	4	6
Arctic char	4	8
Arctic char	4	7
Arctic char	4	9
Arctic char	4	5
Arctic char	4	6
Arctic char	5	8
Arctic char	5	5
Arctic char	5	7

Arctic char	5	5
Arctic char	5	5
Arctic char	5	6
Arctic char	5	6
Arctic char	5	5
Arctic char	5	9
Arctic char	5	6
Arctic char	6	7
Arctic char	6	8
Arctic char	6	7
Arctic char	6	6
Arctic char	6	6
Arctic char	6	7
Arctic char	6	8
Arctic char	6	7
Arctic char	6	8

Poisson regressions were fitted to the data (using the glm function in R) to estimate fish age based on scales, when otolith age estimates were not available.

Brook trout poisson regression model predictions (ages for 6 fish were predicted based on scale ages from 2-4 years):

Scale age = 2, predicted otolith age = 2
Scale age = 3, predicted otolith age = 3
Scale age = 4, predicted otolith age = 5

Arctic char poisson regression model predictions (ages for 9 fish were predicted based on scale ages from 3-6 years):

Scale age = 3, predicted otolith age = 5
Scale age = 4, predicted otolith age = 6
Scale age = 5, predicted otolith age = 7
Scale age = 6, predicted otolith age = 7

Table S2. Lake-specific sample sizes, MMHg concentrations, and $\delta^{15}N$ values of chironomids used to estimate fish trophic position and dietary MMHg exposure near the base of the food web. Chironomids were collected around the same time as fish in all lakes except Lake 9 (fish in 2014, chiromids in 2011). Additional chironomid data from collections in 2011 were included for Lake 11&12 to supplement the 2014 measurements.

Ecoregion	**Nearest community**	**Lake ID**	**Mean ± SD [MMHg] ng/g dry weight**	**Mean ± SD $\delta^{15}N$ (‰)**	**Data Source**
Subarctic taiga	Kuujjuaraapik-Whapmagoustui	Lake 1	75 ± 13 (3)	4.5 [4.7, 4.3] (2)	1
Subarctic taiga	Kuujjuaraapik-Whapmagoustui	Lake 2	160 (1)	4.0 (1)	1
Subarctic taiga	Kuujjuaraapik-Whapmagoustui	Lake 3	32 (1)	2.8 (1)	1
Subarctic taiga	Kuujjuaraapik-Whapmagoustui	Lake 4	37 ± 8 (3)	2.8 [2.9, 2.7] (2)	1
Subarctic taiga	Kuujjuaraapik-Whapmagoustui	Lake 5	32 ± 9 (3)	2.1 [2.4, 1.8] (2)	1
Arctic tundra	Iqaluit	Lake 6	4 ± 2 (4)	6.0 ± 0.7 (4)	1
Arctic tundra	Iqaluit	Lake 7	19 [9, 29] (2)	5.7 [5.9, 5.5] (2)	1
Arctic tundra	Iqaluit	Lake 8	16 ± 7 (3)	3.7 ± 0.2 (3)	1
High Arctic polar desert	Resolute Bay	Lake 9	173 ± 83 (9)	5.6 ± 0.3 (7)	2
High Arctic polar desert	Resolute Bay	Lake 10	78 ± 19 (4)	10.8 ± 0.9 (4)	1
High Arctic polar desert	Resolute Bay	Lake 11	38 ± 13 (15)	6.8 ± 1.5 (16)	1,2
High Arctic polar desert	Resolute Bay	Lake 12	40 ± 28 (10)	4.6 ± 2.3 (8)	1,2

Sample sizes for mean ± SD are provided in parentheses. Individual values are provided in square brackets when n=2.

Data Sources:

1) Chételat et al. (2018)
2) Chételat et al. (2014)

Table S3. MMHg concentrations and values of $\delta^{15}N$ and $\delta^{13}C$ for macroinvertebrate taxa sampled in subarctic taiga lakes containing brook trout. See Table S2 for chironomid data also collected in those lakes.

Lake ID	**Macroinvertebrate taxon**	**Mean ± SD [MMHg] ng/g dry weight**	**Mean ± SD $\delta^{15}N$ (‰)**	**Mean ± SD $\delta^{13}C$ (‰)**
Lake 1	Amphipods (<10 mm)	79 ± 21 (3)	2.9 ± 0.1 (3)	-27.3 ± 0.4 (3)
	Amphipods (>10 mm)	144 (1)		
	March flies*	54 [70, 37] (2)	5.4 [5.5, 5.2] (2)	-26.4 [-26.2,-26.6] (2)
	All taxa	*81 ± 37 (6)*	*3.9 ± 1.3 (5)*	*-26.9 ± 0.6 (5)*
Lake 2	Dragon fly nymphs	482 (1)	5.0 (1)	-29.0 (1)
Lake 3	Amphipods (<10 mm)	43 (1)	1.0 (1)	-20.3 (1)
	Amphipods (>10 mm)	53 [49, 58] (2)	2.7 [2.8, 2.5] (2)	-23.0 [-24.8, -21.2] (2)
	Mayflies	20.2 (1)	0.5 (1)	-20.2 (1)
	All taxa	*42 ± 16 (4)*	*1.7 ± 1.1 (4)*	*-21.6 ± 2.2 (4)*
Lake 4	Amphipods (<10 mm)	43 [40, 45] (2)	1.6 [1.6, 1.5] (2)	-23.2 [-23.0, -23.3] (2)
	Amphipods (>10 mm)	71 (1)	3.0 (1)	-24.5
	Caddisflies	17 (1)	1.2 (1)	-23.3
	All taxa	*43 ± 22 (4)*	*1.9 ± 0.8 (4)*	*-23.5 ± 0.7 (4)*
Lake 5	Caddisflies	49 (1)	2.1 (1)	-25.6 (1)

Sample sizes for the mean ± SD are provided in parentheses. Individual values are provided in square brackets when n=2.

*Obtained from gut contents

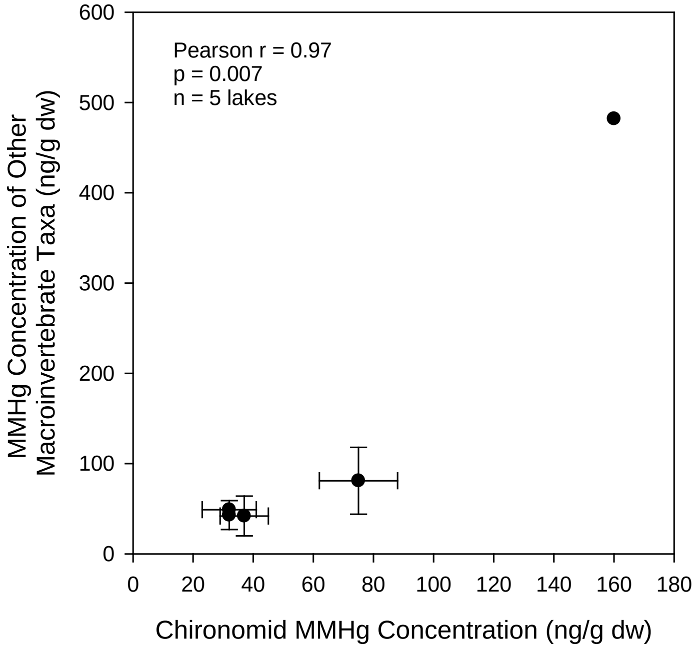

Figure S2. Comparison of MMHg concentrations in chironomids with other macroinvertebrate taxa from the same lake. Values are lake means ±1 standard deviation (see Tables S2&S3 for data).

Table S4. Frequency of occurrence (%) of prey items in the stomachs of brook trout from subarctic taiga lakes. Sample sizes (n) are the number of fish examined in each lake.

	Lake 1	**Lake 2**	**Lake 3**	**Lake 4**	**Lake 5**
Stomach content item	**n=11**	**n=10**	**n=13**	**n=14**	**n=10**
Unidentified flies	9	10	54	57	10
March flies (Bibionidae)	100	70	54	7	10
Chironomids (Chironomidae)	9	10	0	50	40
Beetles (Coleoptera)	18	40	23	7	0
Backswimmers (Notonectidae)	9	0	0	0	0
Amphipods (Amphipoda)	81	0	15	36	0
Dragonfly nymphs (Anisoptera)	0	30	15	0	50
Snails (Gastropoda)	0	50	7	0	0
Caddisflies (Trichoptera)	0	0	54	36	0
Ninespine stickleback (*Pungitius pungitius*)	0	0	7	14	20

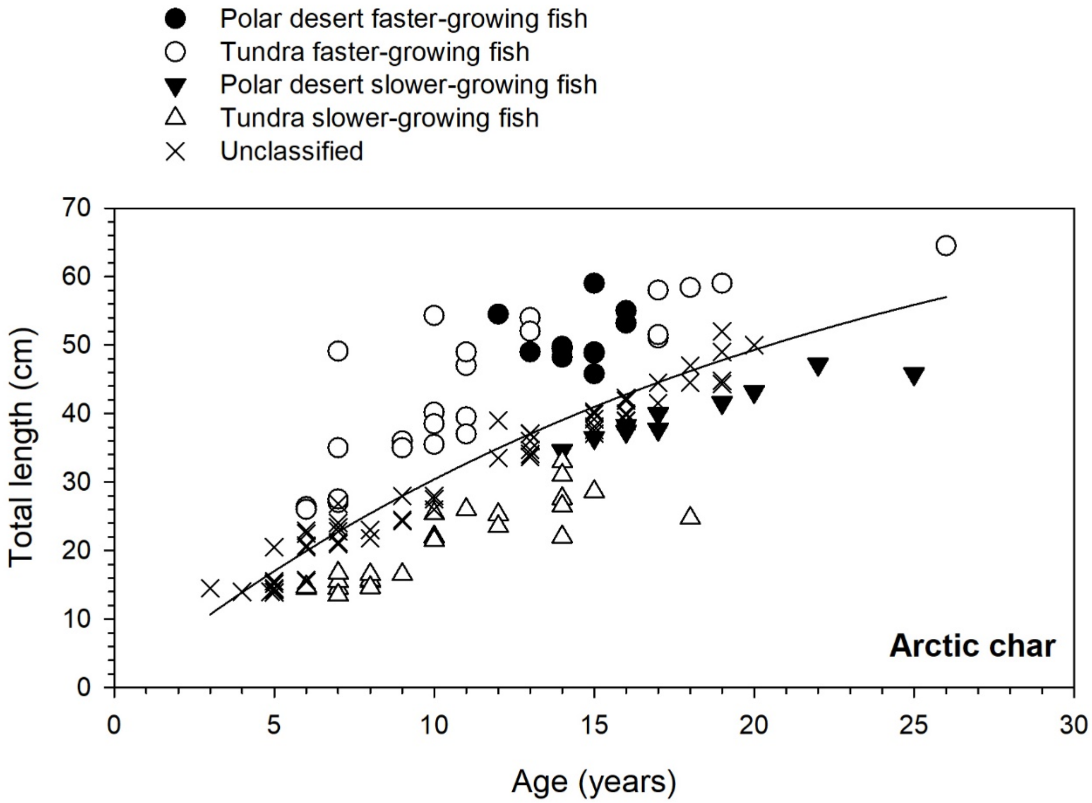

Figure S3. Length-at-age of Arctic char from 7 Arctic lakes (*n* = 133) separated out by ecoregion (polar desert, tundra) in the eastern Canadian Arctic. Individual fish were categorized as faster- or slower-growing or unclassified based on their length compared to the modelled exponential growth curve.

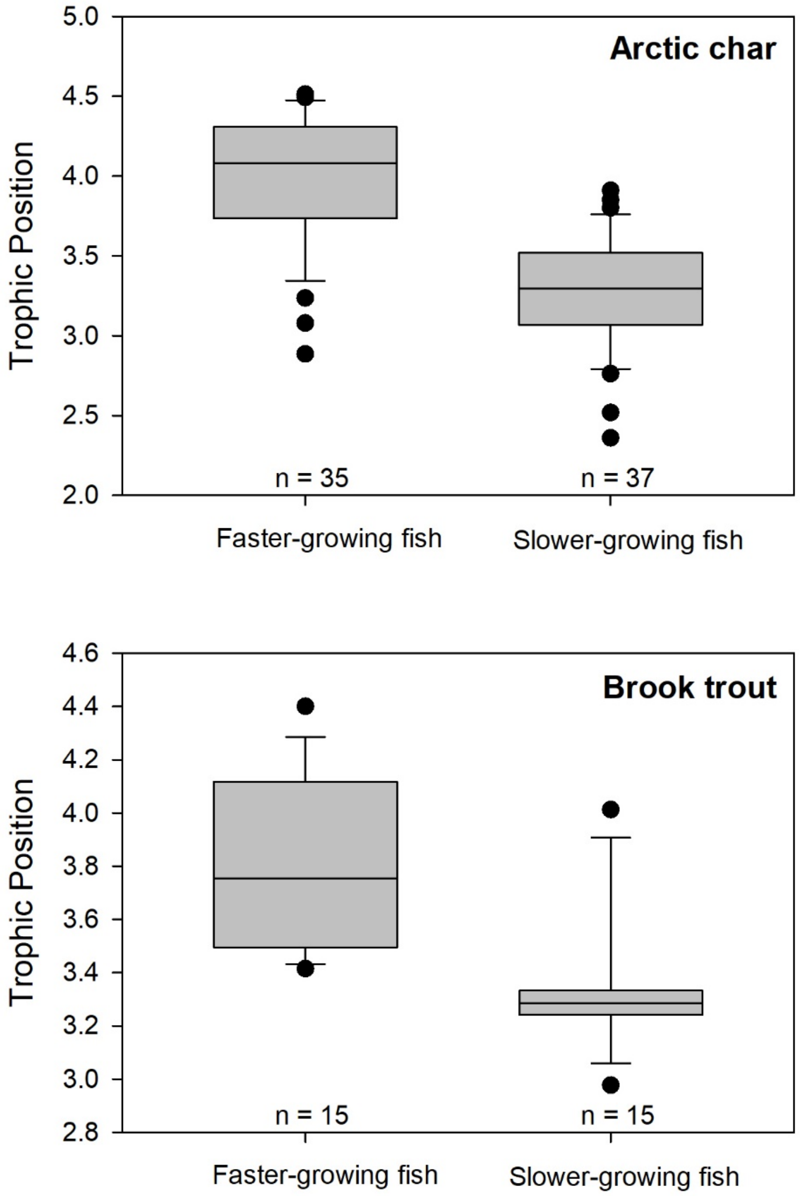

Figure S4. Comparison of trophic position for brook trout and Arctic char categorized as either faster-growing or slower-growing fish.

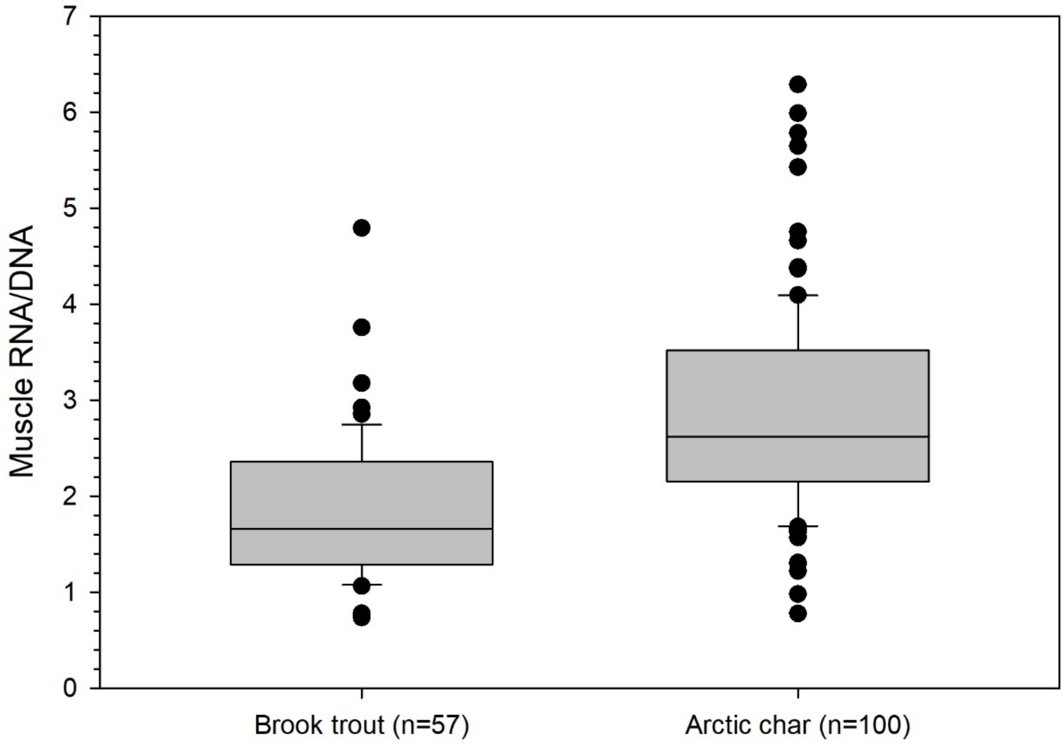

Figure S5. Comparison of muscle RNA/DNA ratios of brook trout and Arctic char.

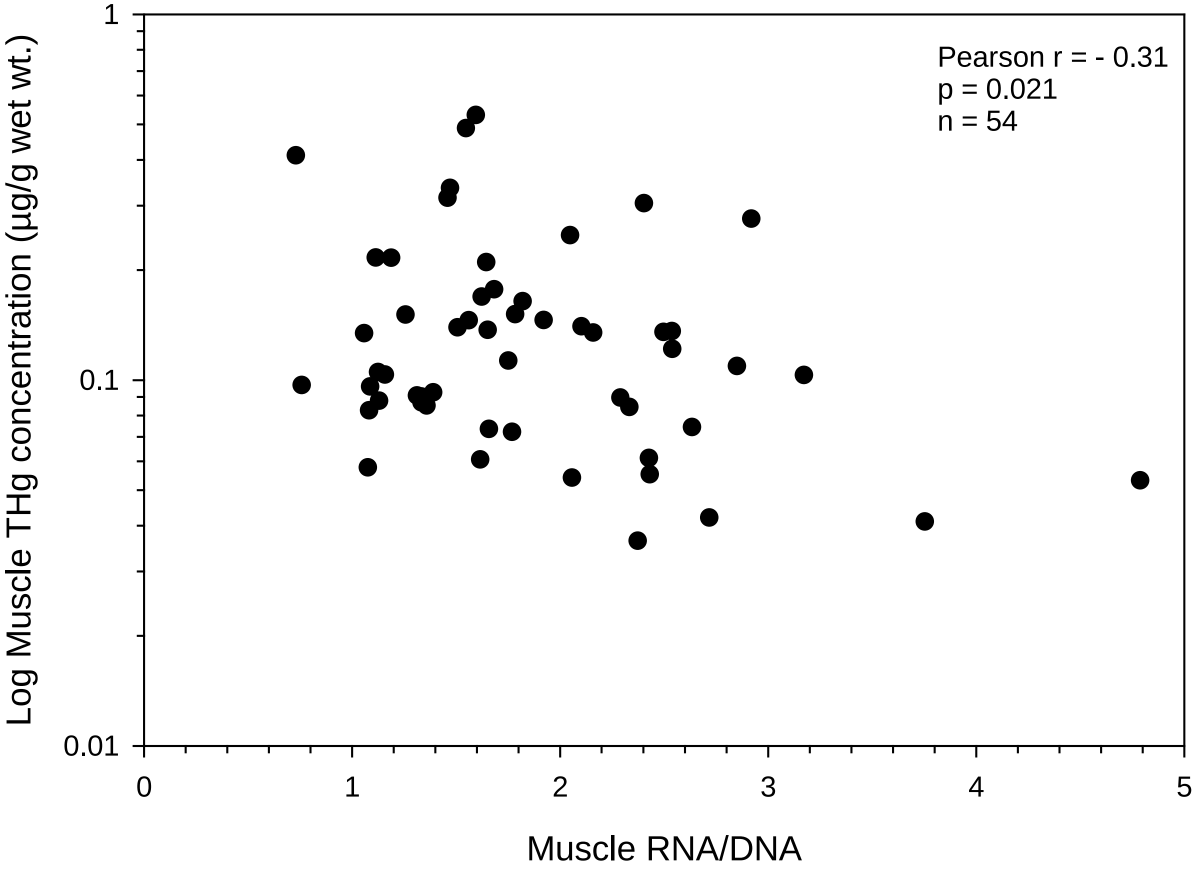

Figure S6. Negative correlation between log muscle THg concentration of brook trout and their muscle RNA/DNA ratio. This pattern would be expected if biodilution from faster growth rates was resulting in lower THg concentrations. However, muscle RNA/DNA ratio was not a significant explanatory variable of THg concentration for brook trout after accounting for the influence of age, trophic position, diet MMHg, and $\delta^{13}C$ in multiple regression models (full model results in Table S5).

Table S5. Results of multiple linear regression models testing the relative importance of muscle RNA/DNA ratios in explaining log-transformed muscle THg concentration for brook trout and Arctic char, after quantifying the influence of diet and age.

Explanatory variable	**Brook trout** **Model $r^2_{adj} = 0.55$, $p < 0.001$, $n = 54$**				**Arctic char** **Model $r^2_{adj} = 0.47$, $p < 0.001$, $n = 98$**			
	F	***P***	**Independent partial r^2**	**Std. Co.**	***F***	***P***	**Independent partial r^2**	**Std. Co.**
Age (years)	13.2	<0.001	0.23	0.43	35.3	<0.001	0.35	0.60
TP	1.8	0.19	---	---	8.4	0.005	0.13	0.37
Diet MMHg (ng/g)	6.2	0.016	0.34	0.54	0	0.96	---	---
RNA/DNA ratio	0.6	0.43	---	---	1.4	0.23	---	---
$\delta^{13}C$ (‰)	2.8	0.10	---	---	1.2	0.27	---	---

TP = trophic position, Diet MMHg = lake-mean MMHg concentration of benthic chironomids, Std. Co. = standardized coefficient, Independent partial r^2 = partial r^2 contribution averaged over all possible orderings of explanatory variables

Table S6. Results of a multiple linear regression model testing the relative importance of muscle RNA/DNA ratios in explaining log-transformed muscle THg concentration for summer and winter captured Arctic char in two lakes, after quantifying the influence of diet and age.

Explanatory variable	**Arctic char Model $r^2_{adj} = 0.87$, $p < 0.001$, $n = 51$**			
	F	***P***	**Independent partial *r2***	**Std. Co.**
Age (years)	29.1	<0.001	0.49	0.46
TP	40.9	<0.001	0.20	0.62
Diet MMHg (ng/g)	28.8	<0.001	0.19	0.58
RNA/DNA ratio	1.5	0.23	---	---
δ^{13}C (‰)	0	0.88	---	---

TP = trophic position, Diet MMHg = lake-mean MMHg concentration of benthic chironomids, Std. Co. = standardized coefficient, Independent partial r^2 = partial r^2 contribution averaged over all possible orderings of explanatory variables

Table S7. Results of a multiple linear regression model testing the relative importance of muscle RNA/DNA ratios in explaining log-transformed muscle THg concentration Arctic char in tundra and polar desert lakes (captured during summer), after quantifying the influence of age and diet.

Explanatory variable	**Arctic char Model $r^2_{adj} = 0.65$, $p < 0.001$, $n = 68$**			
	F	***P***	**Independent partial ^{r2}**	**Std. Co.**
Age (years)	92.5	<0.001	0.44	0.94
Diet MMHg (ng/g)	41.2	<0.001	0.12	-0.60
TP	13.9	<0.001	0.10	0.32
δ^{13}C (‰)	0.2	0.69	---	---
RNA/DNA ratio	0	0.91	---	---

TP = trophic position, Diet MMHg = lake-mean MMHg concentration of benthic chironomids, Std. Co. = standardized coefficient, Independent partial r^2= partial r^2 contribution averaged over all possible orderings of explanatory variables

References

Chételat, J.; Richardson, M. C.; Macmillan, G. A.; Amyot, M.; Poulain, A. J., Ratio of Methylmercury to Dissolved Organic Carbon in Water Explains Methylmercury Bioaccumulation Across a Latitudinal Gradient from North-Temperate to Arctic Lakes. Environmental Science and Technology 2018, 52, (1), 79-88.

Chételat, J.; Poulain, A. J.; Amyot, M.; Cloutier, L.; Hintelmann, H., Ecological determinants of methylmercury bioaccumulation in benthic invertebrates of polar desert lakes. Polar Biology 2014, 37, (12), 1785-1796.

Gantner, N., Muir, D.C., Power, M., Iqaluk, D., Reist, J.D., Babaluk, J.A., Meili, M., Borg, H., Hammar, J., Michaud, W., Dempson, B., Solomon, K.R., 2010. Mercury concentrations in landlocked Arctic char (*Salvelinus alpinus*) from the Canadian Arctic. Part II: Influence of lake biotic and abiotic characteristics on geographic trends in 27 populations. Environmental Toxicology and Chemistry 29, 633−643.

Stolarski, J. T.; Hartman, K. J., An evaluation of the precision of fin ray, otolith, and scale age determinations for brook trout. North American Journal of Fisheries Management 2008**,** 28, (6), 1790-1795.