Health Risk Assessment of Inorganic Arsenic Exposure Through Fish Consumption in Yellowknife, Northwest Territories, Canada

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Abstract

Yellowknife served as a major hub for gold mining industries in the Northwest Territories, Canada, during the 1900s. The Giant Mine was the largest gold mine in Yellowknife, operating adjacent to the Con Mine, a smaller scale gold mine, until the early 2000s. Arsenic trioxide dust was produced as a by-product of the smelting operations. Elevated arsenic concentrations reported in fish caught near the mines are a public health concern. We collected 180 samples of three species of commonly consumed fish; lake whitefish (*Coregonus clupeaformis*), northern pike (*Esox lucius*), and burbot (*Lota lota*) from nine lakes around Yellowknife in 2013-2018. Arsenic species analyzed include As(III), As(V), Monomethylarsonate (MMA), Dimethylarsinic acid (DMA) and arsenobetaine. Concentrations were measured using High-Performance Liquid Chromatography and Inductively Coupled Plasma-Mass Spectrometry. The average concentration of total arsenic in fish muscle tissues was 2.30 ± 1.72 μg/g dry weight and 3.16 ± 2.49 μg/g dry weight in burbot liver tissues. Most of the arsenic species found in fish muscle were non-toxic arsenobetaine (mean= 58.6 ± 34.5%), while in the burbot liver species were predominantly DMA (mean = 76.6 ± 21.6%). Inorganic arsenic species (As(III) and As(V)) on average, accounted for less than 20% of the arsenic detected in fish. Data on the consumption of locally-caught fish were collected from 1,611 residents in Yellowknife in 2017 and 2018, including 1,417 general residents of Yellowknife (1,150 adults and 267 children) and 194 members from the Yellowknives Dene First Nation (123 adults and 71 children). The mean consumption rates of the three fish species of interest were higher among the Yellowknives Dene First Nation at 19±29 g/day (N= 120 consumers) in adults and 7±11 g/day (N=68 consumers) in children, compared to the general residents at 9±15 g/day (N= 1,055 consumers) in adults and 5±8 g/day (N= 246 consumers) in children. We evaluated the long-term non-carcinogenic and cancer health risks from inorganic arsenic exposure through local fish consumption using Monte-Carlo simulations. Our results indicated that there were negligible non-cancer health risks for all groups and the cancer risk associated with arsenic exposure from fish consumption among Yellowknife residents was below the baseline cancer risk levels of arsenic exposure among the Canadian general population.

Keywords: arsenic exposure, fish, inorganic arsenic, mining, probabilistic risk assessment

Key Findings

- Fish from some lakes geographically closer to the mining area had a significantly higher total arsenic concentration in tissues compared to the regional reference lake away from the mines.
- The important factors determining inorganic arsenic concentrations in fish are the location and fish species.
- Arsenic compounds found in fish muscle tissue were predominantly organic arsenobetaine and DMA in burbot liver tissue.
- The Yellowknives Dene First Nation had higher fish consumption rates than the general residents in 2016-2018.
- The long-term health risks associated with the consumption of fish among Yellowknife residents were very low.

Introduction

Arsenic is a ubiquitous trace element that is naturally present in the earth's crust, mainly in the form of arsenopyrite (Mandal & Suzuki, 2002). Exposure to elevated levels of arsenic has been reported in different parts of the world: Bangladesh (Smith, Lingas, & Rahman, 2000), Taiwan (Lai et al., 1994) and South America (Biggs et al., 1997; Concha, Vogler, Lezcano, Nermell, & Vahter, 1998; Mazumder, 2007). Oral exposure is the primary route of human environmental exposure to inorganic arsenic, occurring through the dietary intake of arsenic-contaminated food or drinking water, incidental ingestion of soil or sediments containing arsenic (NRC 2001; US EPA 2019a). In Canada, elevated arsenic levels in drinking water is relatively uncommon; high arsenic exposure is usually from anthropogenic sources, such as wood preservative industries and mining activities (Wang & Mulligan, 2006). The Giant Mine in Yellowknife, Northwest Territories, Canada, was one of the largest and most productive gold mines in Canadian history (Keeling & Sandlos, 2012), yielding more than 20,000 kg of gold over its lifetime. It was operating from 1948 to 1999 and on limited production from 1999 to 2004. Together with its neighbouring Con Mine (1938-2003), it released an estimated 10,000 kg of arsenic trioxide dust daily through the roasting of arsenopyrite ores to extract gold particles (Keeling & Sandlos, 2012). Currently, there are 237,000 tonnes of arsenic trioxide by-product stored in 15 underground chambers on the Giant Mine property, along with three large tailing ponds that drain into the Baker Creek and eventually to the Yellowknife Bay. Giant Mine is recognized as one of the most contaminated sites in Canada, with a projected $1 billion required for remediation costs and up to 15 years to clean up (INAC, 2018). Although both mines are no longer operational, transport of arsenic and other metals by surface runoff and groundwater migration is still possible. The Giant Mine Remediation Project proposed to artificially freeze the underground arsenic trioxide blocks in 2015 to prevent the drainage of arsenic from underground chambers (AANDC, 2015).

Fish is a good source of protein and essential fatty acids, and its consumption has been linked to a reduced risk of cardiovascular diseases, myocardial infarction, inflammatory-related diseases and other health benefits (Daviglus et al., 2002). The Yellowknives Dene First Nation is the Indigenous peoples living in Yellowknife. Based on the data from the NWT Labour Force Surveys conducted in 1998, 2003, 2008, and 2013, about 40% of people residing in the Northwest Territories hunted or fished their own food resources (GNWT, 2015). The NWT Community Survey revealed that 282 households (4% households) in Yellowknife consumed 75% or more of their fish or meat in 2014 acquired from fishing or hunting (GNWT, 2014). The Yellowknives Dene First Nation were exposed to the legacy mining contaminants because of their dependence on land and water as their primary food resources (AFN, 2009). On average, 43% of Indigenous residents in the Northwest Territories hunted or fished for subsistence and recreational purposes, as compared to only 33% in non-Indigenous communities (GNWT, 2015). Fish consumption could be a significant source of arsenic to Yellowknife residents. Fish consumption rates have been shown to correlate with arsenic concentrations in various biomarkers of exposure: blood, cord blood and breast milk (Miklavčič et al., 2013), as well as urine (Navas-Acien et al., 2011), among consumers.

Chronic arsenic exposure at a dose as little as 0.05 mg/kg body weight has a systemic effect on the human body: cardiovascular, integumentary, pulmonary and endocrinal effects, and can lead to cancer in multiple organs (ATSDR, 2007), while acute arsenic exposure at an oral dose of 1-3 mg/kg is lethal (ATSDR, 2007). The toxicity of arsenic compounds has been reported as: As(III) > As(V) > MMA > DMA > organic arsenic species (ATSDR, 2007; NRC, 2001). Inorganic arsenic species, As(III) and As(V), have been classified by the International Agency for Research on Cancer as Class I chemicals, carcinogenic to humans; while MMA and DMA species are classified as Class IIB chemicals, possibly carcinogenic to humans based on *in-vitro* evidence (Escudero-Lourdes et al., 2012; IARC, 2012; Wnek et al., 2011). Several *in-vitro* studies have revealed the trivalent form of MMA to be more toxic to human cells than As(III) by inhibiting DNA repair processes, disrupting enzymatic activities and inducing chromosomal mutations (Escudero-Lourdes et al., 2012; Kligerman et al., 2003; Mass et al., 2001; Wnek et al., 2011). Health effects from arsenic exposure were generally associated with exposure to the inorganic species (As(III) and As(V)). Upon ingestion, inorganic arsenic is metabolized via a series of reduction and methylation processes to As(V), Monomethylarsonic acid (MMA) and Dimethylarsinic acid (DMA).

Previous arsenic speciation studies revealed that most arsenic species in fish muscles are organic arsenobetaine, which is non-toxic in humans and is rapidly excreted in the urine after ingestion (ATSDR, 2007; Ozcan et al., 2016). Inorganic arsenic usually makes up less than 10% of the total arsenic in fish muscle (de Rosemond et al., 2008; Schoof & Yager, 2007). Nevertheless, the pathway of arsenic species biotransformation in fish remains unclear. Previous studies have proposed that fish transform inorganic arsenic into organic arsenic species, marked by the high concentration of organic arsenic species in tissue (Lunde, 1972; Zhang et al., 2012, 2016).

The aims of this study were (1) to measure the concentration of arsenic and its species in fish around Yellowknife, and (2) to evaluate the potential health risks from inorganic arsenic exposure through fish consumption. We hypothesize that (1) the distance between lakes and the mining area is negatively associated with total arsenic and inorganic arsenic concentrations in fish because fish from lakes closer to the mining area have higher arsenic in the food web due to historical As deposition onto the lake; (2) The Yellowknives Dene First Nation have elevated health risks from inorganic arsenic exposure compared to the general population because they consume more fish.

Materials and Methods

Sample Collection and Sites

We collected a total of 180 fish samples from nine lakes around Yellowknife, Northwest Territories (Figure 1). A total of ten dorsal fish muscle samples were collected from each of the following species: lake whitefish (*Coregonus clupeaformis*) and northern pike (*Esox lucius*), with the exception of eight northern pike dorsal muscle samples from Grace Lake. Samples were obtained from the following lakes by Dr. Mark Poesch of the University of Alberta through the Environment and Natural Resources in 2017: Long Lake (62°28'41.30"N, 114°26'3.91"W), Grace Lake (62°25'10.37"N, 114°26'37.90"W), Kam Lake (62°25'19.10"N, 114°24'17.54"W), Lower Martin Lake (62°30'47.21"N, 114°25'16.04"W), Walsh Lake (62°34'54.53"N, 114°16'15.10"W) and Banting Lake (62°38'16.05"N, 114°17'22.61"W). Dr. John Chételat (Environment and Climate Change Canada) also provided a total of eight to ten fish muscle tissue from the 2013-2015 sampling season of the two fish species, respectively, in addition to five burbot liver tissues (*Lota lota*) each, from Yellowknife Bay (62°29'4.40"N, 114°20'13.00"W) and Great Slave Lake (62°20'56.68"N, 114°21'40.33"W). Burbot liver is included in this study because it is a popular food item among residents of Yellowknife, and the consumption rate was collected in the population study. Additional fish samples of lake whitefish and northern pike from Small Lake (62°31'3.96"N, 113°49'35.36"W), were collected by Dr. Pete Cott and Mike Palmer in 2018. The captured fish were euthanized by pithing the head with a sharp knife. Fish were skinned and dissected in the field and shipped to the Laboratory for the Analysis of Natural and Synthetic

Environmental Toxicants at the University of Ottawa using ice coolers. The fork length (in mm), and the total weight (in grams), of all fish were recorded (Table 1). Our fish collection protocol was in accordance with the Canadian Council on Animal Care's *Guidelines on: the care and use of fish in research, teaching and testing* (CCAC, 2005), and was approved by the University of Ottawa's Animal Care Committee under Protocol BL-2894, Fisheries and Oceans Canada for the use of fish for scientific purposes under License S-17/18-3032-YK-A2, and Aurora Research Institute under License #16043.

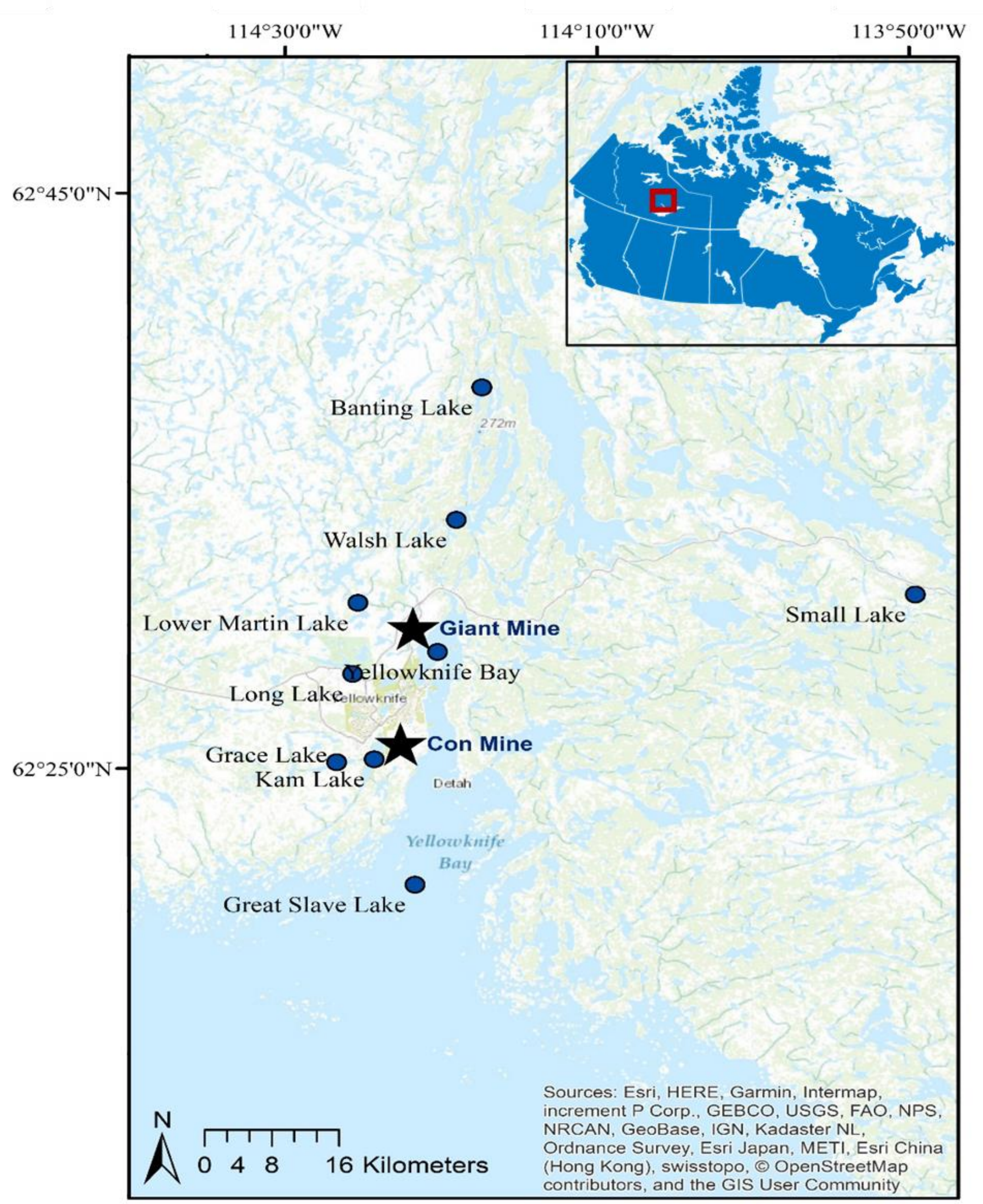

Figure 1. Fish sampling locations in Yellowknife, Northwest Territories.

Table 1. Biometrics of the collected fish samples from the nine lakes around Yellowknife.

Location	Species	N	Tissue	Fork Length (mm) ± std	Total Weight (g) ± std
Yellowknife Bay	Lake whitefish	8	Muscle	413.2 ± 31.9	951.9 ± 225.1
	Northern pike	9	Muscle	580.2 ± 105.6	1399.4 ± 672.7
	Burbot	5	Liver	593.2 ± 181.9	1658.0 ± 1014.1
Great Slave Lake	Lake whitefish	10	Muscle	352.4 ± 35.2	512.0 ± 214.2
	Northern pike	9	Muscle	559.0 ± 92.4	1050.0 ± 400.8
	Burbot	5	Liver	567.8 ± 98.7	1112.6 ± 462.6
Lower Martin Lake	Lake whitefish	10	Muscle	406.8 ± 14.9	921.2 ± 164.2
	Northern pike	10	Muscle	549.1 ± 32.7	1139.7 ± 273.0
Long Lake	Lake whitefish	10	Muscle	379.4 ± 39.1	874.0 ± 243.8
	Northern pike	10	Muscle	555.7 ± 25.3	1240.7 ± 132.6
Kam Lake	Lake whitefish	10	Muscle	421.1 ± 20.9	1312.9 ± 190.6
	Northern pike	10	Muscle	557.4 ± 10.1	1402.7 ± 146.9
Grace Lake	Lake whitefish	10	Muscle	413.1 ± 12.4	1248.4 ± 167.3
	Northern pike	8	Muscle	555.4 ± 62.5	1160.0 ± 442.6
Banting Lake	Lake whitefish	10	Muscle	425.3 ± 15.1	1117.5 ± 180.3
	Northern pike	10	Muscle	562.2 ± 15.5	1028.9 ± 221.4
Walsh Lake	Lake whitefish	10	Muscle	408.6 ± 6.7	903.0 ± 57.2
	Northern pike	10	Muscle	543.9 ± 23.2	1098.0 ± 141.1
Small Lake	Lake whitefish	8	Muscle	446.5 ± 21.2	1280.0 ± 375.4
	Northern pike	8	Muscle	597.1 ± 91.8	1556.1 ± 744.7

Sample preparation and Arsenic Analysis

Sample Preparation: Fish tissue samples were freeze-dried using a commercial SuperModulyo lyophilizer (Thermo Scientific, USA) for 24 to 36 hours, and then homogenized using a Magic Bullet processor before arsenic analysis. The sample weights before and after lyophilization were used to determine % moisture.

Total Arsenic analysis: 0.1 to 0.5 g of homogenized samples were digested with 2.5 mL of 70%v/v OmniTrace HNO_3 (EMD Millipore, USA) on an SCP Science model DigiPREP block digestion at 100°C for 180 minutes, and 1.5 mL of 30% v/v certified ACS H_2O_2 (Fisher Chemical, USA) was later added to each tube on the hotplate and heated for an additional 45 minutes at 95°C. The extracts were cooled to room temperature and diluted with Milli-Q deionized water to 10 mL. The digested solutions were then filtered using 0.45-micron DigiFILTERs and vortexed before analysis. The concentration of total arsenic was determined using inductively coupled plasma-mass spectrometry (ICP-MS: 7700x, Agilent Technologies, USA). Reference materials used were IAEA-407 (IAEA, Monaco) and DOLT-5 (NRC, Canada) for fish tissues. Total arsenic concentrations were within 95-125% of certified values, with a mean average of 104±7%.

Arsenic Speciation Analysis: 0.1 g of dry samples were extracted using 4 mL of 1:1 Methanol:MilliQ-water at 100°C for 180 minutes on DigiPREP block and diluted to 10 mL using Milli-Q deionized water. Extracts were centrifuged at 4000 rpm for 15 minutes and syringe-filtered using 0.2 µm PVDF filter media (Whatman, USA) before analysis. The concentration of various arsenic species: As(III), As(V), MMA, DMA and arsenobetaine, in samples were measured using high-performance liquid chromatography (HPLC: 1200, Agilent Technologies, USA) with inductively coupled plasma-mass spectrometry (ICP-MS: 7700x, Agilent Technologies, USA), in accordance to the FDA standards, Elemental Analysis Manual Section 4.11. The method limits of detection were 0.002 µg/g for arsenobetaine, 0.06 µg/g for As(III), 0.07 µg/g for DMA, 0.004 µg/g for MMA and 0.1 µg/g for As(V). Method blanks, calibration blanks and standards, and various standard reference material: DORM-4 and DOLT-5 (NRC, Canada), were used for quality assurance. Mass balances for all reference materials and samples were tested to be within the range of 95-130% of certified values (mean= 115±10%) for accuracy.

Human Health Risk Assessment

Data on the frequencies and amounts of various fish species consumed among the adult (aged 18 to 65) and child residents (aged 3 to 17) in Yellowknife were obtained from the Food Frequency Questionnaire collected by the Yellowknife Health Effects Monitoring Program for risk assessment studies (Chan et al., *in prep*). Participants were also asked about the specific locations where they obtained their fish. Information on the portion of fish meals was gathered using visual food models. All data used in this study were provided by consenting participants, recruited through random selection and on a voluntary basis. Participants comprised of the general residents of Yellowknife and the Yellowknives Dene First Nation living in Yellowknife for at least twelve months. The Yellowknife Health Effect Monitoring Program applied the First Nations principles of Ownership, Control, Access and Possession of data throughout the entire process (Schnarch, 2004). The protocol used by the research program was approved by the University of Ottawa Research Ethics Board under file #H05-17-07, the Aurora Research Institute license #16497 and Aurora College Research Ethics Committee under protocol #20180401.

Daily fish consumption rates among participants were calculated by adding the total amount of fish consumed in a year (grams) divided by the total days of fish meals in a year (days). The survey was conducted in two waves: fall 2017 and spring 2018, with a total of 1,611 participants: 1,417 general residents (1,150 adults and 267 children) and 194 members of the Yellowknives Dene First Nation (123 adults and 71 children). The daily fish consumption rates (g/day) of lake whitefish, northern pike and burbot liver from various lakes around the city were used to estimate the potential non-carcinogenic and carcinogenic health risks related to long-term arsenic exposure from fish consumption among reporting consumers. Only the inorganic forms of arsenic (As(III) and As(V)) in fish were taken into account for this risk assessment as those were the most toxic and carcinogenic species to humans (ATSDR, 2007). At the time this manuscript was prepared, the US EPA was revising its arsenic risk assessment under IRIS. Therefore, the methodology adopted in this paper was based on the latest available guidelines used by the US EPA and Health Canada. The chronic non-cancer Hazard Quotient (HQ) and the Incremental Lifetime Cancer Risk (ILCR) were evaluated using the following equations (Health Canada, 2010a; US EPA, 2000):

$$HQ_{iAs} = \frac{Cf_{iAs} \times IR}{BW \times RfD_{iAs}}$$

Equation 1. Non-carcinogenic Hazard Quotient (HQ) equation.

$$LADD = \frac{Cf_{iAs} \times IR \times EF \times ED}{BW \times 365\, days/year \times LE}$$

Equation 2. Lifetime Average Daily Dose (LADD) equation.

$$ILCR_{iAs} = \mathrm{LADD} \times CSF_{iAs}$$

Equation 3. Incremental Lifetime Carcinogenic Risk (ILCR) equation.

, where: Cf_{iAs} = concentration of inorganic arsenic in fish (µg/g wet weight)

IR = daily ingestion rate of fish (g/day)

EF = exposure frequency (365 days/year)

ED = exposure duration (adult= 80 years (Health Canada, 2010), child= 10 years (US EPA, 2019b))

BW = body weight of Yellowknife inhabitant (kg BW)

LE = life expectancy (80 years)

RfD_{iAs} = reference dose of inorganic arsenic (3×10^{-4} mg/kg BW.day) (US EPA, 2000)

CSF_{iAs} = cancer slope factor of inorganic arsenic exposure (1.8 kg BW.day/mg) (Health Canada, 2010b)

An HQ value greater than 0.2 indicated an elevated health risk associated when not all sources of exposure were accounted for in the assessment (Health Canada, 2010a). An ILCR value of less than 1×10^{-5} indicated negligible carcinogenic health risks (Health Canada, 2010a). Self-reported body weight was used to estimate daily exposure. The measured inorganic arsenic concentration in fish in dry weight was converted to the wet weight based on the corresponding % moisture, with the average conversion factors of 0.2 in fish muscle tissues and 0.4 in burbot liver.

We used Monte-Carlo simulation to calculate the non-carcinogenic and carcinogenic health risks (HQ and ILCR indices) from inorganic arsenic exposure through fish consumption among Yellowknife residents using the distribution of three variables: body weights and fish consumption rates, which are specific to the population and age groups, and inorganic arsenic concentrations in fish. These simulation tests were generated through the Crystal Ball software version 11.1 for Windows PC, to take into account the uncertainty distributions of all variables in HQ and CR computations using N= 10,000 trials.

Statistical Analysis

All data are presented in average value ± one standard deviation. The concentration of arsenic in fish samples was measured in µg/g dry weight (dw). All figures and statistical analyses were generated in R open-source software version 3.5.2 for Mac OS X. We used two-way ANOVA and *post-hoc* Tukey's multiple comparisons of means tests to compare the total arsenic and inorganic arsenic concentrations in fish samples between the two fish species: lake whitefish and northern pike, and to compare fish total arsenic and inorganic species concentrations in various lakes around Yellowknife. Two-sample t-test was used to compare arsenic species concentration in lake whitefish and northern pike within the lakes. The relationships between the concentrations of different arsenic species detected in fish tissues were measured using Pearson's correlation tests. Statistical significance for all analyses was set at 0.05.

Results and Discussion

Total and Inorganic Arsenic Concentrations in Fish

The average total arsenic concentration in fish muscle tissues from the nine lakes in the Yellowknife area was 2.30 ± 1.72 µg/g dw, with a range of 0.42 to 5.97 µg/g dw (Figure 2), which is comparable to other published results on fish-arsenic concentration in the Yellowknife area: 0.05 to 2.80 µg/g dw (Cott et al., 2016), 0.57 to 1.15 µg/g dw (de Rosemond et al., 2008), and <0.05 to 6.90 µg/g dw (Stantec, 2014). Location was a significant factor determining total arsenic concentration in fish (two-way ANOVA; $p<0.05$) and differences in total arsenic concentration in fish were not species-related. Conversely, both fish species and location were significant factors determining the concentration of inorganic arsenic in fish (two-way ANOVA; $p<0.05$).

The concentrations of arsenic in fish muscle tissue from Yellowknife Bay were not significantly different from those in the Great Slave Lake, the reference surface water body (*post-hoc* Tukey's; $p>0.05$). The concentrations of arsenic in fish from Grace Lake and Lower Martin Lake were significantly higher than the reference Small Lake (Grace Lake: mean difference = 4.44 µg/g dw, $p<0.05$; Lower Martin Lake: mean difference= 4.35 µg/g dw, $p<0.05$). Fish from Lower Martin Lake and Grace Lake had the highest total arsenic concentration in muscle tissue, with 5.97 ± 1.46 µg/g dw and 5.68 ± 5.89 µg/g dw, respectively. Fish from the reference Small Lake, located 27 km east of the mining area, had the lowest average total arsenic concentration in the muscle tissue: 0.46 ± 0.16 µg/g dw. Our results suggested that fish from inland lakes near the mine roasters were more affected by legacy arsenic from mining, as compared to fish from lakes further away from mine roasters with the exception in Kam Lake that was located close to the mining area but had relatively low total arsenic concentrations in fish (lake whitefish: 0.88 ± 0.30 µg/g dw, northern pike: 2.36 ± 0.92 µg/g dw). However, Tukey's tests showed that fish from Kam Lake had a significantly higher inorganic arsenic concentrations, compared to fish from the reference Small Lake (mean difference =0.06 ug/g, $p<0.05$) (Figure 2). Although the concentration of total arsenic in fish from the Kam Lake was low, the inorganic arsenic concentration in these fish was the highest across the lakes, especially in lake whitefish (0.131 ± 0.101 µg/g dw). The results indicated that the importance of measuring arsenic species concentrations in fish for risk assessment for human health.

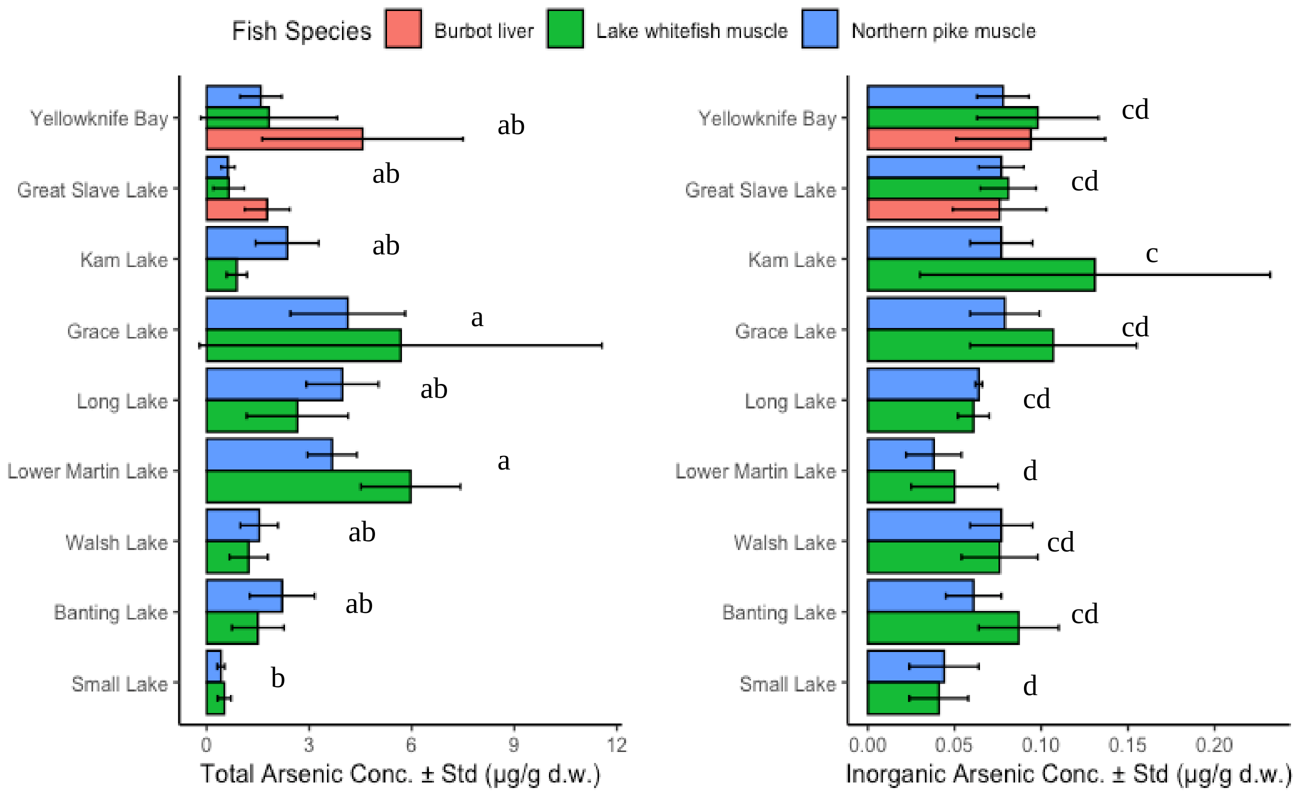

Figure 2. Total Arsenic and inorganic arsenic concentrations in fish tissue from lakes around Yellowknife. Same letter labels (a,b,c,d) means no significant differences (Two-way ANOVA, *Post-hoc* Tukey's; p>0.05) in the mean arsenic concentrations in fish from the lakes.

The average arsenic concentration in burbot liver was 3.16 ± 2.49 µg/g dw. Total arsenic concentrations in burbot liver were higher than those in fish muscle tissue samples collected from the same sites (Figure 2). This is expected as liver is known to accumulate higher arsenic than muscle tissue as it is the main biotransformation organ of arsenic (Lunde, 1972). Previous studies have reported arsenic bioconcentration in fish organs as the following: Gastrointestinal tract > liver > muscle (de Rosemond et al., 2008; Foata et al., 2009). Arsenic concentrations in burbot liver were also higher in sampling site(s) closer to the mines: 4.56 ± 2.94 μg/g dw in Yellowknife Bay, compared to 1.77 ± 0.66 μg/g dw in Great Slave Lake.

Arsenic Speciation in Fish

Arsenic species in fish muscle were predominantly in the form of organic arsenobetaine (mean = 58.6 ± 34.5 %) (Figure 3). Inorganic arsenic on average, comprised less than 20% of total arsenic in fish tissues (Table 2). Lake whitefish had a higher inorganic arsenic concentration in muscle compared to northern pike (mean difference = 0.02 ug/g, $p<0.05$), as well as the proportion of inorganic arsenic to total arsenic (mean difference = 2.96%, $p<0.05$). The theory explaining the higher inorganic arsenic levels found in lake whitefish is two-fold: (1) Adult lake whitefish feed primarily on benthic invertebrates at the lake bottom (COSEWIC, 2005), which might have exposed these fish to high inorganic arsenic through sediment ingestion, contributing to the higher inorganic arsenic concentration in muscle tissue, as opposed to northern pike that feed nearly exclusively on midwater fish (Harvey, 2009); and (2) Lake whitefish occupy a lower trophic position in the food webs than northern pike (Cott et al., 2011; Tanamal et al., *in prep*), which has been associated with higher arsenic concentration and proportion of inorganic arsenic to total arsenic in freshwater organisms (Tanamal et al., *in prep*). Most arsenic species in burbot liver were in the form of DMA (mean = 76.6 ± 21.6 %), and only less than 5% of total arsenic was in the form of inorganic arsenic (mean = 3.9 ± 2.7 %). Since the predominant species of soluble arsenic species in lake water and sediment are inorganic As(III) and As(V) (Pothier et al., 2018), we concluded that the organic arsenicals in fish tissues were products of inorganic arsenic biotransformation and retention through dietary exposure. Inorganic arsenic was taken up by fish through gills and ingestion (Fonseca et al., 2017; Zhang et al., 2012). Northern pike had significantly higher DMA to total arsenic proportion in tissue compared to that in lake whitefish

(Two-sample T-test, mean difference = 34.5%, $p<0.0001$), indicating that inorganic arsenic species are preferably bio-transformed to DMA rather than arsenobetaine in northern pike. Conversely, lake whitefish metabolizes most arsenic into arsenobetaine (mean arsenobetaine proportion= 68.7 ± 36.4%). These findings suggest species-specific retention of arsenic compounds in fish species that could be related to differences in arsenic biotransformation pathways and diets.

Table 2. Summary of total arsenic and inorganic arsenic concentration in various fish species across lakes in Yellowknife.

Location	Species	N	Tissue	Total As (µg/g d.w.) ± std	Total iAs (µg/g d.w.) ± std	%iAs ± std
Yellowknife Bay	Lake whitefish	8	Muscle	1.82 ± 2.00	0.098 ± 0.035	9.3 ± 6.7
	Northern pike	9	Muscle	1.59 ± 0.61	0.078 ± 0.015	6.1 ± 3.7
	Burbot	5	Liver	4.56 ± 2.94	0.094 ± 0.043	3.5 ± 3.9
Great Slave Lake	Lake whitefish	10	Muscle	0.65 ± 0.45	0.081 ± 0.016	19.6 ± 14.9
	Northern pike	9	Muscle	0.60 ± 0.18	0.077 ± 0.013	14.1 ± 5.5
	Burbot	5	Liver	1.77 ± 0.66	0.076 ± 0.027	4.4 ± 0.9
Lower Martin Lake	Lake whitefish	10	Muscle	5.97 ± 1.46	0.050 ± 0.025	0.9 ± 0.4
	Northern pike	10	Muscle	3.67 ± 0.72	0.038 ± 0.016	1.1 ± 0.5
Long Lake	Lake whitefish	10	Muscle	2.65 ± 1.49	0.061 ± 0.009	3.0 ± 2.0
	Northern pike	10	Muscle	3.97 ± 1.06	0.064 ± 0.002	1.7 ± 0.5
Kam Lake	Lake whitefish	10	Muscle	0.88 ± 0.30	0.131 ± 0.101	15.1 ± 10.3
	Northern pike	10	Muscle	2.36 ± 0.92	0.077 ± 0.018	3.7 ± 1.5
Grace Lake	Lake whitefish	10	Muscle	5.68 ± 5.89	0.107 ± 0.048	3.2 ± 2.7
	Northern pike	8	Muscle	4.13 ± 1.68	0.079 ± 0.020	2.2 ± 1.0
Banting Lake	Lake whitefish	10	Muscle	1.50 ± 0.76	0.087 ± 0.023	6.9 ± 3.6
	Northern pike	10	Muscle	2.21 ± 0.95	0.061 ± 0.016	3.1 ± 1.4
Walsh Lake	Lake whitefish	10	Muscle	1.23 ± 0.56	0.076 ± 0.022	7.7 ± 4.8
	Northern pike	10	Muscle	1.54 ± 0.55	0.077 ± 0.018	5.6 ± 2.3
Small Lake	Lake whitefish	8	Muscle	0.52 ± 0.20	0.041 ± 0.017	8.9 ± 4.2
	Northern pike	8	Muscle	0.42 ± 0.11	0.044 ± 0.020	10.4 ± 4.1

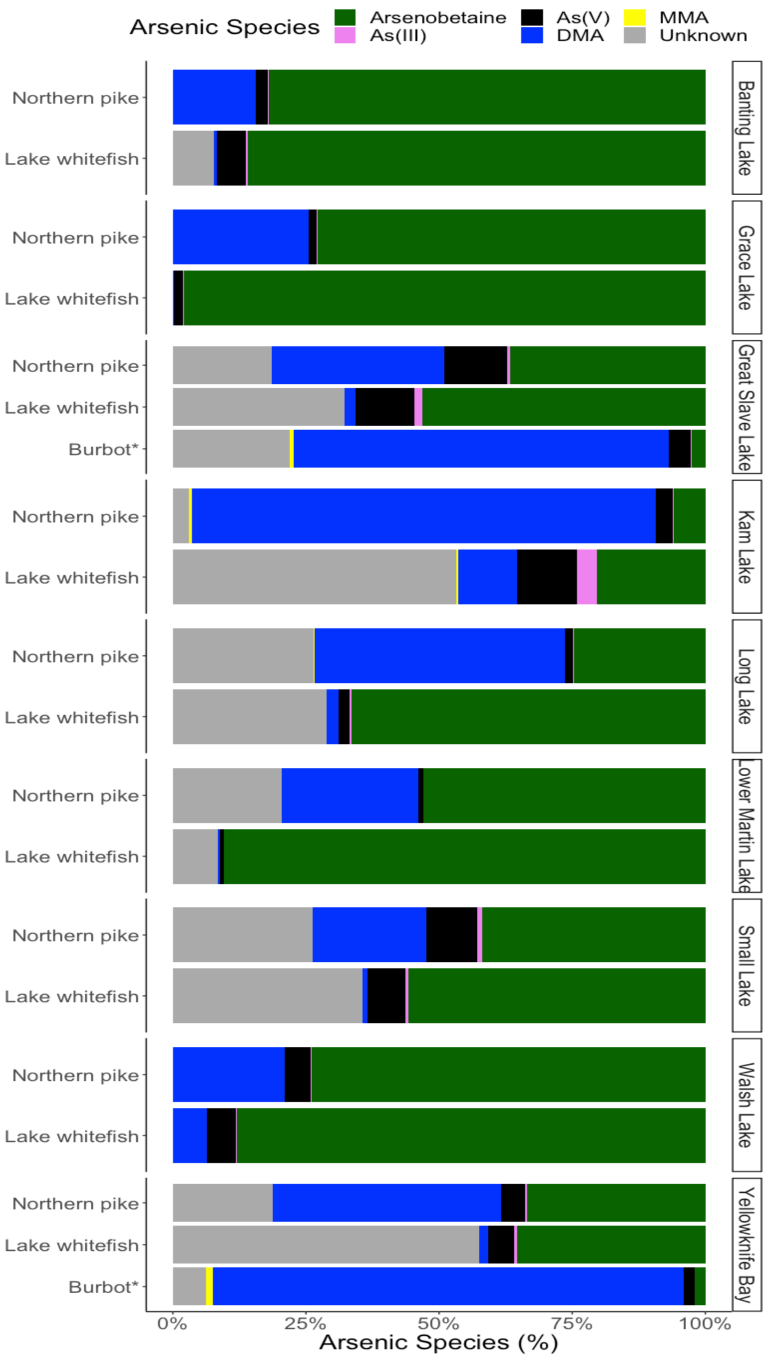

Figure 3. The proportion of detected arsenic species in the muscle tissue of fish across lakes. *Burbot arsenic concentration was measured in liver tissue.

Correlation of Arsenic Species in Fish Tissues

The correlation matrices of arsenic species concentrations in the three fish species were presented in Table 3. In lake whitefish muscle, total arsenic concentration was significantly correlated with concentration of As(V) ($r=0.236$, $p<0.05$) and arsenobetaine ($r=0.960$, $p<0.01$). In northern pike, high total arsenic in muscle was significantly correlated to high MMA ($r=0.480$, $p<0.01$), DMA ($r=0.624$, $p<0.01$) and arsenobetaine ($r=0.721$, $p<0.01$), while in burbot liver tissue, high arsenic levels were strongly correlated to high levels of MMA ($r=0.827$, $p<0.01$), DMA ($r=0.967$, $p<0.01$) and arsenobetaine ($r=0.869$, $p<0.01$). Our results indicated that upon exposure, inorganic arsenic in fish is transformed into predominantly arsenobetaine in lake whitefish; and to MMA, DMA and arsenobetaine in northern pike and burbot liver tissue.

The proportions of inorganic arsenic to total arsenic in fish was inversely related to total arsenic concentration in all three fish species (lake whitefish: $r=-0.434$, $p<0.01$; northern pike: $r=-0.727$, $p<0.01$; burbot liver: $r=-0.655$, $p<0.05$), suggesting that inorganic arsenic concentration in fish does not increase proportionally to total arsenic concentration in tissues. The accumulation of toxic inorganic arsenic in tissues was restricted with the increasing total arsenic in tissues. A similar decline in the retention of inorganic arsenic with an increasing arsenic concentration in fish has also been reported (Jia et al., 2018).In this study, we observed two possible pathways of arsenic biotransformation in fish species: (1) biotransformation to arsenobetaine, as in lake whitefish, and (2) biotransformation to methylated arsenic species (MMA and DMA), as in northern pike and burbot liver. These pathways could be specific to the fish species.

Table 3. Pearson correlation matrices of arsenic concentration and arsenic species in (A) lake whitefish muscle, (B) northern pike muscle, and (C) burbot liver.

A	Total Arsenic	As(III)	DMA	MMA	As(V)	iAs	%iAs	AsB
Total Arsenic	1	-0.063	-0.126	0.060	0.236*	0.131	-0.434**	0.960**
As(III)	-0.063	1	0.058	0.489**	-0.045	0.668**	0.456**	-0.082
DMA	-0.126	0.058	1	0.175	0.208	0.196	0.055	-0.128
MMA	0.060	0.489**	0.175	1	0.277**	0.549**	0.199	0.022
As(V)	0.236*	-0.045	0.208	0.277**	1	0.713**	0.149	0.228*
iAs	0.131	0.668**	0.196	0.549**	0.713	1	0.431**	0.112
%iAs	-0.434**	0.456**	0.055	0.199	0.149	0.431**	1	-0.387**
AsB	0.960**	-0.082	-0.128	0.022	0.228*	0.112	-0.387**	1

B	Total Arsenic	As(III)	DMA	MMA	As(V)	iAs	%iAs	AsB
Total Arsenic	1	0.016	0.624**	0.480**	-0.017	-0.013	-0.727**	0.721**
As(III)	0.016	1	0.058	0.124	-0.074	0.139	0.071	-0.067
DMA	0.624**	0.058	1	0.803**	0.209	0.220*	-0.497**	0.000
MMA	0.480**	0.124	0.803**	1	0.053	0.079	-0.347**	-0.087
As(V)	-0.017	-0.074	0.209	0.053	1	0.977**	0.247*	-0.008
iAs	-0.013	0.139	0.220*	0.079	0.977**	1	0.260*	-0.022
%iAs	-0.727**	0.071	-0.497**	-0.347**	0.247*	0.260*	1	-0.466**
AsB	0.721**	-0.067	0.000	-0.087	-0.008	-0.022	-0.466**	1

C	Total Arsenic	As(III)	DMA	MMA	As(V)	iAs	%iAs	AsB
Total Arsenic	1	-0.037	0.967**	0.827**	0.598	0.612	-0.655*	0.869**
As(III)	-0.037	1	0.063	-0.005	-0.273	-0.081	0.099	0.009
DMA	0.967**	0.063	1	0.870**	0.643*	0.679*	-0.547	0.918**
MMA	0.827**	-0.005	0.870**	1	0.545	0.564	-0.525	0.774**
As(V)	0.598	-0.273	0.643*	0.545	1	0.981**	-0.074	0.703*
iAs	0.612	-0.081	0.679*	0.564	0.981**	1	-0.057	0.731*
%iAs	-0.655*	0.099	-0.547	-0.525	-0.074	-0.057	1	-0.427
AsB	0.869**	0.009	0.918**	0.774**	0.703*	0.731*	-0.427	1

Significance levels at *$p<0.05$ and **$p<0.01$.

Fish Consumption in Yellowknife

Results of fish consumption data are presented in Table 4. Out of 1,417 participants from the general population group, 1,409 participants (99%) provided consumption information for each of the fish species in the FFQ. All 194 participants from the Yellowknives Dene First Nation provided their consumption data for all fish species indicated in the FFQ. The most consumed fish species in both groups were lake whitefish (89-98% consumers), lake trout (49-71% consumers), walleye (21-43% consumers) and northern pike (10-34% consumers) (Table 4). Similar to the prior Dene Dietary Survey in 1998, whitefish and trout remained as the two most commonly consumed fish species (83-97% consumers) among the Yellowknives Dene First Nation. However, the number of pike consumers had declined significantly (1998: 26-50% consumers; 2017-2018: 10-12% consumers) (Receveur et al., 1998). The daily consumption rates of lake whitefish, northern pike and burbot liver included in this risk assessment covered approximately 60% of total fish consumption reported among Yellowknife residents.

We included the most common sources of locally-caught fish among Yellowknife residents in our exposure assessment: Yellowknife Bay, Great Slave Lake, Long Lake, Grace Lake, Kam Lake, Martin Lake, Walsh Lake, Banting Lake and Small Lake. Out of 1,073 participants who reported fishing in Yellowknife, 89% of them reported consuming locally harvested fish (N= 960). More than half of participants (63%) reported fishing in the Great Slave Lake area, and 46% of them reported fishing in Yellowknife Bay and Back Bay area. 15% of participants reported fishing in Walsh Lake, 8% in Long Lake and around 5% or less of participants reported fishing in each of the following locations: Banting Lake, Kam Lake, Grace Lake and Small Lake. Other lakes that were frequently mentioned by the participants but were not covered in this study were Prosperous

Lake, Prelude Lake and Pontoon Lake. These three lakes are large-scale lakes measuring over 300 ha in surface area, situated at least 10 km away from the mining area, with water arsenic concentrations below 10 µg/L based on a previous survey (Palmer et al., 2015). Based on these characteristics, we expect that these lakes will probably have similar or lower arsenic and inorganic arsenic concentrations in fish compared to the range of concentrations that we reported. Therefore, this risk assessment served as an overall assessment of inorganic arsenic exposure through fish intake from the most commonly fished lakes in the area. However, it does not cover all arsenic exposure from all fish consumption.

Daily fish consumption rates of all the fish species combined were the highest among the Yellowknives Dene First Nation adult consumers with a mean average of 32 g/day than the general adult consumers with an average of 14 g/day (Table 4). Children in Yellowknife generally consumed smaller portions of various fish species than adults, with a mean average of 7 g/day among the general population and 14 g/day among the Yellowknives Dene First Nation. Northern pike and burbot were more consumed among the general residents (northern pike: 2-4 g/day; burbot: 2-3 g/day, burbot liver: 0.5-2 g/day, inconnu: 3 g/day), compared to the Yellowknives Dene First Nation residents (northern pike: 1-3 g/day; burbot: 0.3-2 g/day, burbot liver: 0-1 g/day). The recommended fish intake proposed by Health Canada's *Food Guide for Healthy Eating* is at least 150 grams (2 servings) per week (Health Canada, 2007) or equivalent to 21 g/day. The average general resident group in Yellowknife had lower than the recommended total fish intake at 13 g/day among adults and 5 g/day among children, while the Yellowknives Dene First Nation adults had higher than recommended fish intake at 32 g/day, but much lower in children at 11 g/day (Table 4).

Table 4. Summary table of daily fish consumption (g/day) of various fish species among the general residents (N=1,417 participants) and Yellowknives Dene First Nation (N=194 participants).

Fish Species	Group	Variable		YK General Population		YK Dene First Nation	
				Adult	Child	Adult	Child
Lake Whitefish	All Participants	n		1148	267	123	71
		Consumption rate (g/day)	Average	7	4	18	7
			50th percentile (median)	3	2	8	3
			95th percentile	28	16	72	24
	Consumers Only	n (%)		1022 (89)	238 (89)	120 (98)	68 (96)
		Consumption rate (g/day)	Average	8	5	19	7
			50th percentile (median)	4	2	8	4
			95th percentile	29	16	62	19
Lake Trout	All Participants	n		1147	267	123	71
		Consumption rate (g/day)	Average	3	2	10	3
			50th percentile (median)	0.5	0.1	1	0
			95th percentile	16	8	48	23
	Consumers Only	n (%)		678 (59)	135 (51)	87 (71)	35 (49)
		Consumption rate (g/day)	Average	5	3	13	6
			50th percentile (median)	2	1	6	2
			95th percentile	23	10	52	27
Northern Pike	All Participants	n		1143	266	123	71
		Consumption rate (g/day)	Average	1	0.7	0.4	0.1
			50th percentile (median)	0	0	0	0
			95th percentile	7	4	1.3	1
	Consumers Only	n (%)		389 (34)	84 (32)	15 (12)	7 (10)
			Average	4	2	3	1

		Consumption rate (g/day)	50th percentile (median)	2	1	0.7	1
			95th percentile	15	11	13	3
Burbot Liver	All Participants		n	1144	264	123	71
		Consumption rate (g/day)	Average	0.06	0.002	0.1	0
			50th percentile (median)	0	0	0	0
			95th percentile	0	0	0.4	0
	Consumers Only		n (%)	26 (3)	1 (0.3)	14 (11)	0 (0)
		Consumption rate (g/day)	Average	2	0.5	1	0
			50th percentile (median)	0.5	0.5	0.3	0
			95th percentile	11	0.5	4	0
Burbot	All Participants		n	1145	264	123	71
		Consumption rate (g/day)	Average	0.6	0.4	0.2	0.02
			50th percentile (median)	0	0	0	0
			95th percentile	3	1	1	0.3
	Consumers Only		n (%)	233 (21)	39 (15)	18 (15)	4 (6)
		Consumption rate (g/day)	Average	3	2	2	0.3
			50th percentile (median)	1	0.7	0.7	0.3
			95th percentile	12	6	4	0.3
Inconnu (Connie)	All Participants		n	1147	266	123	71
		Consumption rate (g/day)	Average	0.7	0.2	0.6	0.5
			50th percentile (median)	0	0	0	0
			95th percentile	4	1	3	5
	Consumers Only		n (%)	250 (22)	47 (18)	34 (28)	7 (10)
		Consumption rate (g/day)	Average	3	1	2	5
			50th percentile (median)	1	0.7	1	3
			95th percentile	11	5	8	10
			n	1146	265	123	71

Walleye (Pickerel)	All Participants	Consumption rate (g/day)	Average	1	0.7	3	3
			50th percentile (median)	0	0	0	0
			95th percentile	5	3	8	21
	Consumers Only		n (%)	496 (43)	81 (31)	36 (29)	15 (21)
		Consumption rate (g/day)	Average	3	2	10	14
			50th percentile (median)	1	0.7	2	3
			95th percentile	10	8	72	62
Grayling (Bluefish)	All Participants		n	1147	266	123	71
		Consumption rate (g/day)	Average	0.04	0.05	0.04	0.02
			50th percentile (median)	0	0	0	0
			95th percentile	0.1	0	0	0
	Consumers Only		n (%)	64 (6)	9 (3)	5 (4)	1 (1)
		Consumption rate (g/day)	Average	0.8	1	1	1
			50th percentile (median)	0.5	0.8	0.2	1
			95th percentile	2	4	3	1
All fish species	All Participants	Consumption rate (g/day)	Average	13	5	32	11
			95th percentile	47	21	146	57
	Consumers Only	Consumption rate (g/day)	Average	14	7	32	14
			95th percentile	48	29	146	57

Risk Assessment

Results of the estimates of HQ and ILCR using Monte-Carlo simulation are presented in Table 5. Body weight (BW) and daily fish consumption (IR) data were collected from the consumers of whitefish, pike and burbot liver: N= 1,055 adult consumers and 267 child consumers from the general resident group and N= 120 adult consumers and 68 child consumers from the Yellowknives Dene First Nation.

Table 5. Variables used for Monte-Carlo simulation on non-carcinogenic health risk (HQ) and carcinogenic risk (ILCR) on inorganic arsenic exposure from the reported fish consumption among general residents and the Yellowknives Dene First Nation.

Variables	**General population**		**Yellowknives Dene First Nation**	
	Adult (N= 1,055)	**Child (N= 246)**	**Adult (N= 120)**	**Child (N= 68)**
Body weight, BW (kg)	Normal (Mean= 79.7, Std = 19.7)	Normal (Mean= 37.0, Std= 18.1)	Normal (Mean= 86.0, Std= 23.3)	Normal (Mean= 52.9, Std= 22.0)
Daily fish consumption, IR (g/day)	Lognormal (Mean = 9.3, Std = 15.1)	Lognormal (Mean = 5.2, Std = 7.8)	Lognormal (Mean = 19.3, Std = 29.0)	Lognormal (Mean = 7.1, Std = 10.9)
Fish iAs conc., Cf_iAs (μg/g w.w.)	Lognormal (Mean = 0.017, Std = 0.010)			

The probabilistic distributions of non-cancer health risk (HQ) and lifetime cancer risk (ILCR) in the two resident groups are shown in Table 6. Among the adult consumers from the general population, the HQ values ranged from 95%CI: 0.00-0.03, with a mean value of 0.007, while in the Yellowknives Dene First Nation adults, HQ values ranged from 95%CI: 0.00-0.05, with a mean average of 0.01. Since this study did not account for all sources of arsenic intake, we used a standard risk assessment practice that characterizes risk by estimating potential hazards against a hazard benchmark of 0.2. This ensures that site-related exposures do not exceed twenty percent (20%) of the toxicity reference value on a daily basis. Although the Yellowknives Dene First Nation adults had higher HQ values compared to the adult general residents, the values at 95th percentile were still much lower than the value at HQ of 0.2 (Health Canada, 2010a), indicating that there were negligible long-term non-carcinogenic health risks related to fish consumption in adults of both groups. Since the children in the two resident groups consumed much less fish than the adults, the ranges of probabilistic HQ in children were lower than those in adults (General residents: mean= 0.001, 95%CI: 0.00-0.005; Yellowknives Dene First Nation: mean= 0.001, 95%CI: 0.00-0.005).

The probabilistic ILCR values for the average adult residents were within the acceptable level at 3.8 x 10^{-6} and 7.5 x 10^{-6} in general resident group and the Yellowknives Dene First nation, respectively. However, the ILCR values among adults at the 95th percentile exceeded the limit of negligible cancer risk proposed by Health Canada of 1 x10^{-5} (Health Canada, 2010a) with ILCR (general residents)= 1.4 x 10^{-5} and ILCR (Yellowknives Dene First Nation)= 2.7 x 10^{-5}, suggesting that there was slight cancer risk associated with fish intakes at 95th percentiles among the adult population in Yellowknife. In children, the probabilistic ILCR values at the 95th percentile were within the acceptable value (ILCR<10^{-5}) at 3.0 x 10^{-6} among the general residents and 2.4 x 10^{-6} among the Yellowknives Dene First Nation. Although our probabilistic ILCR values in adults were higher at the 95th percentile, these values were still lower than the ILCR values at the 5th percentile of arsenic exposure group among the general population in Canada (ILCR= 1.4 x 10^{-4}) (Faure et al., 2019). These results suggest that the cancer risk associated with arsenic exposure from fish consumption among Yellowknife residents were below the baseline cancer risk levels of arsenic exposure among the Canadian general population.

Table 6. Monte-Carlo simulation (N=10,000) of non-carcinogenic health risk (HQ) and carcinogenic risk (ILCR) of inorganic arsenic exposure based on the reported fish consumption rates among the general population and Yellowknives Dene First Nation.

Population Group	**Age Group**	**HQ**			**ILCR**		
		Mean	**50th percentile**	**95th percentile**	**Mean**	**50th percentile**	**95th percentile**
General population	Adult (18-79)	0.007	0.003	0.03	3.8×10^{-6}	1.7×10^{-6}	1.4×10^{-5}
	Child (3-17)	0.001	0.0005	0.005	9.8×10^{-7}	2.8×10^{-7}	3.0×10^{-6}
Yellowknives Dene First Nation	Adult (18-79)	0.01	0.006	0.05	7.5×10^{-6}	3.4×10^{-6}	2.7×10^{-5}
	Child (3-17)	0.001	0.0005	0.005	1.1×10^{-6}	2.6×10^{-7}	2.4×10^{-6}

In summary, our risk assessment concluded that fish consumption in Yellowknife did not pose any substantial chronic health risks to the average residents, and the cancer risk associated with arsenic exposure from fish consumption among Yellowknife residents were below the baseline cancer risk levels of arsenic exposure among the Canadian general population. There are a number of weaknesses in the design of the study that might result in an underestimation of health risks. We did not consider arsenic exposure from store-bought fish, other local fish species consumed, or fish caught in other lakes in the area. We covered approximately 60% of reported fish consumption in Yellowknife population using the consumption data for lake whitefish, northern pike and burbot liver in our risk assessment. Assuming that other fish species had similar inorganic arsenic concentrations, the estimated daily exposure rate of inorganic arsenic from fish consumption was 0.26 µg/day among the general resident adults, 0.02 µg/day among the general resident children, 0.54 µg/day among the Yellowknives Dene First Nation adults and 0.03 µg/day among the Yellowknives Dene First Nation children. Using the distribution of body weights, we estimated that the daily doses of inorganic arsenic exposure from fish consumption in Yellowknife encompassed 1-2% of the US EPA's reference dose of 3 x 10^{-4} mg/kg.day (US EPA, 2000).

Fish consumption serves as an essential source of nutrition, especially for eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), among other nutrients that are irreplaceable by other food substitutes. Fishing also has a significant cultural value in the Indigenous communities that rely on fishing for nourishment. A Yellowknife Dene Dietary Survey in 1998 showed that ~70% of Dene households reported fishing and 30% of participants revealed that they could not afford to buy all their food from the store if traditional sources of food were not available (Receveur et al., 1998). Fish consumption has been linked to many health benefits, such as reduced cardiovascular-related mortality (Mozaffarian & Rimm, 2006), reduced obesity and diabetes (Nkondjock & Receveur, 2003), and improved neuropsychological performances in children and adolescents (Butler et al., 2017). Incorporation of sufficient seafood in maternal diets of more than 340 grams per week has been correlated to developmental benefits in children, according to an Avon Longitudinal Study of Parents and Children involving 11,875 pregnant women, and limiting this source of nutrients could be detrimental to children (Hibbeln et al., 2007). Our findings show that the risk of lost nutrients from fish outweighs the health risks associated with inorganic arsenic exposure from fish consumption in the majority of the Yellowknife population. Therefore, we support incorporating sufficient fish in diets, in accordance with Health Canada's recommendation of at least 150 grams of fish per week and following site-specific fish consumption advisories posted by the Health and Social Services in Yellowknife. However, our results suggest that fish consumption from Kam Lake might be discouraged as it had a significantly higher concentration of inorganic arsenic species, compared to fish from the regional reference lake. Large-bodied fish occupying a higher trophic position in food webs generally accumulate less inorganic arsenic in the tissues (Tanamal et al., *in prep*), posing little in the way of consumption issues. However, large-bodied fish that were found to have low inorganic arsenic concentrations in tissue could still have high concentrations of methylmercury or other chemicals of potential concern. The Health and Social Services of of the Government of the Northwest Territories has provided advice to residents of Yellowknife to avoid fishing around David Lake, Fox Lake, Frame Lake, Gar Lake, Handle Lake, Jackfish Lake, Kam Lake, Niven Lake, Peg Lake, Meg Lake, and Rat Lake based on the concern of arsenic exposure (Health and Social Services, 2019).

We calculated the allowable daily intake and weekly servings for each of the fish species in each location without exceeding 20% of the RfD (Table 7). The results show that there is a negligible risk of inorganic arsenic exposure, even with the consumption of multiple servings of fish per day. It is important to note that this study did not address the potential long-term effects of legacy arsenic exposure of the populations in Yellowknife when Giant Mine was still in operation. Also, the Yellowknives Dene First Nation may have taken special precautions to lower their arsenic exposure, e.g. by avoiding fish from lakes that are known to have higher arsenic levels and reducing their local fish consumption. This study also does not address other indirect health risks associated with changes in their traditional diet and lifestyle as a result of the mining operations.

Table 7. The allowable daily intake (g) and weekly servings for each fish species in each location without exceeding 20% of the RfD. One serving = 150 gram.

Location	**Fish Species**	**Allowable intake per day (g)**	**Allowable servings per week**
Yellowknife Bay	Lake whitefish	245	11
	Northern pike	308	14
	Burbot liver	128	6
Great Slave Lake	Lake whitefish	296	14
	Northern pike	312	14
	Burbot liver	128	7
Lower Martin Lake	Lake whitefish	480	22
	Northern pike	631	29
Long Lake	Lake whitefish	393	18
	Northern pike	375	17
Kam Lake	Lake whitefish	183	8
	Northern pike	312	14
Grace Lake	Lake whitefish	224	10
	Northern pike	304	14
Banting Lake	Lake whitefish	276	13
	Northern pike	393	18
Walsh Lake	Lake whitefish	316	15
	Northern pike	312	14
Small Lake	Lake whitefish	585	27
	Northern pike	545	25

Conclusion

Elevated concentrations of total arsenic in fish were still seen after almost two decades after the closing of both Giant Mine and Con Mine. An important factor determining the variability in total arsenic concentrations in fish around Yellowknife was the location, the proximity of the lakes to the legacy mining operations, while the speciation of arsenic in fish was influenced by both fish species and the location of lakes. Arsenic species in fish muscle was predominantly arsenobetaine, with less than 20% of total arsenic in inorganic arsenic forms. Burbot liver consisted of primarily DMA, and less than 5% of total arsenic was inorganic arsenicals. Inorganic arsenic concentration in fish was inversely related to the total arsenic concentration in the tissues, indicating that the inorganic arsenic concentration in fish tissue does not increase proportionally with the total arsenic concentration in tissue. Therefore, it is important to measure arsenic species for human health risk assessment.

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