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Plasma concentrations of perfluoroalkyl acids and their determinants in youth and adults from Nunavik, Canada

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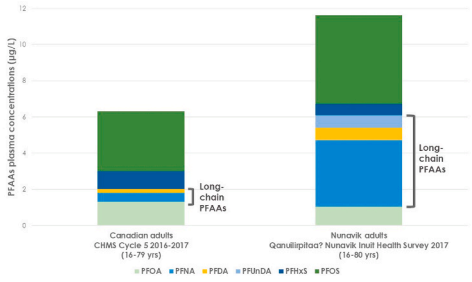
HIGHLIGHTS

- Perfluoroalkyl acids (PFAAs) are detected at high concentrations in Arctic wildlife.
- Long-chain PFAAs levels were 4–7 fold higher in Nunavik compared to the Canadian population.
- PFAAs levels differed by sex, age, and region.
- PFAAs levels increased with seafood consumption.

GRAPHICAL ABSTRACT



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ABSTRACT

Perfluoroalkyl acids (PFAAs), a subset of per- and poly-fluoroalkyl substances (PFAS), are environmentally stable, mobile and bioaccumulative compounds. This leads to high concentrations in wildlife species essential to the cultural identity and subsistence of Arctic populations. Our objective was to characterize the distribution and exposure determinants of PFAAs among Nunavik Inuit adults. The study included up to 1322 Nunavik residents aged 16–80 years who participated in the *Qanuilirpitaa?* 2017 Nunavik Inuit Health Survey (Q2017). Plasma concentrations were compared to those the general Canadian population using data from the Canadian Health Measures Survey Cycle 5 (2016–2017). Associations between plasma concentrations of nine PFAAs, determined by liquid chromatography-tandem mass spectrometry, and sociodemographic factors and traditional activity participation were examined using multiple linear regression models. Overall exposure to PFAAs was twice as high compared to the general Canadian population and less regulated perfluorononanoic acid (PFNA) and perfluoroundecanoic acid (PFUnDA) concentrations were 7-fold higher, and perfluorodecanoic acid (PFDA) concentrations were 4-fold higher. Males had higher concentrations of perfluorooctanoic acid (PFOA) and perfluorohexane sulfonate (PFHxS), whereas females had higher concentrations of PFDA and PFUnDA. PFAAs concentrations increased with age and were highest among those aged 60+ years. PFNA and PFOA

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concentrations followed a J-shaped pattern: those aged 16–29 years had higher concentrations than those aged 20–29 and 30–39 years. Ungava Bay generally had lower concentrations of all PFAAs congeners compared to Hudson Bay and Hudson Strait, with the exception of PFNA, which tended to have the lowest concentration in Hudson Strait. PFAAs concentrations were highly associated with hunting activity, omega-3 polyunsaturated fatty acids, and drinking water from environmental sources. The results highlight the importance of characterizing PFAAs exposure sources in Arctic communities and provide further evidence for the long-range transport of long-chain PFAAs and their precursors that necessitate international action.

1. Introduction

Perfluoroalkyl acids (PFAAs) are a subset of per- and poly-fluoroalkyl substances (PFAS), a group of chemicals that represent a large family of synthetic compounds with various industrial, commercial and residential applications and used for their ability to repel both oil and water (Buck et al., 2011). Increasingly recognized for their human toxicity, PFAAs are persistent and ubiquitous bioaccumulative chemicals with multiple biomagnification pathways and a very large number of parent and degradation congeners. These characteristics make them some of the most complex industrial contaminants to study from analytical, toxicological, epidemiological and regulatory perspectives (Sunderland et al., 2019).

PFAAs' stability and mobility in the environment lead to their travel north via long-range atmospheric and oceanic transport (Li et al., 2018; MacInnis et al., 2017; Wong et al., 2018), and subsequent high concentrations in the Arctic environment (e.g. in air, snow, soil, water and sediments) (AMAP, 2021a). They accumulate in the Arctic marine and (to a lesser extent) terrestrial food webs, and have been measured in some wildlife species consumed by Inuit populations living in the Arctic, such as marine mammals, fish and caribou (AMAP, 2021a; Muir et al., 2019). PFAAs are also degradation products of fluorotelomer alcohols

Fig. 1. Map of Nunavik, Quebec. Borders are approximate.

(FTOHs), which are a group of highly volatile and less persistent PFAS still globally used as intermediates in many consumer and industrial products (Dinglasan et al., 2004). FTOHs can migrate to the Arctic and have been identified as an important source of PFAAs bioaccumulation in Arctic wildlife (Ahrens et al., 2011; Muir et al., 2019; Shoeib et al., 2006). In the Arctic, some of the congeners regularly measured and detected in human samples include perfluoroalkane sulfonates such as perfluorooctane sulfonate (PFOS) and perfluorohexane sulfonate (PFHxS), and perfluoroalkyl carboxylic acids (PFCAs) such as perfluorooctanoic acid (PFOA) and long-chain congeners (with 9 and more carbons) perfluorononanoic acid (PFNA), perfluorodecanoic acid (PFDA) and perfluoroundecanoic acid (PFUnDA).

PFOS use has been restricted under the Stockholm Convention since 2009; PFOA was included in the Convention in May 2019; and, PFHxS was included in June 2022 (Secretariat of the Basel, Rotterdam and Stockholm Conventions, 2022). Long-chain (C9–C20) PFCAs, their precursors and salts satisfied the Annex D screening criteria for inclusion in January 2022 after being nominated by Canada (Secretariat of the Basel, Rotterdam and Stockholm Conventions, 2022). As a result, while overall PFAAs exposure remains a major concern, PFOA and PFOS concentrations in Arctic wildlife and human populations have been decreasing over the last couple of decades (AMAP, 2021a; Caron-Beaudoin et al., 2020). However, increasing levels of long-chain PFAAs (specifically PFCAs including PFNA, PFDA, PFUnDA) have been reported in Arctic terrestrial and marine wildlife in different circumpolar regions, as well as pregnant Inuit women in Nunavik (Caron-Beaudoin et al., 2020; Muir et al., 2019).

Nunavik is located in the northernmost region of Quebec, Canada, and lies in the Arctic and subarctic climate zones (Fig. 1). It is a large area made up of three ecological regions: Hudson Bay in the west, Hudson Strait in the north, and Ungava Bay in the east, and is part of the larger Inuit Nunangat (homeland) in Canada. The Nunavik regional capital, Kuujjuaq, is in Ungava Bay. A large population-based survey, *Qanuilirpitaa?* 2017 Nunavik Inuit Health Survey (Q2017), was conducted in 2017 to document the state of community, mental and physical health in all 14 villages of Nunavik. It was also meant to update the results of the *Qanuippitaa?* survey conducted in 2004. Q2017 is currently the largest survey of its kind in the Arctic and provides an excellent opportunity to examine the concentrations of PFAAs in a large representative Inuit population. To be included under the Stockholm Convention, chemicals must demonstrate persistence, bioaccumulation, long-range transport, and adverse health effects. As such, documenting PFAAs concentrations in an Inuit population living in Arctic regions devoid of known contamination sites could directly inform such global policies on the reach of PFAAs' persistence, bioaccumulation, and environmental transport capabilities. In 2019, 30 pooled samples were analyzed for PFAAs concentrations. This was expanded to measure PFAAs concentrations in individual samples in the total Q2017 population.

The objectives of this study were to document the plasma concentrations of PFAAs in Nunavik using Q2017 data in individual samples, compare these to plasma concentrations of PFAAs first analyzed in pooled samples, compare PFAAs concentrations in Nunavik to other populations, and to identify potential exposure determinants.

2. Materials and methods

2.1. Study population

Q2017 included the collection, analysis, and dissemination of information on the health status of Nunavimmiut (Inuit living in Nunavik). The survey was conducted from August 19 to October 5, 2017 and collected data across all 14 Nunavik villages in the three ecological regions. The villages were reached by the *Amundsen*, a Canadian Coast Guard Icebreaker, and study participants were invited upon the ship for data collection. The target population included all Nunavik permanent residents aged 16 years and over and a stratified proportional model was implemented for respondent selection. A total of 1326 residents were recruited. Data collection included questionnaires, clinical measurements, and biological samples (urine and blood) collection. A total of 1322 participants provided a blood sample. Survey weights were used in all analyses for target population inference. Further details on the 2017 survey have been described elsewhere (Hamel et al., 2020). The survey and this study were conducted in close collaboration with several Nunavik organizations and was governed by the OCAP® principles (Ownership, Control, Access, and Possession). The Q2017 Data Management Committee, which was heavily represented by Inuit colleagues and partners, were involved in the discussion and interpretation of survey results. Additionally, the Q2017 Steering Committee has members from across Nunavik organizations and the 14 municipalities. The Steering Committee was responsible for overseeing all research using these data. Several of the co-authors were involved in the co-design, management, and data collection steps of Q2017. The Q2017 survey received ethical approval by the Comité d'éthique de la recherche du Centre Hospitalier Universitaire de Québec - Université Laval.

2.2. Chemical analysis

Research nurses collected blood samples via venipuncture using K2-EDTA vacutainers. Samples were centrifuged at 2000×*g* for 10 min and the plasma was transferred into polypropylene tubes for storage at −20 °C until analysis.

PFAAs analyses were conducted in three stages. First, PFAAs measurements were done in 30 pooled samples in 2019 for cost-effectiveness and to ensure sufficient sample volumes for several contaminant measurements. The PFAAs concentrations from pooled samples were used to inform the Arctic Monitoring Assessment Programme (a working group of the Arctic Council mandated to monitor and document trends on pollution and human health) on PFAAs and other persistent organic contaminants in Nunavik (AMAP, 2021b). Next, 500 randomly selected individual plasma samples of participants aged 18 years old and above were analyzed for PFAAs measurement in 2020. The data from this subsample were used to inform a public thematic report summarizing persistent organic compound distributions in Nunavik (Aker et al., 2021). Finally, the remaining individual plasma samples (N = 822) were measured for PFAAs concentrations in 2021.

Pools had a total volume of 15 mL of plasma and were made by adding equal amounts of plasma from participants that were grouped according to: sex (male and female); age (5 age groups:16-19y; 20-29y; 30-39y; 40-59y; 60+); and region of residence (Hudson Bay; Hudson Strait; Ungava Bay). Thus, these pooled samples are reflective of the population of Nunavik aged 16 and older in 2017. Further details on the pooled samples have been described previously (Aker et al., 2022).

The PFAA congeners perfluorobutanoic acid (PFBA), perfluorohexanoic acid (PFHxA), perfluorooctanoic acid (PFOA), perfluorononanoic acid (PFNA), perfluorodecanoic acid (PFDA), perfluoroundecanoic acid (PFUnDA), perfluorobutane sulfonic acid (PFBS), perfluorohexane sulfonic acid (PFHxS) and perfluorooctane sulfonic acid (PFOS) were measured in plasma at the Centre de Toxicologie du Québec (CTQ) of the Institut national de santé publique du Québec (INSPQ) (accredited by the Canadian Association for Environmental Analytical Laboratories and ISO 17025) The PFAAs analysis was performed as following: plasma samples (100 μL) were enriched with labeled internal standards (PFBA-13C4, PFHxA-13C6, PFOA-13C4, PFNA-13C9, PFDA-13C9, PFUndA-13C7, PFHxS-13C3 and PFOS-13C4) and were acidified with a 50% formic acid solution. Thereafter, the samples were extracted using a solid phase extraction (SPE) with SiliaPrepX WAX cartridges 100 mg/3 mL (Silicycle; Québec, Canada). The cartridges were washed first with 5% NH4OH in methanol to remove contaminants and were conditioned with methanol and 2% formic acid prior to process the samples. After loading the samples on the cartridges, these were washed with a 2% formic acid solution and methanol and

analytes were eluted by 3 mL of 5% NH4OH in methanol. The extracts were evaporated to dryness and dissolved in 1 mL of 5 mM ammonium acetate in 20% acetonitrile.

The samples were analyzed by Ultra Performance Liquid Chromatography (UPLC Waters Acquity) with a tandem mass spectrometer (MS/MS Waters Xevo TQ-S) (Waters, Milford, MA, USA) in the MRM mode with an electrospray ion source in the negative mode. The column used was an ACE EXCEL C18-PFP 100 mm × 2.1 mm, 2.0 μm (ACE; Aberdeen, Scotland). The mobile phase was consisted of a gradient of (10:90) acetonitrile:H2O with 5 mM ammonium acetate to 100% acetonitrile with 5 mM ammonium acetate in 7.0 min with a flow rate of 0.5 mL/min. This analytical method is an improved version of the method described in (Caron-Beaudoin et al., 2020). Moreover, these two analytical methods were cross-validated and the results were equivalents. The LODs were between 0.01 and 0.07 μg/L for the perfluorinated compounds. The intra-day precision varied between 2.0 and 3.8% and the inter-day precision varied between 3.8 and 5.0% depending on the analytes. The calibration curve was made in bovine serum and was linear with a weighting of 1/x. Two laboratory blanks constituted with demineralized water were inserted in each analysis sequence to monitor contamination. Polypropylene materials (tubes, microvials) were used to prevent the adsorption of the PFAAs. Most of the material (glassware, pipette tips, etc.) was also washed with methanol before use to prevent the contamination. An isolator column was inserted before analytical column to control contaminants coming from the UPLC system.

The internal reference materials used to control the quality of the analyses were the certified reference material SRM-1958 from the National Institute of Standards and Technology (NIST; Gaithersburg, MD) and some in-house quality controls (QCs) for PFAAs. The overall quality and accuracy for the analytical method was monitored by the participation to the interlaboratory program as the AMAP External Quality Assessment Scheme (Centre de Toxicologie du Québec (CTQ), Institut National de Santé Publique du Québec (INSPQ), Québec, Canada) for the analytes PFHxA, PFOA, PFNA, PFDA, PFUnDA, PFHxS and PFOS as well as the German External Quality Assessment Scheme (G-EQUAS; Erlangen, Germany) for the analytes PFOA and PFOS.

Red blood cell fatty acid composition was analyzed at the Laboratory of Nutritional Lipidomics of the University of Waterloo, Ontario, using a Varian 3900 gas chromatograph equipped with a 15 m DB-FFAP capillary column (df = 0.10 μm). Total RBC eicosapentaenoic acid, docosahexaenoic acid and docosapentaenoic acid were summed and expressed as a percent of total fatty acids. The variable was further categorized into quartiles (n-3 PUFA).

2.3. Statistical analyses

Population descriptive analysis was conducted to describe the distribution of sociodemographic and lifestyle variables in the population. Overall distributions of PFAAs congeners were described, which included calculation of the percent below the LOD, geometric means and their associated 95% confidence intervals, and percentile distributions (25th, 50th, 75th, and 95th). Geometric means were not reported if ≥ 70% of the measurements were below the LOD. Pearson correlation coefficients were calculated for each of the paired log-transformed PFAAs concentrations. PFAAs distributions in the complete dataset (N up to 1322) were also compared to PFAAs distributions in pooled samples (n = 30) and in the subsample (N = 500) previously described.

For PFAAs concentrations from the complete Q2017 sample, non-linear associations between PFAAs and age (continuous) were explored in the total dataset using LOESS smoothing lines. These plots were further stratified by sex to observe differences in the associations between PFAAs and age by females versus males. PFAAs concentrations from the complete Q2017 sample were then compared to the Canadian Health Measures Survey (CHMS) Cycle 5 (2016–2017) concentrations in those aged 16+ years, the Nunavik Health Survey *Qanuippitaa?* 2004 targeting Inuit aged 18+ years (Dewailly et al., 2007), and the Nunavik *Nutaratsaliit qanuingisiarningit niqituinnanut* - Pregnancy Wellness with Country Foods (NQN) 2016–2017 study targeting pregnant women (Caron-Beaudoin et al., 2020). The CHMS is a cross-sectional survey conducted by the Canadian federal agencies Statistics Canada, Health Canada and the Public Health Agency of Canada to determine the health status of Canadians and promote health (Government of Canada, 2022). Differences in concentrations across different groups were considered significant if the confidence intervals did not overlap.

Multiple linear regressions were constructed to examine potential PFAAs exposure determinants. These determinants included sociodemographic variables (sex, age, ecological region, education, and marital status), waist circumference, smoking status, and traditional lifestyle variables (including hunting and n-3 PUFAs- an indication of consumption of marine country food) and main source of drinking water in the summer season. PFAAs concentrations were log-transformed to approach normality for the linear models, and linear regression beta coefficients were transformed to represent percent changes in PFAAs concentrations compared to the respective reference category. All models were adjusted *a priori* for age (categorical: 16–19, 20–29, 30–39, 40–59, 60+ years), sex (female, male), education status (less than high school, at least some high school, and at least some college), and marital status (married/living with partner versus single).

Models examining associations between PFAAs and source of drinking water were further adjusted for participating in hunting activities, n-3 PUFAs, and marine mammal consumption in a sensitivity analysis to ensure that the associations were not confounded by PFAAs contamination of country foods.

All distributions and models were weighted applying survey weights calculated using sex, age, and ecological region distribution of the underlying Nunavik population in 2017 to ensure more representative population-level estimates (Hamel et al., 2020). Weighted population distributions and regression models were conducted in SAS 9.4 (SAS Institute Inc., Cary, NC).

3. Results

A total of 1322 participants were included in the study (Table 1). There was an equal distribution of males and females, over half were aged either 20–29 or 40–59 years, and 42.8% lived in Hudson Bay. Almost half (46.1%) the population had an income <$20,000 versus 11.8% of the population with an income >$60,000. Similarly, 37.2% had less than a Grade 9 education versus 12.8% of the population that had at least some college. Over three quarters of the population smoked daily or occasionally. Additionally, approximately 60% of the population participated in hunting activities at least once a month and 10.5% relied largely on environmental sources for drinking water (from a lake, river, stream, or melted snow, ice or iceberg).

No meaningful differences were observed when comparing PFAAs concentrations in the total population, the sub-sample (N = up to 500) and the pooled samples (N = 30) (Supplementary Table 1). Geometric means from pooled samples were slightly elevated compared to concentrations from individual samples in the total population. The 25th percentile of PFAAs concentrations from the pooled samples were also elevated compared to the 25th percentiles in the individual samples; however, the 95th percentiles of the pooled samples were lower than those in the individual samples. Nevertheless, there were no differences in the concentration trends by sex, age, or region when comparing the individual samples in the total population and the pooled samples (Supplementary Table 2).

In individual samples in the total population (Table 2), PFOS had the highest concentration (GM 4.91, 95% CI 4.70–5.13), followed by PFNA (GM 3.70, 95% CI 3.57–3.85), PFOA (GM 1.02, 95% CI 1.00–1.05), and similar concentrations of PFDA (GM 0.67, 95% CI 0.64–0.71), PFUnDA (GM 0.69, 95% CI 0.65–0.72), and PFHxS (GM 0.63, 95% CI 0.60–0.65). PFAAs congeners (with the exception of undetected PFBA, PFHxA, and PFBS) were moderately to highly correlated (Fig. 2). PFDA and PFUnDA

Table 1
Population demographics of the Qanuilirpitaa? 2017 Health Survey.

Characteristic	Total Population (%)
Sex	
Female	49.6
Male	50.4
Age (years)	
16–19	15.6
20–29	26.2
30–39	17.8
40–59	29.7
60+	10.7
Region	
Hudson Strait	23.9
Hudson Bay	42.8
Ungava Bay	33.3
Marital status	
Married or living with partner	52.2
Single	47.7
Missing	0.1
Income	
<$20,000	46.1
$20,000-$59,999	28.9
>$60,000	11.8
Missing	13.2
Education	
<Grade 9	37.2
At least some high school	47.6
At least some college	12.8
Missing	2.4
Waist Circumference[a] (cm)	
Q1	24.2
Q2	24.0
Q3	24.4
Q4	24.6
Missing	2.7
Smoking	
Never	9.8
Previous smoker	10.5
Daily/Occasionally	78.5
Missing	1.3
Hunting	
Never	23.0
<1/month	15.9
≥1/month	58.9
Missing	2.2
n-3 PUFA in red blood cells (%)	
Q1 (<5.83)	28.2
Q2 (5.83–7.40)	25.0
Q3 (7.40–9.39)	23.6
Q4 (>9.39)	22.6
Missing	0.5
Drinking water source	
Municipal/Bottles	85.0
Environmental[b]	10.5
Missing	4.5

[a] Waist circumference quartiles based on sex. Females: Q1<82, 82 ≤ Q2<94, 94 ≤ Q3<105, Q4≥105; Males: Q1<79, 79.5 ≤ Q2<86.75, 86.75 ≤ Q3<103.5, Q4≥103.5.
[b] Water collected from a lake, river, stream, or melted snow, ice or iceberg.

had a correlation coefficient of 0.97 and were also highly correlated with PFOS (r = 0.91 and 0.87, respectively). PFOA was mostly correlated with PFHxS (r = 0.82). PFNA was correlated with other long-chain PFAAs (PFDA: r = 0.77; PFUnDA: r = 0.74), as well as PFOA (r = 0.68) and PFHxS (r = 0.67).

Females had higher concentrations of PFDA (0.75, 95% CI 0.71–0.78 versus 0.61, 95% CI 0.56–0.66) and PFUnDA (0.79, 95% CI 0.75–0.82 versus 0.60, 95% CI 0.55–0.65) compared to men, whereas males had higher concentrations of PFOA (1.26, 95% CI 1.21–1.31 versus 0.83, 95% CI 0.80–0.86) and PFHxS (0.80, 95% CI 0.76–0.84 versus 0.49, 95% CI 0.47–0.51) compared to females (Table 3). The concentrations of all PFAAs generally increased with age; however, PFOA and PFNA concentrations in Inuit aged 16–19 years were higher than in Inuit aged 20–29 and 30–39 years. This J-shaped non-linear trend of PFOA and PFNA by age was also observed in analyses with age as a continuous variable (Supplementary Fig. 1).

Trends with age also differed by sex (Fig. 3). Older females had the highest concentrations of all PFAAs congeners. However, while PFAAs concentrations generally increased linearly with age in males (with the exception of PFNA), among females, the associations between PFOA, PFNA and PFHxS and age were non-linear. Females aged 25–30 years had the lowest concentrations of these congeners compared to other sex-age groups. Trends by sex were consistent after adjustment for education and marital status (Supplementary Figs. 2 and 3).

Long-chain PFCAs (PFNA, PFDA and PFuDA) and PFOS concentrations were higher in Q2017 compared to CHMS Cycle 5 2016–2017, while PFOA and PFHxS concentrations were higher in CHMS compared to Q2017 (Table 4). Compared to CHMS, PFNA concentrations were 7-fold higher, while PFDA and PFUnDA were approximately 3.5-fold, and PFOS was 1.5-fold higher. Trends in PFAAs concentrations were similar in the Nunavik Pregnancy Wellness with Country Foods (NQN) and expectedly lower (due to the younger population in NQN). PFOS concentrations in Q2017 were almost 4-fold lower than concentrations in Nunavik in 2004.

After adjustment for age, sex, education and marital status, PFOA and PFHxS had higher concentrations in males versus females [PFOA: percent change in chemical concentration in comparison to the respective reference group (a%Δ) 52.43 95% confidence interval (CI) 44.85, 60.42; PFHxS: a%Δ 65.58 95% CI 54.69, 77.24]; PFDA and PFUnDA had higher concentrations in females versus males (PFDA: a%Δ −18.92 95% CI -26.07, −11.08; PFUnDA: a%Δ −24.46 95% CI -31.37, −16.86) (Table 5). Inuit aged 60+ had the highest concentrations of all PFAAs compared to Inuit aged 16–19 years, and the percent change in concentration ranged from approximately 59.10% (PFNA) to 259.01% (PFHxS). PFNA concentrations were 29.58% (95% CI -37.94, −20.09) and 24.35% (95% CI -34.88, −12.13) lower among those aged 20–29 and 30–39 years, respectively, compared to Inuit aged 16–19 years. A similar trend was observed for PFOA. Inuit living in Hudson Bay had the highest concentrations of PFNA (a%Δ 15.90 95% CI 7.00, 25.54) versus Ungava Bay while PFDA, PFUnDA, PFHxS, and PFOS were higher in both Hudson Bay and Hudson Strait compared to Ungava Bay. PFHxS was particularly higher in Hudson Strait (a%Δ 29.68 95% CI 18.74, 41.63) compared to Ungava Bay. PFDA and PFUnDA concentrations were up to 22% lower with increasing education levels. PFOS, PFDA and PFUnDA concentrations were between 16 and 20% higher in married (or common law) participants versus single. Only PFUnDA was associated with waist circumference, such that Inuit in the fourth waist circumference quartile had lower concentrations compared to the first quartile (a%Δ −21.59 95% −33.34, −7.78). No associations were observed between PFAAs and smoking.

All PFAAs concentrations were higher with participation in hunting activities, n-3 PUFAs quartiles, and using environmental sources as a primary source of drinking water (Table 6). In particular, between 228 and 241% increases in PFDA and PFUnDA concentrations were observed in the fourth quartile compared to the first quartile of n-3 PUFAs. PFOA concentrations increased the least with increases in n-3 PUFA quartiles (a%Δ 46.05 95% 32.3, 61.22). The increase in PFAAs concentrations with environmental sources of drinking water remained after additional adjustment of n-3 PUFA levels (Supplementary Table 5).

4. Discussion

This study reported the plasma concentrations of nine PFAAs congeners in the largest and most recent population-based survey in the circumpolar region and explored potential exposure determinants. We detected up to seven-fold higher concentrations of long-chain PFCAs in Nunavik, northern Quebec, compared to the general Canadian population. Concentrations differed by population demographics. Namely, while PFOA and PFHxS were higher among males, PFDA and PFUnDA

Table 2
Overall distributions of PFAAs concentrations in individual samples (μg/L).

	N	%<LOD	GM (95% CI)	25th	50th	75th	95th
PFBA	1318	78.7	<LOD	<LOD	<LOD	<LOD	0.14
PFHxA	1316	99.9	<LOD	<LOD	<LOD	<LOD	<LOD
PFOA	1322	0.1	1.02 (1.00–1.05)	0.83	1.08	1.48	2.27
PFNA	1322	0.1	3.70 (3.57–3.85)	2.17	3.39	5.60	11.12
PFDA	1313	0.8	0.67 (0.64–0.71)	0.38	0.64	1.11	2.62
PFUnDA	1322	1.8	0.69 (0.65–0.72)	0.40	0.71	1.12	2.59
PFBS	1297	99.7	<LOD	<LOD	<LOD	<LOD	<LOD
PFHxS	1322	0.1	0.63 (0.60–0.65)	0.45	0.65	1.00	2.37
PFOS	1322	0.1	4.91 (4.70–5.13)	2.84	4.77	8.68	21.13

N = 1322 for PFOA, PFNA, PFUnDA, PFHxS, and PFOS; N = 1318 for PFBA; N = 1316 for PFHxA; N = 1313 for PFDA; N = 1297 for PFBS.
GM: Geometric mean; 95% CI: 95% confidence intervals.

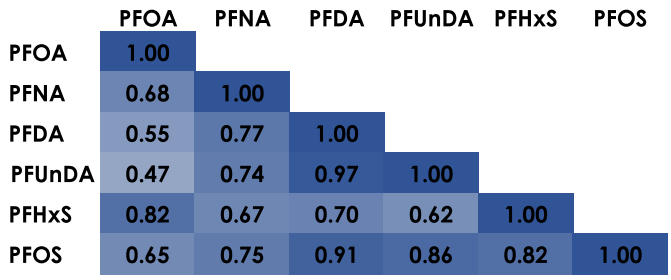

Fig. 2. Pearson correlation coefficients for PFAAs congeners in individual samples from Q2017

were higher among females. PFAAs concentrations generally increased with age, and those aged 60+ years had the highest concentrations of any congener. PFNA, conversely, was associated with age in a non-linear fashion, and Inuit aged 16–19 years had concentrations higher than those aged 20–39 years, and more similar to those aged 40–59 years. Furthermore, PFAAs concentrations were higher with participation in hunting, n-3 PUFA levels (a marker of seafood and marine mammal consumption), and using environmental sources as primary sources of drinking water. These results indicate a unique exposure pathway to PFAAs in Arctic populations compared to those in southern populations and point to the environmental injustice surrounding the elevated PFAAs concentrations in Nunavik in relation to traditional activities and country food consumption.

Concentrations of long-chain PFAAs congeners in Nunavik were also higher than concentrations detected in the U.S. National Health and Nutrition Examination Survey (NHANES) 2017–2018 among individual aged 20 years and over. The geometric mean of PFNA was almost nine times higher in Nunavik compared to NHANES (0.42 μg/L), and PFDA and PFUnDA were 3–5 times higher than NHANES (PFDA: 0.20 μg/L; PFUnDA 0.13 μg/L) (Centers for Disease Control and Prevention (CDC), 2021). Likewise, long-chain PFCAs concentrations were several-fold higher in Nunavik compared to U.S. Red Cross adult blood donors in 2015 (Olsen et al., 2017), French adults in 2014–2016 (Fillol et al., 2021), Swedish mothers (Gyllenhammar et al., 2020), and Australian adults in 2016–2017 (Toms et al., 2019). The latest Arctic Monitoring and Assessment Programme (AMAP) report reported similarly elevated concentrations of long-chain PFCAs (PFNA in particular) and PFOS, indicating a potentially unique exposure profile in Arctic communities (AMAP, 2021c; *AMAP, 2017*, 2017; Muir et al., 2019). Among pregnant or child-bearing aged women, the highest levels of PFNA were reported in Nunavik and Alaska Native communities followed by Greenland (AMAP, 2021c). PFNA was also elevated in Indigenous communities in the Northwestern Territories, Canada (Garcia-Barrios et al., 2021). Another recent study conducted in Greenland examined PFAAs concentrations in 177 mothers and fathers with mean ages of 34–37 years (Wielsøe et al., 2022). While concentrations of PFOS and PFHxS were higher in Greenland compared to Nunavik adults aged 30–39 years, PFOA, PFNA and PFDA concentrations were markedly lower than in Nunavik, but still higher than in the CHMS or NHANES. The unique exposure profile of elevated PFOS and long-chain PFCAs concentrations points to the bioaccumulative properties of these specific congeners in Arctic wildlife and local Indigenous populations, as well as the role of increasingly used FTOHs reaching the Arctic and degrading into long-chain PFCAs (Eriksson et al., 2016; Haukås et al., 2007; Muir et al., 2019; Müller et al., 2011). PFNA, PFDA, PFUnDA and PFOS have greater bioaccumulative properties compared to PFOA and PFHxS (Conder et al., 2008; Dassuncao et al., 2017; Pan et al., 2019), and this could, in part, explain why PFOA and PFHxS were not detected at similarly high concentrations in Nunavik compared to other southern populations.

Pooled samples are a cost-effective method that also allow for better quantification of some chemicals by increasing the volume size and increasing detection frequencies, and are commonly used by the

Table 3
Comparison of PFAAs geometric mean concentrations (μg/L) and their associated 95% confidence intervals in individual samples by sex, age, and region.

	PFOA	PFNA	PFDA	PFUnDA	PFHxS	PFOS
Sex						
Female	0.83 (0.80–0.86)^{a}	3.70 (3.55–3.86)	0.75 (0.71–0.78)^{a}	0.79 (0.75–0.82)^{a}	0.49 (0.47–0.51)^{a}	4.81 (4.58–5.06)
Male	1.26 (1.21–1.31)^{b}	3.71 (3.49–3.95)	0.61 (0.56–0.66)^{b}	0.60 (0.55–0.65)^{b}	0.80 (0.76–0.84)^{b}	5.01 (4.67–5.37)
Age						
16–19	0.92 (0.86–0.99)^{a,c}	3.91 (3.55–4.31)^{a}	0.43 (0.38–0.48)^{a}	0.49 (0.44–0.54)^{a}	0.41 (0.38–0.44)^{a}	3.12 (2.81–3.46)^{a}
20–29	0.83 (0.79–0.87)^{b}	2.86 (2.68–3.05)^{b,c}	0.54 (0.50–0.59)^{b}	0.56 (0.51–0.61)^{b}	0.46 (0.43–0.49)^{b}	3.83 (3.52–4.16)^{b}
30–39	0.86 (0.81–0.92)^{c}	3.08 (2.81–3.39)^{c}	0.61 (0.54–0.69)^{b,c}	0.62 (0.54–0.71)^{b,c}	0.54 (0.50–0.58)^{c}	4.45 (4.01–4.94)^{c}
40–59	1.16 (1.10–1.22)^{d}	4.07 (3.80–4.37)^{a,d}	0.83 (0.77–0.90)^{d}	0.82 (0.75–0.89)^{d}	0.81 (0.75–0.86)^{d}	6.05 (5.59–6.53)^{d}
60+	1.88 (1.72–2.05)^{e}	6.71 (5.90–7.62)^{e}	1.41 (1.20–1.66)^{e}	1.33 (1.13–1.57)^{e}	1.58 (1.41–1.77)^{e}	11.40 (9.81–13.24)^{e}
Region						
Hudson Bay	1.05 (1.00–1.10)^{a}	4.09 (3.82–4.36)^{a}	0.77 (0.71–0.84)^{a}	0.74 (0.67–0.80)^{a}	0.63 (0.59–0.67)^{a}	5.45 (5.03–5.91)^{a}
Hudson Strait	0.98 (0.92–1.04)^{b}	3.31 (3.07–3.58)^{b}	0.71 (0.65–0.78)^{a}	0.80 (0.73–0.88)^{b}	0.72 (0.66–0.77)^{b}	5.78 (5.30–6.29)^{a}
Ungava Bay	1.02 (0.98–1.06)^{b}	3.54 (3.37–3.72)^{b}	0.55 (0.52–0.59)^{b}	0.56 (0.52–0.60)^{b}	0.57 (0.54–0.60)^{c}	3.81 (3.59–4.06)^{b}

$^{a\text{-}e}$ Estimates with different superscripts are significantly different between groups at $p < 0.05$. Likewise, estimates with similar subscripts represent groups that were significantly similar with $p > 0.05$.

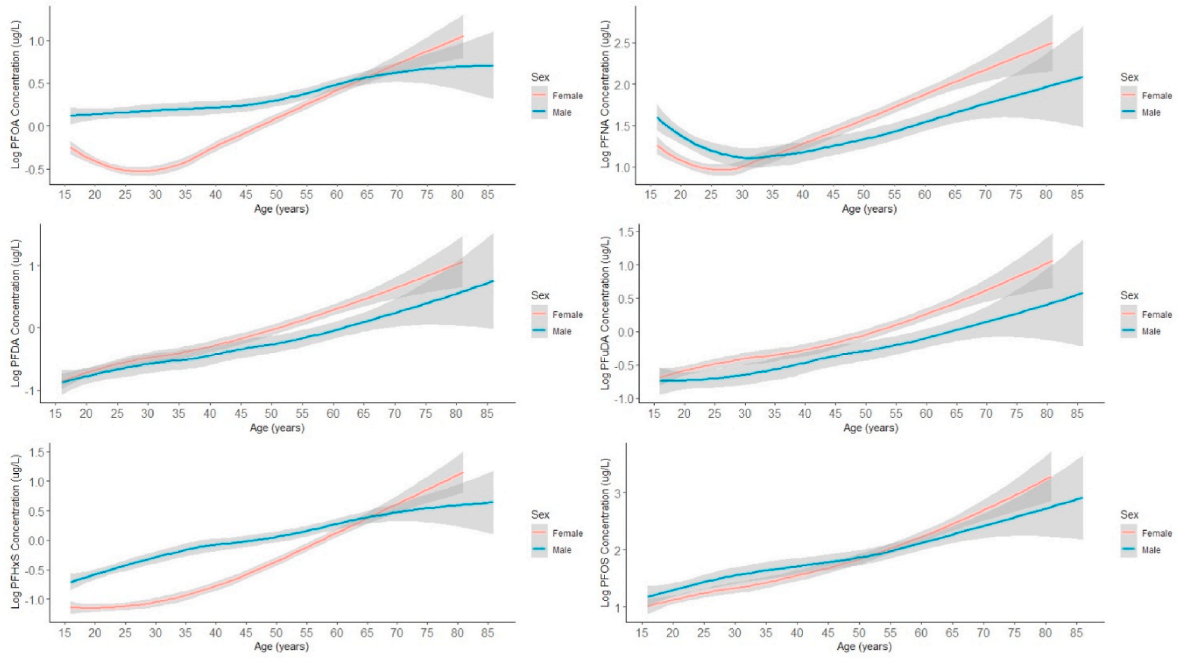

Fig. 3. PFAAs concentrations by age and sex.

Table 4
Comparison of PFAAs geometric means and 95% confidence intervals (μg/L) in Qanuilirpitaa? 2017 against Qanuippitaa? 2004, NQN Pregnancy Wellness with Country Foods, and the Canadian Health Measures Survey Cycle 5 2016–2017.

	Qanuilirpitaa? 2017 16–81 years	CHMS Cycle 5 2016–2017 16–79 years	Qanuippitaa? 2004 18–74 years	NQN Pregnancy Wellness with Country Foods 2016–2017 16–40 years
	GM (95% CI)	GM (95% CI)	GM (95% CI)	GM (95% CI)
PFBA	<LOD	<LOD	–	<LOD
PFHxA	<LOD	<LOD	–	<LOD
PFOA	1.02 (1.00–1.05)	1.30 (1.20–1.40)	–	0.54 (0.49–0.58)
PFNA	3.70 (3.57–3.85)	0.52 (0.47–0.58)	–	2.30 (2.10–2.70)
PFDA	0.67 (0.64–0.71)	0.19 (0.17–0.21)	–	0.51 (0.46–0.61)
PFUnDA	0.69 (0.65–0.72)	<LOD	–	0.54 (0.43–0.60)
PFBS	<LOD	<LOD	–	<LOD
PFHxS	0.63 (0.60–0.65)	0.96 (0.85–1.10)	–	0.27 (0.23–0.31)
PFOS	4.91 (4.70–5.13)	3.30 (2.90–3.70)	18.0 (18.0–19.0)	3.30 (2.80–3.90)

Canadian Health Measures Survey (CHMS) (Health Canada, 2020) While the concentrations were slightly elevated in pooled compared to individual samples; we observed no differences across the two datasets with regards to trends by sub-population and were able to detect the J-shaped relationship between PFNA and age in both datasets. Given the high costs associated with PFAAs analyses, this indicates that future studies may benefit from conducting pilot pooled analyses to identify key vulnerable populations of exposure to PFAAs and provide an overall picture of concentrations in a population.

While PFOA and PFHxS concentrations were higher in men versus women, PFDA and PFUnDA concentrations were higher in women versus men. Conversely, a recent study in Greenland detected higher concentrations of all PFAAs congeners in men versus women, likely due to the increased consumption of traditional foods (hunted or harvested from the land and sea) contaminated with PFAAs (Wielsøe et al., 2022). Men in Nunavik also reported overall higher frequency of consumption of country foods compared to women (Allaire et al., 2021); however, the data available for the report did not consider the **amount** consumed. Other studies have also detected higher concentrations in men versus women and this has been linked to the excretion of PFAAs via menstruation and the transfer of PFAAs through the placenta and breastfeeding (Macheka-Tendenguwo et al., 2018; Rickard et al., 2022; Seo et al., 2018; Upson et al., 2022). The unique excretion pathways in females could, in part, explain the non-linear associations observed between some PFAAs congeners and age in females. We observed lower PFAAs concentrations among younger females compared to young males, possibly indicating a loss of PFAAs through menstruation, which has been shown to explain approximately 30% of discrepancies in concentrations between females and males in other studies (Rickard et al., 2022). Menopausal women were also reported to have higher concentrations of PFAAs (particularly PFHxS) compared to non-menopausal women (Colles et al., 2020). This likely suggests the influence of menstruation as an excretory pathway. In our study, PFHxS concentrations in females started increasing at approximately 30 years, and PFNA and PFOA were lowest in females aged 25–30 years, indicating a possible additional route of excretion for these specific congeners via pregnancy and/or breastfeeding. A recent study in 62 Korean women reported higher placental transfer with PFOA and PFHxS compared to PFOS (Kang et al., 2021). This was consistent with other studies, most of which detected the highest placental transfer of PFOA, followed by PFHxS and PFNA, compared to PFOS (Eryasa et al., 2019; Kim et al., 2011; Li et al., 2020; Yang et al., 2016; Zhao et al., 2017). In fact, a mother may transfer 40% or more of her PFAAs body burden onto an infant via placental transfer (Aylward et al., 2014; Verner et al., 2016).

The higher concentrations of PFAAs in the Hudson Bay and/or Hudson Strait were as anticipated. Ungava Bay includes Kuujjuaq, which is the largest village in Nunavik and where there may be greater access to market foods. Beluga whales are primarily hunted in Hudson Strait (Lemire et al., 2015). The increased consumption of beluga whale in this region may explain the higher concentrations of PFUnDA, PFHxS, and PFOS compared to other regions. It is interesting to note the lack of association between PFOA and ecological region of residence, indicating a potentially different exposure source compared to other PFAAs congeners. This is further evidenced by the magnitude of the associations

Table 5
Multiple linear regression between PFAAs and sociodemographic variables in Qanuilirpitaa? 2017.

	PFOA		PFNA		PFDA	
	%Δ	a%Δ	%Δ	a%Δ	%Δ	a%Δ
Sex						
Female	**1.00**	**1.00**	1.00	1.00	**1.00**	**1.00**
Male	**51.8 (44.05, 59.96)**	**52.43 (44.85, 60.42)**	0.31 (−6.98, 8.18)	−1.09 (−8.19, 6.56)	**−18.51 (-25.82, -10.48)**	**−18.92 (-26.07, -11.08)**
Age						
16–19	1.00	1.00	1.00	1.00	1.00	1.00
20–29	**−10.18 (-18.54, -0.96)**	**−5.81 (-13.88, 3.01)**	**−26.94 (-34.88, -18.05)**	**−29.58 (-37.94, -20.09)**	**26.94 (10.30, 46.09)**	**19.70 (3.21, 38.83)**
30–39	−6.55 (−15.43, 3.27)	−3.61 (−12.66, 6.39)	**−21.15 (-31.61, -9.08)**	**−24.35 (-34.88, -12.13)**	**42.47 (20.42, 68.56)**	**33.06 (11.55, 58.72)**
40–59	**25.87 (15.58, 37.07)**	**30.75 (19.33, 43.26)**	**4.15 (-7.25, 16.94)**	**−0.65 (-12.47, 12.77)**	**94.69 (70.00, 122.97)**	**78.05 (54.22, 105.57)**
60+	**104.2 (82.72, 128.20)**	**100.48 (76.11, 128.21)**	**71.44 (45.93, 101.4)**	**59.1 (32.56, 90.96)**	**229.95 (170.18, 302.94)**	**194.21 (135.78, 267.12)**
Region						
Ungava Bay	1.00	1.00	1.00	1.00	1.00	1.00
Hudson Bay	2.73 (−3.46, 9.32)	3.42 (−2.51, 9.72)	**15.36 (6.37, 25.12)**	**15.90 (7.00, 25.54)**	**39.86 (25.72, 55.59)**	**43.94 (30.05, 59.33)**
Hudson Strait	−4.56 (−11.44, 2.86)	−4.15 (−10.37, 2.50)	−6.45 (−14.9, 2.84)	−7.50 (−15.00, 0.65)	**29.03 (15.85, 43.71)**	**28.6 (16.00, 42.56)**
Education						
< High school	1.00	1.00	1.00	1.00	1.00	1.00
Some high school	**−13.84 (-19.65, -7.61)**	−5.61 (−11.09, 0.20)	**−9.83 (-17.97, -0.87)**	−1.34 (−9.75, 7.85)	**−20.57 (-29.24, -10.84)**	**−11.62 (-20.68, -1.52)**
Some college	−4.33 (−13.61, 5.95)	0.40 (−7.58, 9.08)	−5.67 (−17.02, 7.23)	−4.55 (−15.38, 7.67)	−11.61 (−24.89, 4.02)	**−19.84 (-30.90, -7.00)**
Marital Status						
Single	1.00	1.00	1.00	1.00	1.00	1.00
Married	5.59 (−0.82, 12.42)	−1.77 (−7.46, 4.27)	**9.00 (0.45, 18.29)**	8.04 (−0.73, 17.58)	**31.34 (19.17, 44.75)**	**16.54 (5.97, 28.16)**
Waist Circumference						
Q1	1.00	1.00	1.00	1.00	1.00	1.00
Q2	3.53 (−4.87, 12.67)	4.41 (−3.20, 12.61)	7.84 (−3.27, 20.22)	8.11 (−2.46, 19.82)	6.58 (−7.35, 22.61)	4.11 (−8.64, 18.64)
Q3	8.64 (−1.10, 19.34)	0.70 (−8.39, 10.70)	**14.46 (0.78, 30.00)**	8.14 (−5.02, 23.12)	**23.96 (4.89, 46.49)**	4.26 (−11.09, 22.25)
Q4	6.50 (−2.75, 16.63)	−1.25 (−9.47, 7.71)	14.19 (1.37, 28.63)	7.67 (−4.19, 20.99)	**18.89 (1.85, 38.78)**	−3.07 (−16.66, 12.74)
Smoking						
Never	1.00	1.00	1.00	1.00	1.00	1.00
Previous smoker	−8.72 (−20.95, 5.41)	−4.8 (−16.04, 7.94)	−8.14 (−23.63, 10.49)	−7.73 (−22.53, 9.90)	0.04 (−23.17, 30.28)	0.02 (−21.64, 27.66)
Daily/ Occasionally	**−17.81 (-26.32, -8.32)**	−4.12 (−13.01, 5.68)	**−15.16 (-26.89, -1.56)**	−3.62 (−15.73, 10.23)	−10.03 (−26.77, 10.53)	5.95 (−11.26, 26.50)

	PFUnDA		**PFHxS**		**PFOS**	
	%Δ	**a%Δ**	**%Δ**	**a%Δ**	**%Δ**	**a%Δ**
Sex						
Female	1.00	1.00	1.00	1.00	1.00	1.00
Male	**−23.89 (-30.88, -16.19)**	**−24.46 (-31.37, -16.86)**	**63.66 (52.96, 75.12)**	**65.58 (54.69, 77.24)**	4.08 (−4.51, 13.44)	3.71 (−4.65, 12.81)
Age						
16–19	1.00	1.00	1.00	1.00	1.00	1.00
20–29	15.17 (0.10, 32.52)	7.10 (−7.71, 24.29)	11.00 (−0.51, 23.84)	**15.00 (3.42, 27.87)**	**22.81 (7.59, 40.18)**	**16.49 (1.08, 34.26)**
30–39	27.35 (6.56, 52.20)	17.19 (−2.84, 41.34)	**30.92 (16.72, 46.85)**	**32.49 (18.37, 48.30)**	**42.81 (22.74, 66.17)**	**32.63 (13.27, 55.30)**
40–59	**68.19 (47.41, 91.91)**	**51.04 (31.41, 73.61)**	**96.51 (77.60, 117.44)**	**99.00 (79.18, 121.02)**	**94.05 (70.93, 120.30)**	**78.98 (56.19, 105.09)**
60+	**173.86 (123.83, 235.09)**	**140.23 (93.39, 198.43)**	**286.1 (236.94, 342.44)**	**259.01 (205.05, 322.51)**	**265.75 (203.26, 341.12)**	**220.96 (158.5, 298.52)**
Region						
Ungava Bay	1.00	1.00	1.00	1.00	1.00	1.00
Hudson Bay	**31.77 (18.03, 47.12)**	**35.69 (22.09, 50.81)**	**10.85 (2.10, 20.35)**	**14.17 (5.84, 23.15)**	**42.89 (29.21, 58.01)**	**49.25 (35.69, 64.17)**
Hudson Strait	**43.96 (28.01, 61.90)**	**42.35 (27.18, 59.34)**	**26.73 (14.85, 39.83)**	**29.68 (18.74, 41.63)**	**51.45 (36.06, 68.57)**	**54.54 (39.44, 71.27)**
Education						
< High school	1.00	1.00	1.00	1.00	1.00	1.00
Some high school	**−21.25 (-30.33, -10.99)**	**−13.59 (-23.03, -3.00)**	**−20.16 (-27.43, -12.16)**	**−8.72 (-15.56, -1.33)**	**−14.24 (-23.11, -4.33)**	−4.22 (−13.33, 5.86)
Some college	−14.34 (−27.87, 1.72)	**−21.59 (-33.34, -7.78)**	−6.45 (−17.96, 6.67)	−5.06 (−15.38, 6.51)	−2.82 (−16.02, 12.45)	−8.58 (−19.99, 4.44)
Marital Status						
Single	1.00	1.00	1.00	1.00	1.00	1.00
Married	**25.69 (13.31, 39.43)**	**15.48 (4.18, 28.00)**	**24.44 (14.10, 35.71)**	5.30 (−2.43, 13.66)	**37.27 (24.94, 50.81)**	**19.89 (9.33, 31.48)**
Waist Circumference						
Q1	1.00	1.00	1.00	1.00	1.00	1.00
Q2	3.86 (−10.53, 20.57)	0.58 (−12.34, 15.40)	2.70 (−8.79, 15.64)	1.08 (−8.31, 11.44)	2.27 (−10.44, 16.79)	−0.50 (−12.30, 12.90)
Q3	16.05 (−2.07, 37.51)	−1.24 (−15.84, 15.88)	**25.67 (10.94, 42.35)**	5.05 (−6.37, 17.86)	**35.23 (16.28, 57.26)**	12.59 (−3.29, 31.08)
Q4	1.22 (−14.17, 19.38)	**−15.46 (-28.02, -0.71)**	**21.10 (6.61, 37.56)**	−1.21 (−11.84, 10.70)	**35.65 (17.32, 56.85)**	9.44 (−5.31, 26.49)
Smoking						
Never	1.00	1.00	1.00	1.00	1.00	1.00

(*continued on next page*)

Table 5 (*continued*)

Previous smoker	11.03 (−15.67, 46.18)	8.31 (−16.16, 39.93)	−1.84 (−20.33, 20.95)	0.74 (−14.46, 18.64)	4.83 (−18.12, 34.21)	4.57 (−15.73, 29.75)
Daily/ Occasionally	3.45 (−17.17, 29.19)	16.01 (−4.61, 41.10)	−16.41 (−29.55, −0.81)	5.28 (−8.34, 20.91)	−18.21 (−33.29, 0.27)	−0.96 (−17.17, 18.41)

a%Δ: Models adjusted for age, sex, education and marital status.

Table 6
Multiple linear regression between PFAAs and traditional lifestyle variables in Qanuilirpitaa? 2017.

	PFOA		PFNA		PFDA	
	%Δ	a%Δ	%Δ	a%Δ	%Δ	a%Δ
Hunting						
Never	1.00	1.00	1.00	1.00	1.00	1.00
<1/month	5.51 (−4.45, 16.49)	7.42 (−1.20, 16.79)	5.49 (−6.27, 18.72)	**12.56 (0.18, 26.47)**	2.52 (−12.51, 20.14)	15.21 (−0.62, 33.56)
≥1/month	**19.31 (9.94, 29.48)**	**16.23 (8.36, 24.67)**	**21.99 (10.96, 34.13)**	**27.26 (16.09, 39.51)**	**25.81 (11.12, 42.43)**	**40.88 (24.82, 59.01)**
n-3 PUFA						
Q1	1.00	1.00	1.00	1.00	1.00	1.00
Q2	6.88 (−1.43, 15.88)	**12.75 (5.16, 20.89)**	**33.28 (20.58, 47.33)**	**35.55 (22.38, 50.15)**	**72.59 (54.76, 92.47)**	**69.46 (51.14, 90.01)**
Q3	**24.81 (14.98, 35.49)**	**25.43 (16.37, 35.19)**	**61.6 (46.66, 78.05)**	**63.68 (47.26, 81.93)**	**149.51 (122.42, 179.89)**	**123.11 (95.97, 154)**
Q4	**60.91 (47.40, 75.65)**	**46.05 (32.3, 61.22)**	**146.46 (121.72, 173.96)**	**131.23 (103.18, 163.15)**	**302.71 (256.71, 354.66)**	**228.14 (183.22, 280.17)**
Water source						
Municipal/ Bottles	1.00	1.00	1.00	1.00	1.00	1.00
Environmental	**20.04 (9.02, 32.17)**	**13.54 (4.88, 22.91)**	**28.22 (12.86, 45.67)**	**18.11 (5.06, 32.79)**	**36.27 (16.71, 59.12)**	**29.55 (12.02, 49.82)**

	PFUnDA		PFHxS		PFOS	
	%Δ	**a%Δ**	**%Δ**	**a%Δ**	**%Δ**	**a%Δ**
Hunting						
Never	1.00	1.00	1.00	1.00	1.00	1.00
<1/month	3.15 (−12.73, 21.93)	14.97 (−1.81, 34.60)	6.89 (−6.40, 22.06)	**13.06 (1.38, 26.08)**	4.38 (−8.63, 19.24)	**14.00 (0.17, 29.73)**
≥1/month	**25.13 (9.95, 42.42)**	**41.07 (24.13, 60.33)**	**26.69 (13.43, 41.49)**	**25.67 (14.82, 37.55)**	**32.88 (18.14, 49.46)**	**40.3 (25.06, 57.41)**
n-3 PUFA						
Q1	1.00	1.00	1.00	1.00	1.00	1.00
Q2	**74.23 (54.27, 96.76)**	**70.63 (50.4, 93.59)**	**16.61 (4.79, 29.77)**	**22.7 (12.06, 34.36)**	**45.62 (30.97, 61.91)**	**45.62 (30.24, 62.81)**
Q3	**154.12 (125.35, 186.57)**	**133.28 (103.55, 167.34)**	**58.44 (42.28, 76.43)**	**47.78 (34.45, 62.42)**	**111.04 (88.43, 136.37)**	**91.33 (68.87, 116.77)**
Q4	**298.37 (251.66, 351.28)**	**241.4 (193.73, 296.79)**	**153.15 (126.29, 183.19)**	**102.11 (79.95, 127.00)**	**247.2 (208.51, 290.75)**	**178.98 (142.38, 221.10)**
Water source						
Municipal/ Bottles	1.00	1.00	1.00	1.00	1.00	1.00
Environmental	**34.71 (14.48, 58.52)**	**27.32 (8.99, 48.73)**	**40.71 (21.51, 62.96)**	**32.07 (17.33, 48.66)**	**46.41 (24.48, 72.19)**	**38.12 (18.75, 60.65)**

a%Δ: Models adjusted for age, sex, education and marital status.

observed between PFAAs congeners and hunting activities and n-3 PUFA quartiles (a marker of seafood and marine mammal consumption). Although PFOA was associated with the fourth quartile of n-3 PUFA, the percent difference for PFOA was at least three times lower than other PFAAs congeners. Likewise, PFDA, PFUnDA, PFHxS, PFOS and PFNA (albeit a weak association with PFNA) were associated with marriage status. Hunting, harvesting and preparation of country foods are time consuming activities that are performed complementarily between women and men. As such, married (or living together) couples tend to have greater access to country foods (Collings et al., 2016).

Market foods and personal care products may be other important exposure sources of PFOA and PFNA (Dubeau et al., 2022; Pasecnaja et al., 2022; Whitehead et al., 2021). Migration of PFAAs into foods has been identified, particularly in highly salty or oily foods (Schaider et al., 2017; Susmann et al., 2019). Additionally, a large Flemish study detected a significant association between use of at least seven personal care products in the three days prior to sampling and PFNA (Colles et al., 2020), and other studies detected associations between PFOA, PFNA, and PFHxS and personal care products (Fujii et al., 2013; Thépaut et al., 2021).

No direct sources of PFAAs contamination are known to be present in Nunavik. As such, unlike other regions in southern latitudes, drinking water was not anticipated to be an important exposure source of PFAAs. However, we detected significant and consistent associations between all PFAAs congeners and drinking water from environmental sources (lakes, streams, snow, ice, etc.), even after adjustment of country food and marine mammal consumption patterns. A recent report identified elevated PFAAs concentrations in rainwater globally, including PFOA concentrations exceeding the US EPA drinking water health advisory in remote Tibet and Antarctica (Cousins et al., 2022). Further water analyses are currently underway to validate these findings.

The Q2017 survey is the largest survey conducted among adults in the circumpolar region. The study also included nine PFAAs congeners and allowed for the identification of key long-chain PFCAs exposures in the population. Among the limitations to the study was our inability to examine the trends of all PFAAs concentrations in Nunavik over time. The survey did not include questions on product use, which may have contributed to some of the PFAAs exposure (Glüge et al., 2020; Nilsson et al., 2013). The recruitment rate of Q2017 was also not as high as anticipated; however, weighting by population estimates helped rectify this limitation (Hamel et al., 2020). Additional studies in the region are using targeted- and non-targeted analyses to further examine exposure to PFAS of emerging concern, including long-chain PFAAs of 12 carbons and above (C12 to C21), which are currently nominated for inclusion in the Stockholm Convention, and understand their origin in the Arctic.

5. Conclusions

We analyzed nine PFAAs plasma concentrations in up to 1322 individuals part of a population-representative survey in the Arctic region of Nunavik, Quebec. We observed exceptionally high long-chain PFAAs concentrations, such that PFNA and PFUnDA concentrations were approximately 7-fold higher, and PFDA concentrations were 4-fold higher compared to the general Canadian population. Trends in the concentrations measured in the total survey dataset closely mimicked those in the pooled samples, albeit pooled samples revealed higher overall concentrations. PFAAs concentrations differed by age, sex, ecological region, and participation in traditional activities. The results highlight the importance of further characterizing PFAAs exposure sources in Arctic communities, including in drinking water from different local sources, and provide additional evidence for the long-range transport of long-chain PFCAs and their precursors that necessitate international actions to control PFAAs exposure.

Author contributions

AA: Conceptualization; Formal analysis; Methodology; Writing-original draft. PA: Conceptualization; Validation; Data curation; Funding acquisition; Supervision; Writing-review & editing. ECB: Validation; Writing-review & editing. ADS: Validation; Writing-review & editing. SR: Validation; Data curation; Writing-review & editing. ML: Conceptualization; Validation; Funding acquisition; Supervision; Writing-review & editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.chemosphere.2022.136797.

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