Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Natural Sciences
Department of Biology

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Arctic Hunter: a dietary toxicity advisory and monitoring platform for Arctic indigenous populations

Master's thesis in Environmental Chemistry and Toxicology
Supervisor: Bjørn Munro Jenssen
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Sammendrag

Bakgrunn

Inuittenes tradisjonelle livsstil fremmer sosial samhørighet og ernæringsmessig helse gjennom høsting og konsum av vilt, inkludert sjøpattedyr og fugl som er rik på essensielle næringsstoffer. Langtransportert transport av miljøgifter fra lavere breddegrader har imidlertid ført til ekstreme forurensningsbelastninger og gift-effekter i høytrofiske arktiske marine arter. Dette truer urfolks helse og matsikkerhet. Denne utfordringen forsterkes av vanskeligheter med datainnsamling og overvåking av miljøgifter og human eksponsering i Arktis. Dette prosjektet har som mål å utvikle en plattform som gjør det mulig for inuitter og forskere å overvåke eksponering for miljøgifter som følge av diettinntak. To svært relevante studier brukes for å belyse den høye eksponeringen for kvikksølv og PFOS i to urbefolknings populasjoner på Grønland.

Metoder

Plattformprototypen ble designet med fire elementer: et nettbasert admin-brukergrensesnitt for forskere å lage studier og administrere innhold; en mobilapp for inuittdeltakere for å logge diettinntak og selvmonitoreksponering; en dokumentdatabase for å lagre deltaker- og forskningsdata; og en API som kobler disse komponentene sammen gjennom strenge regler for tilgangskontroll. I tillegg ble to studier på inuittenes dietteksponering i Avanersuaq og Ittoqoortoormiit tilpasset i pilotsimuleringer, med henholdsvis 630 og 353 genererte deltakere for å analysere populasjonsomfattende kvikksølv- og PFOS-eksponering via diettinntak av narhval (*Monodon monoceros*) og isbjørn (*Ursus maritimus*).

Resultater

En nettbasert plattform ble utviklet for å tillate forskere å lage studier med basert på geografiske og tidsrelatertemessige data om hos arter som inngår i dietten og miljøgift-vevskonsentrasjoner i relevante vev. Plattformen støtter brukerprofiler, logging av diettinntak og beregning av eksponeringsnivåer for forurensningermiljøgifter. Forskeres tilgang til brukerdata reguleres gjennom en abonnementsmodell for studienes varighet. I tillegg ble er en mobilapp prototype mobilapp vistpresentert frem for å demonstere selvovervåking ave diettinntak og eksponering. Analysen av studiene i Avanersuaq og Ittoqoortoormiit viste at konsum av narwhval Hg og isbjørn PFOS gjennomsnittlig inntak mellommedførte en ekponering for Hg og PFOS som var 1,78-7,64 og 0,53-3,06 ganger høyere enn det tolerable ukentlige inntaket (deres TWI: tolerably weekly intake) for henholdsvis Hg og PFOS., Dette stemmer godt overens med prognosene til i den plattform-simuleringent forskning, som viste gjennomsnittlige populasjonseksponeringer på 473% Hg og 180% PFOS over TWI.

Konklusjoner

Kostholdseksponering for miljøgifter utgjør en trussel ovenfor inuittsamfunn. Dette prosjektet foreslår et samarbeidsforhold mellom forskere og inuittsamfunn, basert på datadeling. Dette vil legge til rette for storskala datainnsamling som vil bidra bedret forståelse og håndtering av miljøhelserisko på individ og populasjonsnivå. og sette scenen for innovative AI-applikasjoner for å forstå og håndtere miljøhelserisiko.

Abstract

Background

The traditional Inuit way of life fosters social cohesion and nutritional health through harvesting and consuming country food, rich in essential nutrients. However, long-range transport of pollutants from lower latitudes has led to extreme contaminant loads and toxicity in high-trophic Arctic marine species, threatening indigenous health and food security. This challenge is exacerbated by data collection and monitoring difficulties in the Arctic. This project aims to develop a platform that enables Inuit and scientists to monitor dietary intake and contaminant exposure collaboratively. Two highly relevant studies are used to highlight the disproportionate exposure to mercury and PFOS in two indigenous populations from Greenland.

Methods

The platform prototype was designed with four elements: a web-based admin user interface for researchers to create studies and manage content; a mobile app for Inuit participants to log dietary intake and self-monitor exposure; a document database to store participant and research data; and an API that connects these components through strict access control rules. Additionally, two Greenland studies on Inuit dietary exposure in Avanersuaq and Ittoqoortoormiit were adapted as pilot simulations, with 630 and 353 generated participants, respectively, to analyze population-wide mercury and PFOS exposure via narwhal (*Monodon monoceros*) and polar bear (*Ursus maritimus*) dietary intake.

Results

A web-based platform was developed for researchers to create studies with geographical and temporal data of species and tissue concentrations. The platform supports user profiles, dietary intake logging, and the calculation of contaminant exposure levels. Access to user data is regulated through a subscription model for the duration of the studies. Additionally, a prototype mobile app was showcased to self-monitor dietary intake and exposure. The analysis of the Avanersuaq and Ittoqoortoormiit studies revealed that narwhal Hg and polar bear PFOS mean intake were between 1.78-7.64 and 0.53-3.06 times higher than their tolerably weekly intake (TWI), respectively, aligning well with the projections of the platform simulated research, which showed mean population exposures of 473% Hg and 180% PFOS over the TWI.

Conclusions

Dietary exposure to pollutants is a threat to Inuit societies. This project proposes a collaborative relationship between scientists and Inuit communities, based on data sharing, to facilitate large-scale data collection. This will contribute to an improved understanding and management of environmental health risks at the individual and population levels.

Acknowledgments

I want to express my heartfelt gratitude to everyone who has supported and contributed to the development of this thesis.

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A special mention to Christian Sonne. Thank you for inviting me to learn more about the idea of creating an app for the Inuit population. I have added my little contribution to that original project, and I hope it can become a reality one day.

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This work and part of my life have opened my eyes to previously unknown realities in the Arctic. I can say now with confidence that I deeply care about these issues. My most sincere thanks to all of you who have contributed to this journey, giving me the gifts of purpose and knowledge.

Table of Contents

Abbreviations

API	application programming interface
$BMDL_{10}$	benchmark dose (lower confidence limit)
BMI	body-mass index
bw	body weight
C	carbon
CECs	contaminants of emerging concern
CMS	content management system
CNS	central nervous system
CRUD	create, read, update, delete
dw	dry weight
EFSA	European Food Safety Authority
EPA	United States Environmental Protection Agency
F	fluoride
FAIR	Findability, Accessibility, Interoperability, Reuse
FFQs	food-frequency questionnaires
GUI	graphical user interface
GraphQL	Graph Query Language
Hg	mercury
Hg^0	gaseous elemental mercury
Hg^{1+}	inorganic mercury (mercurous)
Hg^{2+}	inorganic mercury (mercuric)
HTML	HyperText Markup Language
HTTP	HyperText Transfer Protocol
JSON	JavaScript Object Notation
LC-PFCAs	long-chain perfluorocarboxilates
MeHg	methylmercury
MQL	MongoDB Query Language
NILU	Norwegian Institute for Air Research
NNDFs	non-nutrient dense foods
NPI	Norwegian Polar Institute
NTNU	Norwegian University of Science and Technology
OS	operating system
PFAAs	perfluoroalkyl acids
PFAS	per- and poly-fluoroalkyl substances
PFHxS	perfluorohexane sulfonic acid
PFOA	perfluorooctanoic acid
PFCAs	perfluorocarboxilates
PFOS	perfluorooctane sulfonic acid
PFSAs	perfluoroalkyl sulfonates
POPs	persistent organic pollutants
PTMI	provisional tolerable monthly intake
PTYI	provisional tolerable yearly intake
PUFAs	polyunsaturated fatty acids
REST	Representational State Transfer
SaaS	software as a service
SC-POPs	Stockholm Convention persistent organic pollutants
Se	selenium
SQL	Structured Query Language
TWI	tolerable weekly intake
UI	user interface
ww	wet weight

1 Introduction

1.1 Food Security and Dietary Transition

The traditional Inuit food system is a cornerstone of the subsistence economy of Arctic indigenous populations (Dietz et al., 2018; Flora et al., 2018) and an integral part of the Inuit identity and way of life (Inuit Tapiriit Kanatami, 2021; Kenny, 2017). Inuit have historically conformed to highly mobile hunter-gatherer communities in which food sharing is as much a natural component of their culture as it is an adaptation mechanism to the harsh Arctic environment (Inuit Tapiriit Kanatami, 2021).

The social networks around subsistence hunting contribute to creating stronger bonds between communities and their land, and food sharing helps to mitigate the effects of poverty in Arctic communities, driven by the poor socio-economic status of the region (Arriagada and Bleakney, 2019; Little et al., 2021). However, this traditional Inuit way of life is being challenged on multiple fronts, from the environmental impacts of climate change and contamination on Arctic ecosystems (Basu et al., 2022; Caron-Beaudoin et al., 2020; Dietz et al., 2018; Flora et al., 2018; Long et al., 2023; Wielsøe et al., 2022), to restrictions imposed by federal governments and the disintegration of the Inuit culture by colonial influence (Inuit Tapiriit Kanatami, 2021; Kenny, 2017; Little et al., 2021).

The consumption of Inuit country food (*Kalaalimernit*), rich in essential micronutrients and polyunsaturated fatty acids (PUFAs) necessary for their physical well-being (AMAP, 2021a; Inuit Tapiriit Kanatami, 2021; Little et al., 2021), is discouraged due to the high contaminant loads present in the tissues of the top marine predators in the diet, such as beluga (*Delphinapterus leucas*), narwhal *(Monodon monoceros)*, polar bear *(Ursus maritimus)*, or ringed seal (*Pusa hispida*) (Basu et al., 2022; Dietz et al., 2018; Long et al., 2023; Sonne et al., 2023). Moreover, the consumption of meat from certain species, such as reindeer (*Rangifer tarandus*), an important source of iron (Kenny et al., 2018, 2019) with significantly lower concentrations of contaminants (Dietz et al., 2022; Muir et al., 2019), has been reduced due to hunting moratoria and restrictions prompted by an overall decline of their population numbers (57%; 1970-2017) in the last decades (Rusell et al., 2018). In addition, harvest activities are increasingly difficult due to unpredictable climate effects, like deteriorated sea ice conditions that make it more dangerous to reach traditional hunting grounds or unexpected changes in species migratory patterns, ecosystem species composition, and predator-prey dynamics (Andersen et al., 2017; Flora et al., 2018).

In comparison, the consumption of imported western foods (*Qallunaamernit*) is encouraged via targeted marketing campaigns, increasing social contact with non-indigenous communities, and the lack of integration of traditionally shared country foods into the market economy (Inuit Tapiriit Kanatami, 2021; Little et al., 2021). Most Arctic populations are undergoing a dietary transition towards imported food, with reports of much higher consumption than country foods across Greenland towns (40-70%) and Canadian regions (76%) (Pars et al., 2001; Wielsøe et al., 2021). While this has the potential to lower dietary exposure, most affordable market products are non-nutrient-dense foods (NNDFs) of low nutritious quality, abundant in refined carbohydrates, and lacking the vitamins, minerals, and fatty acids required in a well-balanced diet (AMAP, 2021a; Calder et al., 2019; Little et al., 2021).

Public health concerns in Inuit populations imply a dietary influence on the prevalence rates of certain diseases, such as iron deficiency (20-36% in women), diabetes (3-9%), overweight and obesity (52-63%), hypertension (19-25%), or increased cancer mortality (2‰) (Bjerregaard and Dahl-Petersen, 2010; Little et al., 2021). Moreover, western notions of health and well-being do not align well with the indigenous understanding of these concepts, leading to a progressive loss of traditional values that has deep effects on mental health (King et al., 2009; Sharma, 2010). Indeed, in interviews with Canadian Inuit community leaders, the substitution of country food consumption with imported market products has been associated with laziness and unfulfillment, whereas participation in harvest activities strengthened spiritual and social well-being (Little et al., 2021).

This duality of the contemporary Inuit food system, a blurred boundary between the consumption of country food and imported products, constitutes the Arctic Dilemma. Its effects go much further than just nutrition versus contamination implications, permeating every aspect of the Inuit way of life (Inuit Tapiriit Kanatami, 2021; Little et al., 2021; Shafiee et al., 2022).

Therefore, it appears critical that new initiatives take a larger-scale approach to address these issues, leveraging new technologies and Inuit traditional knowledge to create a modern solution to monitor dietary exposure. In this thesis, I propose a solution shaped as a digital platform prototype that would allow Inuit to self-monitor dietary exposure while supporting a bidirectional collaboration between the indigenous and research communities, enabling researchers to collect dietary intake from Inuit households directly.

1.2 Contaminant Exposure

1.2.1 Mercury

Mercury (Hg) is a contaminant of major concern due to its atmospheric ubiquity and potent neurotoxic effects. Since the 2017 entry into force of the Minamata Convention, several bans and regulations have aimed to reduce Hg emissions due to its harmful effects on human health and the environment (AMAP, 2021b). The majority of Hg emissions originate from anthropogenic sources, such as industrial activities, fuel combustion, and small-scale gold mining (AMAP, 2021b). Globally, the Arctic regions contribute to less than 1% (~14 / 2220 tons) of the total Hg emissions (AMAP, 2021b; Figure S19), yet Arctic ecosystems and the human indigenous populations that depend on them for their subsistence are among the most contaminated in the planet (AMAP, 2021b, 2021a).

Gaseous elemental mercury (Hg^0) has long been known to have a considerable residence time of 6-18 months in the atmosphere, so even though it is emitted at lower latitudes, it travels to the Arctic regions via long-range transport processes (Durnford et al., 2010). Once in the Arctic, wet and dry deposition (Dastoor et al., 2015; Steffen et al., 2015) and tundra vegetation uptake (Jiskra et al., 2018; Obrist et al., 2017; Olson et al., 2019) act in concert to create a large Hg sink in the permafrost soils (Obrist et al., 2017; Olson et al., 2018; Schuster et al., 2018). Terrestrial Hg deposited on drainage basins or the snowpack, along with thawing permafrost soils, becomes readily available for transport to the ocean via river runoff (AMAP, 2021b). Additionally, a net influx of Hg is transported into the Arctic Ocean via Pacific and North Atlantic currents, then sedimented onto the continental shelves and ocean basins or re-emitted into the atmosphere (AMAP, 2021b).

Once in the environment, inorganic mercury (Hg^{1+}, Hg^{2+}) can be transformed into the potent neurotoxin Methylmercury (MeHg). This organic form has a much higher uptake rate through the intestinal mucosa (10-100%) and it can accumulate in liver, muscle, and central nervous system (CNS) tissues, where it exerts its toxicity (AMAP, 2021b). Although MeHg uptake and accumulation mechanisms are not fully understood, a high affinity for cysteine thiol groups has been previously documented (Simmons-Willis et al., 2002). This complexing would confer chemical similarity with the amino acid L-Methionine, making it a substrate for the ubiquitous L-type neutral amino acid transporter.

MeHg bioaccumulates and biomagnifies along the trophic food chain (AMAP, 2021b). Uptake of MeHg occurs primarily via gastrointestinal absorption after dietary intake, whereas detoxification involves demethylation in tissues followed by excretion in bile and feces (Hong et al., 2012). Additionally, excretion via hair, feathers, nails, or tusks is possible for certain species (Dietz et al., 2021). In the marine environment, rich in selenium (Se), complexing with selenoneine to the inert Hg-Se complex tiemanite followed by excretion is a detoxification mechanism of particular relevance (Dietz et al., 2013; Little et al., 2023; Yamashita et al., 2013).

In the Arctic, high (≥22.7 µg/g ww) and severe (≥30.5 µg/g ww) risk Hg concentrations associated with harmful effects in wildlife have been reported for many predator species of the marine food web, such as hooded seal (*Cystophora cristata*), ringed seal, polar bear, orca (*Orcinus orca*), beluga, or narwhal (Dietz et al., 2022, 2018). Conversely, terrestrial species like reindeer or muskox (*Ovibos moschatus*) usually fall around or below the low (≤7.3 µg/g ww) and no-risk (<4.2 µg/g ww) Hg threshold (Dietz et al., 2022).

These species are all an integral part of the traditional Inuit food system, with Hg exposure depending on the loads and amounts of each tissue consumed. Previous studies have shown that narwhal, beluga, ringed seal, and reindeer meat are among the top contributors to Hg exposure in Inuit populations (Basu et al., 2022; Dietz et al., 2018). Most of this exposure was also in the form of MeHg, partly due to the reduced demethylation and lack of hair excretion mechanisms of toothed whales (AMAP, 2021b). Conversely, narwhal and beluga *muktuk*, a traditional Inuit food consisting of skin and blubber, contains Hg and Se in quantities close to or above 1:1 molar ratios and, therefore, is generally considered to counteract the toxicity of meat intake (Dietz et al., 2000). However, the skin portion of the *muktuk*, richer in Se (Little et al., 2023) and with lower Hg concentrations than the blubber, is often traded away for cash to support the Inuit households and further hunting activities (Dietz et al., 2018; Flora et al., 2018).

Human studies have found blood Hg levels in Arctic populations consuming these species to range from elevated (8-20 µg/L) to moderately high (20-40 µg/L) and high (>40 µg/L) at several locations in Canada and Greenland (Basu et al., 2022). In biological systems, MeHg induces tissue-dependent oxidative stress, producing highly deleterious effects on human health, including neurotoxicity in the CNS, developmental neurotoxicity, and cardiovascular disease (AMAP, 2021b; Basu et al., 2022). Combined with other contaminants, it can compound with a decreased immunological function, endocrine dysregulation, and reproductive effects related to fertility and fetal development (AMAP, 2021a, 2021b). Moreover, significant economic losses (US $117 billion globally) have been associated with decreased IQ and fatal heart attack endpoints (Zhang et al., 2021).

The tolerable weekly intake (TWI) for MeHg varies among countries. The European Food Safety Authority (EFSA) has set it at 1.3 µg/kg bw (EFSA, 2012). In contrast, Health Canada follows the guidelines established by the World Health Organization (WHO) of 1.6

µg/kg bw (Legrand et al., 2010). The United States Environmental Protection Agency (EPA) recommends a daily reference dose (RfD) for oral exposure of 0.1 µg/kg bw (Rice, 2004).

1.2.2 Per- and Poly-Fluoroalkyl Substances

Per- and Poly-fluoroalkyl substances (PFAS) refer to a group of synthetic compounds categorized as persistent organic pollutants (POPs) and contaminants of emerging concern (CECs) due to their ubiquity in the environment, potential for bioaccumulation and biomagnification, and wide range of toxicological effects (Fenton et al., 2021; Wang et al., 2017). PFAS can be further classified (Figure S20) according to their chemical structure (Brase et al., 2021; Muir et al., 2019). Their most documented compounds belong to the perfluorosulfonic acids (PFSAs) and perfluorocarboxylic acids (PFCAs), which include perfluorooctane sulfonic acid (PFOS), perfluorohexane sulfonic acid (PFHxS), perfluorooctanoic acid (PFOA), and perfluorononanoic acid (PFNA) (Sonne et al., 2023).

These compounds are listed under annexes A or B of the Stockholm Convention POPs (SC-POPs) and/or regulated by European and US environmental agencies (Ling, 2024; UNEP, 2022). However, many PFAS compounds are still not regulated, including the more recent substitutes for those in the SC-POPs list (Sonne et al., 2021). A more encompassing proposal currently being reviewed aims to include all long-chain PFCAs (LC-PFCAs), postulated to have an increased persistence potential in comparison to their short-chain counterparts, under Annexes A, B, or C of the SC-POPs (UNEP, 2022).

Their prevalence in the environment is due to their chemical properties, including a strong C-F bond stability that protects them from degradation, and a highly coveted diverse range of industrial and consumer applications (Buck et al., 2011; Evich et al., 2022). They can be found in disposable polymer-based products, from food containers or water- and stain-repellent textile items, to surfactant applications, like mist suppressants in the electro-plating industry or fire-suppressing foams for aircraft fire emergencies (Buck et al., 2011).

PFAS emitted in lower latitudes can travel to the Arctic (Figure S21) through either direct or indirect long-range transport via atmospheric and ocean currents (Ahrens et al., 2023; Armitage et al., 2009; Joerss et al., 2020; Pickard et al., 2017). In the atmosphere, volatile perfluoroalkyl acids (PFAAs) can be directly transported as gases or aerosols, whereas PFCA precursors can be chemically transformed on arrival (Pickard et al., 2017; Stock et al., 2007). Past and present estimations suggest that atmospheric and oceanic transport contributes to a net inflow of PFAS into the Arctic (Joerss et al., 2020; Pickard et al., 2017; Wania, 2007). Moreover, atmospheric deposition can rapidly reflect changes in source emissions, for example, due to the restrictions on PFAAs. In contrast, slower transport via oceanic boundary currents will continue to be a source of long-chain PFCAs decades after the emissions have ceased (Joerss et al., 2020; Wania, 2007).

In the Arctic, detectable concentrations of well-known PFAS congeners have been found in all environmental compartments and their species (Khan et al., 2023). In particular, the highest PFAS concentrations, dominated by PFOS and LC-PFCAs, are consistently being reported in the tissues of top marine mammal predators, like polar bear, harbor porpoise (*Phocoena phocoena*), orca, beluga, ringed seal, and to some extent Arctic fox (*Vulpes lagopus*) (Khan et al., 2023; Muir et al., 2019; Routti et al., 2017). Especially concerning are the extremely high PFAS concentrations reported for polar bears, orders of magnitude higher than other marine mammal species (Khan et al., 2023; Muir et al., 2019).

In terrestrial ecosystems, comparatively lower levels of PFCAs have been detected in the liver and muscle tissues of reindeer, muskox, ptarmigan (*Lagopus muta*), Arctic fox, and wolf (*Canis lupus*) (Khan et al., 2023; Muir et al., 2019). Conversely, freshwater species like Arctic char (*Salvelinus alpinus*) and lake trout (*Salvelinus namaycush*) have much lower concentrations of the PFCA congeners but show substantial accumulation of their break-down products (Khan et al., 2023; Muir et al., 2019).

Many of the most contaminated species in these studies are an essential component of the traditional Inuit diet (AMAP, 2021a). Previous studies in Inuit communities have shown significant correlations between PFAS exposure, a diet rich in marine mammals (Caron-Beaudoin et al., 2020; Wielsøe et al., 2022), and socioeconomic factors (Wielsøe et al., 2022), underlining the relevance of the traditional Inuit diet for both contaminant exposure and food security. Moreover, some studies have found that polar bear meat can be a significant source of PFAS exposure (Long et al., 2023), its consumption alone accounting for a large percentage of Inuit in East Greenland populations (>85%) having higher levels than the recommended EFSA safety thresholds (Sonne et al., 2023).

Human health studies of PFAS exposure have shown a multitude of deleterious effects. From immune function impairment, including overall immunosuppression and decreased vaccine effectiveness (Brase et al., 2021; Fenton et al., 2021), to endocrine alterations of the thyroid function, vitamin D activity, and lipid and glucose metabolism (Di Nisio et al., 2020; Fenton et al., 2021). Moreover, studies have associated liver and kidney disease with long-chain PFAS exposure (Fenton et al., 2021), and both PFOA and PFOS have been associated with breast and testicular cancer, respectively (Brase et al., 2021).

In 2020, EFSA regulations established a TWI value of 4.4 ng/kg bw for the sum of PFOA, PFNA, PFHxS, and PFOS (Schrenk et al., 2020). This value was derived using combined pharmacokinetic modeling for these four highly immunotoxic compounds based on the decreased immune response observed in 1-year-old children (Schrenk et al., 2020). In that study, a benchmark dose lower confidence limit ($BMDL_{10}$) of 17.5 ng/mL was estimated to be 6.9 ng/mL blood serum concentration in mothers, corresponding to daily oral intake of 0.63 ng/kg bw (hence the weekly 4.4 ng/kg bw).

1.3 Dietary Data Collection

Analog methods for dietary data collection in research involve using food frequency questionnaires (FFQs) and 24-hour recalls. FFQs have been a valuable tool to gather quantitative and qualitative dietary data in toxicology studies (Laird et al., 2013; Long et al., 2023; Sonne et al., 2023; Wielsøe et al., 2022), establish disease risk associations (Ryman et al., 2015), identify dietary patterns (Jeppesen et al., 2012; Ryman et al., 2014; Sharma, 2010), assess nutrient intake (Laird et al., 2013; Sharma et al., 2013), and issue public dietary advisory to the indigenous population (Bjerregaard and Mulvad, 2012).

FFQs are inexpensive and easy to administer by interviewers or self-administration, and their reproducibility and results can be validated using a diverse range of methodologies (Cade et al., 2002; Pakseresht and Sharma, 2010). In addition to dietary data, participants can be questioned about socioeconomic and psychosocial factors, lifestyle choices, and physical health parameters using a mixed methodology of interviews and various questionnaire types (Pars et al., 2001; Sharma, 2010).

However, these methods are not without challenges. Inferring portion sizes and nutrient intake from FFQs requires the use of external databases, special care must be taken to provide culturally appropriate questions, dietary choice is limited to the provided options, participants can misinterpret questions, long questionnaires may reduce the accuracy of the responses, and both methods are prone to recall bias (Cade et al., 2002; Johnson et al., 2009; Pakseresht and Sharma, 2010).

Moreover, interviews require scheduled sessions between participants and trained interviewers, increasing the potential for error and the effort required for data collection (Johnson et al., 2009; Pakseresht and Sharma, 2010). In addition, random sampling methods used to select participants may lead to unbalanced demographics, small sample sizes, limited access due to legal ramifications related to the use of human data, or unwillingness of individuals to participate in the research (AMAP, 2021a; Johnson et al., 2009; Pakseresht and Sharma, 2010).

1.4 Digital Platforms

Large-scale digital platform initiatives in the international scene have been developed to unify life-sciences research infrastructure (Figure S22) across state members (Harrow et al., 2021), as well as provide hardware and software tooling to analyze, visualize, and share biomedical data (The Galaxy Community, 2022).

Extensive knowledgebases are indispensable to conducting omics research and providing high-quality protein (Mistry et al., 2021; Paysan-Lafosse et al., 2023; The UniProt Consortium, 2023) and gene sequences (Camacho et al., 2023; The Gene Ontology Consortium et al., 2023; Yuan et al., 2024) for structural, functional, and ontological annotations. In toxicological research, comprehensive chemical databases with structural and adverse effects information facilitate resources for drug screening analyses and pharmacovigilance studies (Kim et al., 2023; Wishart et al., 2018; Zdrazil et al., 2024). More specific knowledgebases target chemicals and species relevant for environmental toxicology modeling and risk assessment studies (Olker et al., 2022; Varshavsky et al., 2022; Williams et al., 2017).

These platforms have in common a mission to allow researchers globally to integrate their projects within frameworks that enable advanced compute power, provide large data storage buckets, enhance interoperability, or expose research data using standardized interfaces (Harrow et al., 2021; The Galaxy Community, 2022). Most are built on FAIR data principles, an acronym for **F**indability, **A**ccessibility, **I**nteroperability, and **R**euse of digital assets (Wilkinson et al., 2016). Under this guidance, digital platforms adopt a unified set of procedures that allow machines to operate with each other and the data they expose. This is possible using standardized application programming interfaces (APIs) that connect domain-specific research applications to these knowledge and resource hubs.

In the Arctic, digital-based approaches have been successfully explored in initiatives that engaged with Greenland’s indigenous hunters to generate datasets of harvested species, map the use of resource spaces, and document hunting patterns in great detail (Andersen et al., 2017; Flora et al., 2018). Toxicology studies have leveraged the self-reporting hunter statistics database *Piniarneq*, also maintained by the Government of Greenland, to integrate decades of dietary exposure data (Dietz et al., 2018). Canadian researchers used digitalized survey data, collected initially through a mix of analog and computer-assisted approaches (Statistics Canada, 2020), to analyze the land- and wage-based economic activity of indigenous populations within their borders (Arriagada and Bleakney, 2019; Kumar et al., 2019). In Norway, the extensive Research in Svalbard (RIS) projects database is used to coordinate research efforts, fund promising initiatives, and store the generated datasets for public availability (Research Council of Norway, 2024). Moreover, both the Norwegian Institute for Air Research (NILU) and Norwegian Polar Institute (NPI) maintain public datasets relevant to environmental toxicology research (NILU, 2024; Re3data.Org, 2016). Furthermore, the International Council for the Exploration of the Sea (ICES, 2024) maintains a database of the marine environment (DOME) for the joint monitoring activities of the Arctic Monitoring and Assessment Programme (AMAP), the Baltic Marine Environment Protection Commission (HELCOM), and the Oslo and Paris Conventions (OSPAR) initiatives.

Existing social media platforms have also been explored in risk communication efforts, but their use in research studies is scarce and public adoption reportedly low (AMAP, 2021a). To the best of my knowledge, real-time digital platforms have yet to be developed to collect dietary intake data and monitor contaminant exposure in Arctic indigenous populations. Therefore, in the present thesis, I designed a proof-of-concept platform that allows toxicology researchers to collect dietary intake and exposure data from harvested species in Inuit households. This platform, hereby termed *Arctic Hunter*, consists of four parts: a web-browser interface for researchers to manage study content; a companion mobile app for consumers to subscribe to studies, record dietary intake, and self-monitor contaminant exposure; a high-performance database to store user and study data; and a custom API to access this information programmatically.

Such a framework can be successfully deployed and further scaled to support dietary exposure research efforts in Arctic nations. The mission objectives of this thesis can be summarized in the following points: 1) develop a platform that integrates user dietary data collection with the management of toxicology research studies; 2) prototype a mobile app that can be used to collect dietary intake and monitor contaminant exposure in Inuit households; and 3) showcase the usability of this system from previously published data on two contaminants of interest, Hg and PFOS, in narwhal and polar bear meat, respectively.

2 Methods

2.1 Software Development

2.1.1 Database and Object Storage

The MongoDB document database (v7.0.2; https://www.mongodb.com) was chosen to store user and researcher information and study content. A production version was deployed using the MongoDB Atlas (https://www.mongodb.com/atlas/database) cloud solution and linked to the Norwegian University of Science and Technology (NTNU) using an academic promotion provided by the GitHub Student Developer Pack program (https://education.github.com/pack). During development, a local database installed natively in the host OS was used instead. Running Payload and MongoDB in containers is also supported using the provided Dockerfile and Docker Compose configuration files (https://www.docker.com). Connections to the MongoDB Atlas database from the API server are protected by a `user:password` combination with a built-in `dbAdmin` role and configured with the options `retryWrites=true&w=majority` to address transaction errors and write durability concerns.

To handle media uploads such as images, an Azure Blob Storage bucket was deployed (https://azure.microsoft.com/products/storage/blobs) using the Azure for Students promotion and linked to NTNU. This solution allowed for a simple deployment process at no cost. In the event of a public release, our recommendation to be consistent with the open-source philosophy of this project is to switch to a self-hosted S3-compatible solution such as MinIO (https://min.io).

2.1.2 API and Content Management System

Payload (v2.3.1; https://payloadcms.com) was used as an application framework to implement the content management system (CMS) and API features. The Node.js (v18.16.0; https://nodejs.org/en) framework Express.js (v4.17.1; https://expressjs.com) was used for the web server, whereas the React library (v18.2.0; https://react.dev) was used to compose the Admin User Interface (UI) in the browser. During development, the Nodemon utility (v3.0.2; https://nodemon.io) was used to automatically reload the server when project files were edited, leveraging the `ts-node` engine (v10.9.1; https://typestrong.org/ts-node/) to execute TypeScript code without a pre-compilation step. Several official Payload plugins were also used to integrate the framework with the MongoDB and Azure Object Storage solutions.

2.1.3 Mobile Apps

React Native (v0.72.6; https://reactnative.dev) and Expo (v49.0.21; https://expo.dev) frameworks were used to implement the native mobile apps. Both Android and iOS projects must be run via development builds, as several packages require native compilation (for more information, see https://docs.expo.dev/develop/development-builds/introduction/ and https://docs.expo.dev/workflow/prebuild/). Note that while this creates the `ios` and `android` artifacts, no custom modifications have been added to the native projects, and therefore, they are ignored in version control. To create the iOS build, the Apple-exclusive Xcode developer app (v15, 15A240d; https://developer.apple.com/xcode/) and the Ruby programming language (v3.1.3; https://www.ruby-lang.org/en/) were used. To create the Android build, the Android SDK (Android 13 "Tiramisu"; API level 33), which can be configured via the Android Studio IDE (https://developer.android.com/studio), and the Java Development Kit (JDK zulu64-11.0.20.1; https://www.azul.com/downloads/#zulu) were used. To assist in setting up the Android environment, we used the JetBrains Toolbox app (https://www.jetbrains.com/toolbox-app/). In general, it is recommended to follow the official setup guides for React Native CLI (https://reactnative.dev/docs/environment-setup) and Expo (https://docs.expo.dev/get-started/installation/).

The mobile app graphical user interface (GUI) was designed using Figma (v116.15.15; https://www.figma.com). Custom visualizations to display contaminant exposure were created with D3 (v7.8.5; https://d3js.org) for its mathematical scale functions, and React Native Skia (v0.1.196; https://shopify.github.io/react-native-skia/) as the graphics rendering engine. SVG icons were rendered using the React Native SVG library (v13.9.0; https://github.com/software-mansion/react-native-svg), using a transformer to resolve dynamically imported images at build-time. Licensed SVG assets were downloaded from Icons8 (https://icons8.com/) with access granted as part of the previously mentioned GitHub Student Developer Pack promotion.

Client app state was handled with the Jotai library (v2.6.0; https://jotai.org). Network requests, retries, cache invalidation, and overall server state was handled using Tanstack Query (v5.12.2; https://tanstack.com/query/v5), in combination with Axios (v.1.6.2; https://axios-http.com/docs/intro) to send the requests, and integrated with Jotai via its Tanstack Query plugin (v0.8.0; https://jotai.org/docs/extensions/query). Client-side forms were implemented using the React Hook Form library (v7.49.2; https://react-hook-form.com) and validated using the Zod library (v3.22.4; https://zod.dev).

2.1.4 Codebase Structure

The entire project was hosted on GitHub (https://github.com), a version control and project management platform. The codebase was written using Typescript (v5.3.3; https://www.typescriptlang.org) and structured as a monorepo. PNPM was used as the package manager (https://pnpm.io). The same Node.js, Java, and Ruby versions previously described were used project-wide. Environment files are provided so the relevant software managers can automatically install (if necessary) and switch to their correct versions. Code checking and formatting were done with ESLint (v8.56.0; https://eslint.org) and Prettier (v3.1.1; https://prettier.io), respectively.

In addition to the main backend and frontend projects previously described, several packages were developed to support shared functionality, abstract code logic, and maintain a healthy separation of concerns. 1) `@arctic-hunter/api`, API request types and endpoint function services and helpers; 2) `@arctic-hunter/constants`, configuration constant values used across all projects; 3) `@arctic-hunter/seed`, database seeding scripts to generate the user and dietary data used to validate this research project; and 4) `@arctic-hunter/utils`, utilities with generic functions agnostic to specific project implementations. None of these dependencies were published to the NPM repository (https://www.npmjs.com) or elsewhere, and therefore their usage is private.

2.2 Data Selection

Two previously published research studies were selected to showcase the features of the *Arctic Hunter* prototype (Dietz et al., 2018; Sonne et al., 2023). These studies investigated patterns of Inuit dietary intake and contaminant exposure in two distinct areas within the Greenland territory, Avanersuaq and Ittoqoortoormiit. Each original study was further simplified to a single species of interest, tissue, and contaminant, selected for their relevance in dietary exposure monitoring. These simpler fictitious pilot studies were thus integrated within the platform as research projects: 1) Hg exposure in Avanersuaq from narwhal meat, and 2) PFOS exposure in Ittoqoortoormiit from polar bear meat (Table 1).

In addition, to simulate population exposure in each region, random study participant subscriptions and their weekly dietary intake were generated with parameters as described in each respective paper. Briefly, user body weight, relevant for calculating safe dietary intake limits, was randomized between 30-80kg with binned probability ranges of 30-50 (10%), 51-70 (60%), and 71-80 (30%). Additional age, sex, and pregnancy parameters were also randomized. Finally, to showcase the mobile application prototype screens, a hypothetical global user that simultaneously consumed species from both regions was also created with a body weight of 70kg.

Table 1 Simulated pilot study parameters derived from published literature data. Mercury and PFOS exposure from narwhal and polar bear meat.

Study Name	**Location**	**Species**	**Tissue**	**Contam.**	**Conc.**	**Reference**
Mercury Exposure in Avanersuaq	Avanersuaq	Narwhal	Meat	Hg	1.132 (µg/g)	Dietz et al., 2018
PFAS Exposure in Ittoqoortoormiit	Ittoqoortoormiit	Polar bear	Meat	PFOS	10.79 (ng/g)	Sonne et al., 2023

2.2.1 Mercury Exposure in Avanersuaq

From Dietz et al. (2018), narwhal meat was chosen as the tissue of reference and Hg as the contaminant of interest. Tissue loads were computed as the total average of male and female muscle loads (1.132 µg/g ww; n = 66, Table 1) and the Hg TWI was set in the database as 1.3 µg/kg bw, according to current EFSA guidelines (EFSA, 2012). A total of 630 users, emulating the total population of Qaanaaq (Figure S1), were subscribed to the study with a mean narwhal weekly intake of 439.65g (min: 167.62, max: 702.18).

The selection of narwhal meat as the reference tissue for this study was based on two factors: 1) narwhal meat consumption was among the highest of all species in the study (Dietz et al., 2018), only second to ringed seal; and 2) exposure to MeHg from this species is exacerbated due to the reduced ability of toothed whales to demethylate and excrete MeHg compared to other marine mammals (AMAP, 2021b).

2.2.2 PFAS exposure in Ittoqoortoormiit

From Sonne et al. (2023), polar bear meat was chosen as the reference tissue and PFOS as the contaminant of interest. Muscle tissue loads were computed as the total average of both sexes (10.79 ng/g ww; n = 30; Table 1) and a TWI value of 4.4 ng/kg bw (EFSA, 2020) was set in the database. A total of 353 users, emulating the total population of Ittoqoortoormiit (Figure S1), were subscribed to the study with a mean polar bear daily intake of 64.23g (min: 17.00, max: 100.00).

The selection of polar bear meat and PFOS was again based on two factors: 1) while estimations of polar bear meat consumption were not substantially different than of ringed seal, concentrations of known immunotoxic PFOS, PFOA, PFNA, and PFHxS were 2- to 5-fold higher in polar bear meat; and 2) PFOS exposure dominated both species tissue concentrations, ranging 5- to 10-fold higher than the other congeners.

3 Results

3.1 Platform Architecture

The tech stack used in this project can be roughly divided into three base components: a data storage system for documents and media objects, an application framework that doubles as API and CMS, and a cross-platform codebase to build web and native mobile applications (Figure 1). The first two components constitute the *backend* services for data storage and management. The API includes a web-browser admin interface for researchers to manage their studies and a set of endpoints to retrieve data programmatically. The mobile and web apps constitute the *frontend* and target the final users. The combination of code, services, and functionality from *backend* and *frontend* is considered the *full-stack application*. The following subsections thoroughly explain the implementation of each of these components.

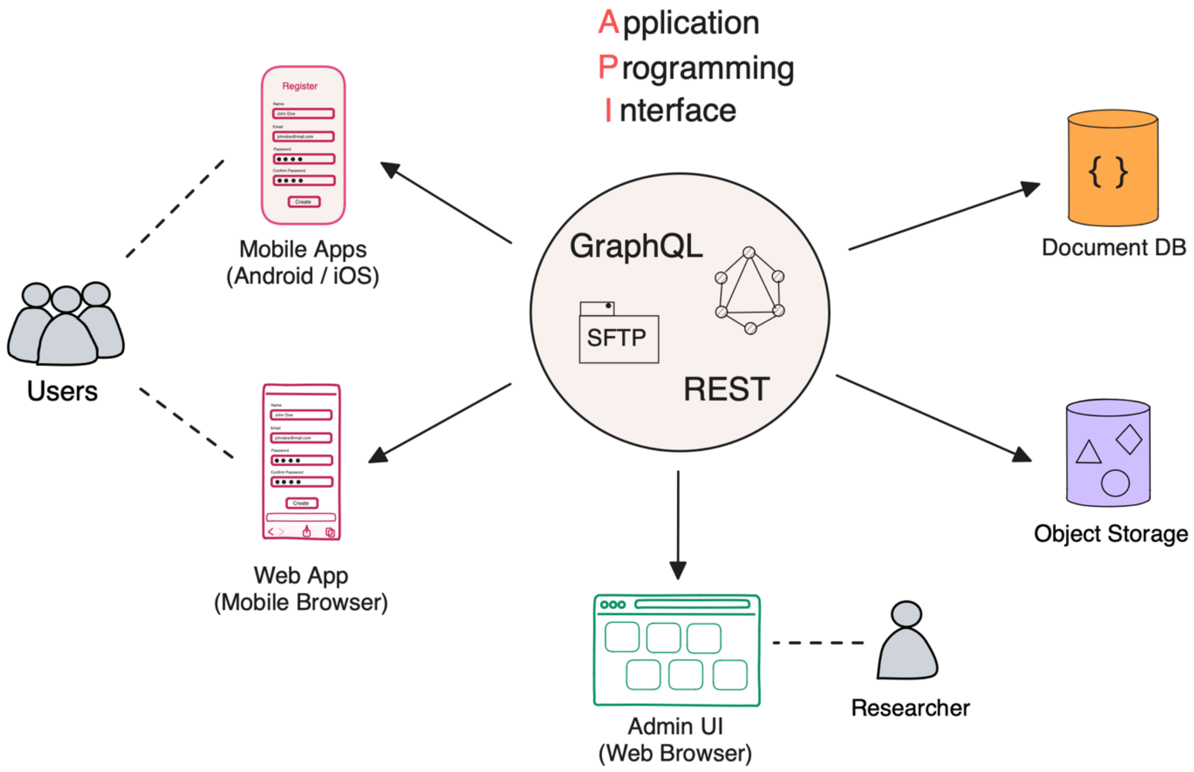


Figure 1 Full-stack application architecture consisting of two data storage systems, an API with an admin UI, and a companion frontend app compiled to native OS (iOS/Android) and web platforms. Each component exists separately from the others and is deployed as an independent service. Interaction with the data storage is done via the API, which supports distinct end-user and researcher functionalities depending on the interface being accessed, mobile apps and admin UI, respectively.

3.1.1 Database Schema

User information and study content data are stored in a MongoDB document database. MongoDB is a complete open-source ecosystem and a Software as a Service (SaaS) cloud platform that can be used to set up data warehouse and data lake solutions.

MongoDB was selected for its document object model, which allowed the project to dynamically evolve from an initial set of data structures into higher complexity models as the platform features grew in scope. In addition, its hosting model is prepared to respond to increasing scalability requirements via sharding (Figure 2), a horizontal scaling approach to fragment large datasets, typical in biological science research, that supports geographic data distribution and high-throughput operations from millions of devices. Moreover, its query language allows the natural construction of data queries, facilitating the assembly of analysis pipelines, a feature supported via its aggregation API (Figure S5).

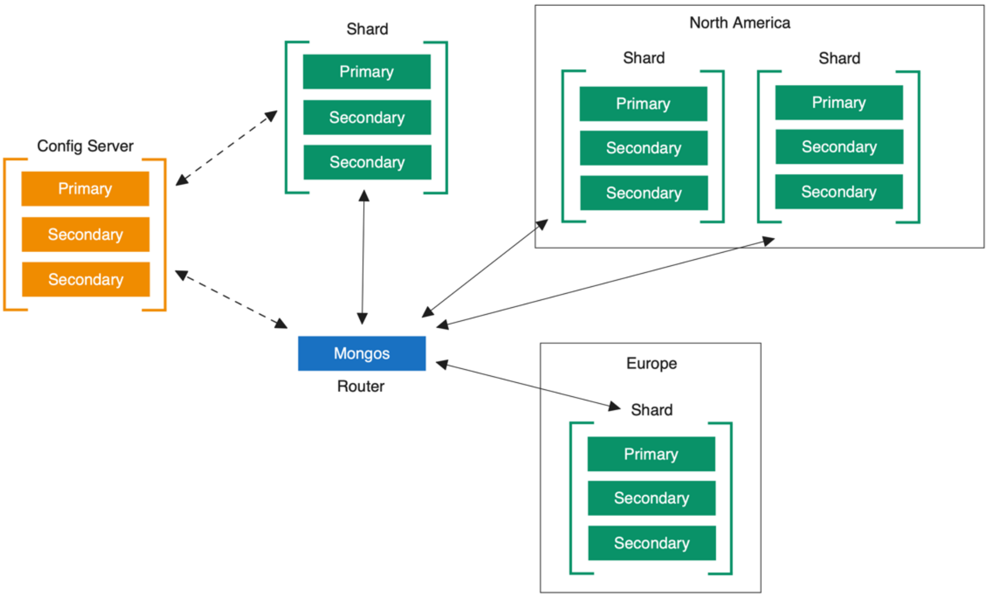


Figure 2 MongoDB data sharding model. Read/Write operations are orchestrated by the router. The config server stores sharding organization metadata. Datasets can be distributed across regions and accessed in parallel for increased performance. Locality allows the enforcement of geographic distributions of data. Primary and secondary replica sets provide data redundancy in each shard. For more information, see the MongoDB documentation at https://www.mongodb.com/basics/sharding.

Data was stored in a single database and structured as two semi-independent schemas (Figure 3). The first schema is designed around dietary information and contains collections for users, diet, and exposure. The second schema is designed around research study content and contains collections for admins with different roles, studies, forms, locations, species, and contaminants. This structure leverages the flexibility of the

MongoDB document model to favor a hierarchical structure over document relationships, making dietary data more self-contained. It also allows data queries to minimize external collection lookups (equivalent to table join operations in SQL databases) and thus search and process large amounts of data more efficiently.

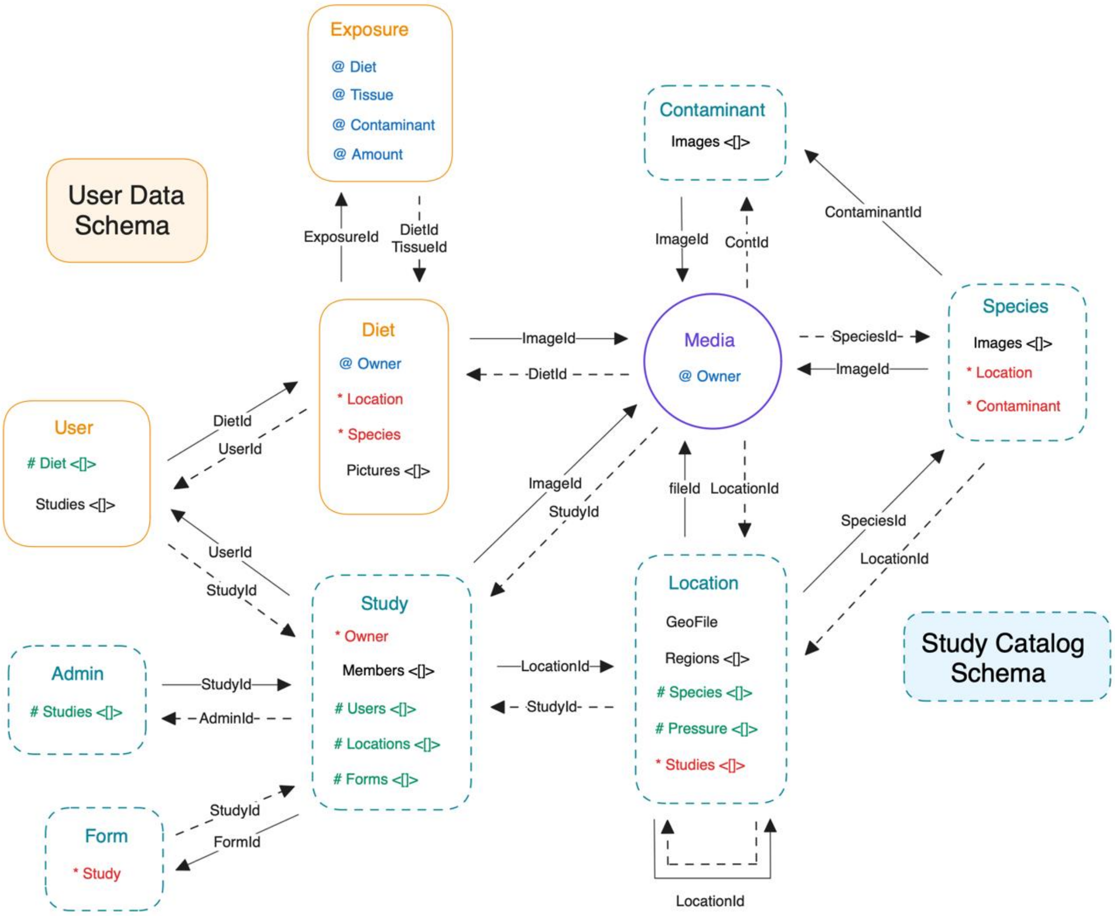


Figure 3 Simplified database architecture with only field relations. Boxes represent document collections; Solid: User Data schema; Dashed: Study Catalog schema. Arrows indicate relationships via primary and foreign keys; Solid: primary relation; Dashed: reverse relation. Container shapes signify the storage solution; Box: MongoDB; Circle: Azure Blob Storage. Symbols indicate field properties from the document perspective; At (@): automatically assigned field; Hash (#): read-only, automatically handled when fields from other collections are updated; Asterisk (*): mandatory, required at document creation; Brackets <[]>: multiple document relation.

Data creation workflows for each schema also run semi-independently, as will be discussed in the following subsections. Briefly, users are responsible for updating their data and inputting dietary information, whereas creating study data for specific locations, species, and tissue loads is the responsibility of the researchers. When users add a new diet entry from a study location, the species tissue loads are used to automatically generate the appropriate contaminant exposure entries. Therefore, researchers and users act in coordination to provide location-specific species loads and dietary intake data, respectively. Updating the primary contaminant data and ensure consistency with current regulations is the responsibility of platform maintainers.

Additionally, a Microsoft Azure Blob Storage solution was implemented for media files. This feature is required to support adding study images as well as other potential features, such as uploading dietary intake pictures, including geospatial location files, or adding images to species and contaminants. While this solution does not fit an open-source criteria, it was selected due to specific support for academic usage and to avoid incurring storage costs in the initial prototyping phase. In the event of a public release, the plugin system currently employed in the CMS implementation will simplify its replacement with an open-source S3-compatible storage solution, such as MinIO.

Finally, a UI-based desktop application (Compass), provided by MongoDB, can be used to navigate document collections, create indexes to improve search efficiency, explore the database schema, add validation rules, and compose queries (Figure S5). Moreover, it features an AI-powered assistant that allows users to generate complex data queries using natural language. This feature is currently available only to platform maintainers. In the future, it should be possible to grant controlled access to the database to external researchers to facilitate the composition of their processing and analysis pipelines in bioinformatics applications. Interacting with the API is described further in later sections.

3.2 Content Management System

A browser-based GUI allows platform administrators to manage document collections according to their respective permissions (Figure 4). This complete CMS enables data management based on a set of access control rules that apply to the currently signed-in user. The presentation and functionality of almost every GUI component are extendable and customizable, making it an excellent choice for dynamic development projects.

In this prototype, admins can have either the role of *developer* or *researcher* (Figure S6). Other custom roles, like *editor* or *maintainer*, can be easily configured to increase access granularity for different features. Admins with a *developer* role have unrestricted access to all document collections, including create, read, update, and delete (CRUD) operations. Admins with a *researcher* role have access to study-related features, as well as data from their study participants.

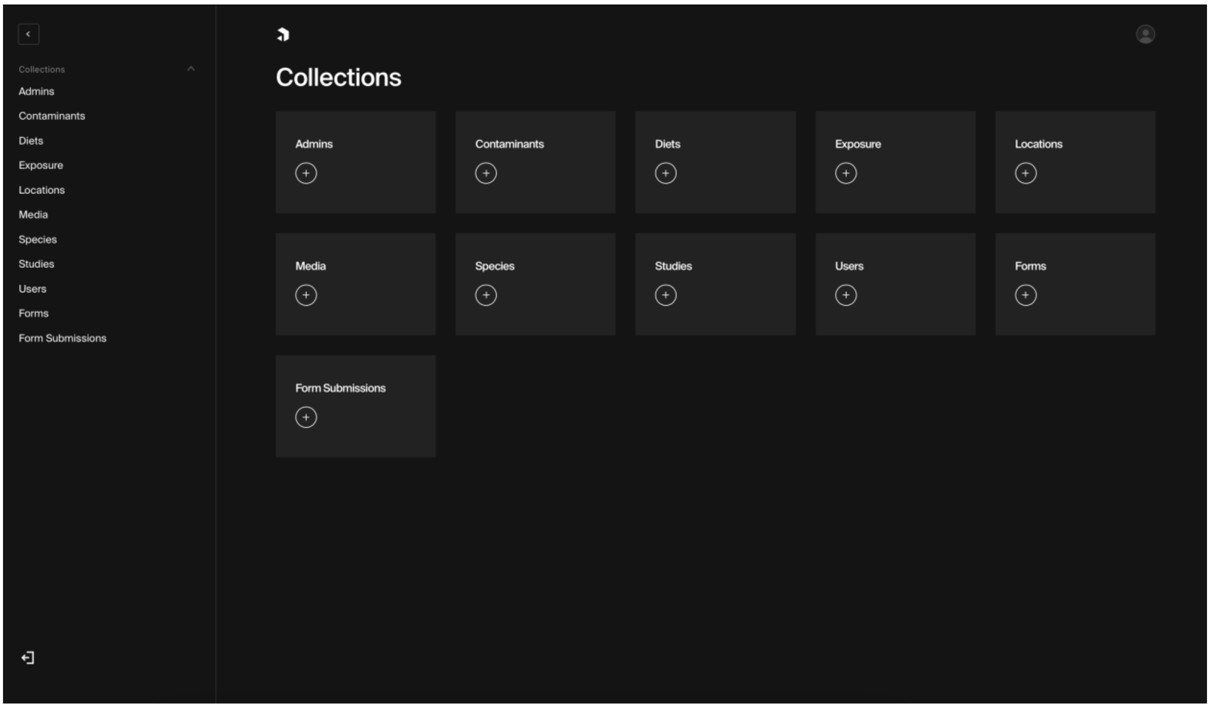


Figure 4 Payload CMS dashboard. The main area showcases cards with the document collections in the database. A collapsible side navigation drawer lists the same collections while browsing through the collections and allows the current user to sign out.

3.2.1 Study Management

Each of the *Studies* collection documents provides a custom UI to edit its properties (Figure S7). The main screen contains inputs to add cover images and a rich text editor supporting HTML elements via Markdown syntax or a contextual menu that appears upon text selection. Additional media files, such as images or videos, can also be embedded within the study description. Multiple locations can be assigned to the study, each referencing the species and tissue loads that will be part of the user's dietary intake (Figure 5). The start and end dates define the duration of the study, which controls access to subscribed user profiles, dietary intake, and contaminant exposure documents.

All study attributes can be edited while in *draft* state. Once the study is published, its start date becomes read-only and can no longer be modified. The purpose of this screen is to provide researchers with the means to add study content to the database, whereas the final presentation style is the responsibility of the mobile apps.

3.2.2 Forms and Questionnaires

Adding a custom questionnaire to a study is a two-step process. First, in the Forms collection, a new questionnaire can be created with various options: a title, the study for which this questionnaire is being created, fields to fill by study participants, and whether to display a message or send an email to multiple recipients upon form submission (Figure S8). What fields to add is up to the study researchers, which they can choose from a set of default components, including text, number, select, or checkbox, among others (Figure S9). New components can be added to the platform as needed.

After the questionnaire is created, researchers can activate it on the study management page. This will make the questionnaire available to study participants. During activation, questionnaires can receive a description and additional target demographics, such as sex, pregnancy status, or age group (Figure S7). Researchers can activate as many questionnaires as desired, including several instances of the same questionnaire at different points in time. In the *frontend*, study participants who meet the selected demographics will be notified about active questionnaires.

3.2.3 Locations, Species, and Contaminants

For a study to measure dietary intake and exposure, it must reference one or more geographical locations. Locations are defined by their name, one or more unique species, and, optionally, the parent region they belong to, which is a reference to another location in the database (Figure S10). The ability of studies to reference several locations, even from other studies, combined with this hierarchical parent-child relationship, enables the composition of a geographical network of different locations and species (Figure 5).

In the frontend, users subscribed to the studies that reference a location are allowed to use its species to input dietary intake and self-monitor toxicity. In addition, platform maintainers with the *developer* role can create public locations that are available to all users. Public locations allow app users to access the platform's dietary and exposure monitoring features without any active study subscriptions.

A species can only be assigned to one location, its uniqueness defined by the scientific name. Adding a common name or image files is also possible for easier identification (Figure S11). Each species can define multiple contaminant tissue loads, each described by a list of unique tissues and their concentrations. Currently, available tissues are statically defined at the platform code level and, therefore, not customizable.

Contaminants are dynamic documents, but it is the responsibility of platform maintainers to keep them updated according to regulations. Each contaminant is a unique entry in the database containing its name and type, as well as the TWI value-unit pair (Figure S12). Optionally, images can be added to provide visual representations of the contaminant, and a rich text input field can be used to add a styled description.

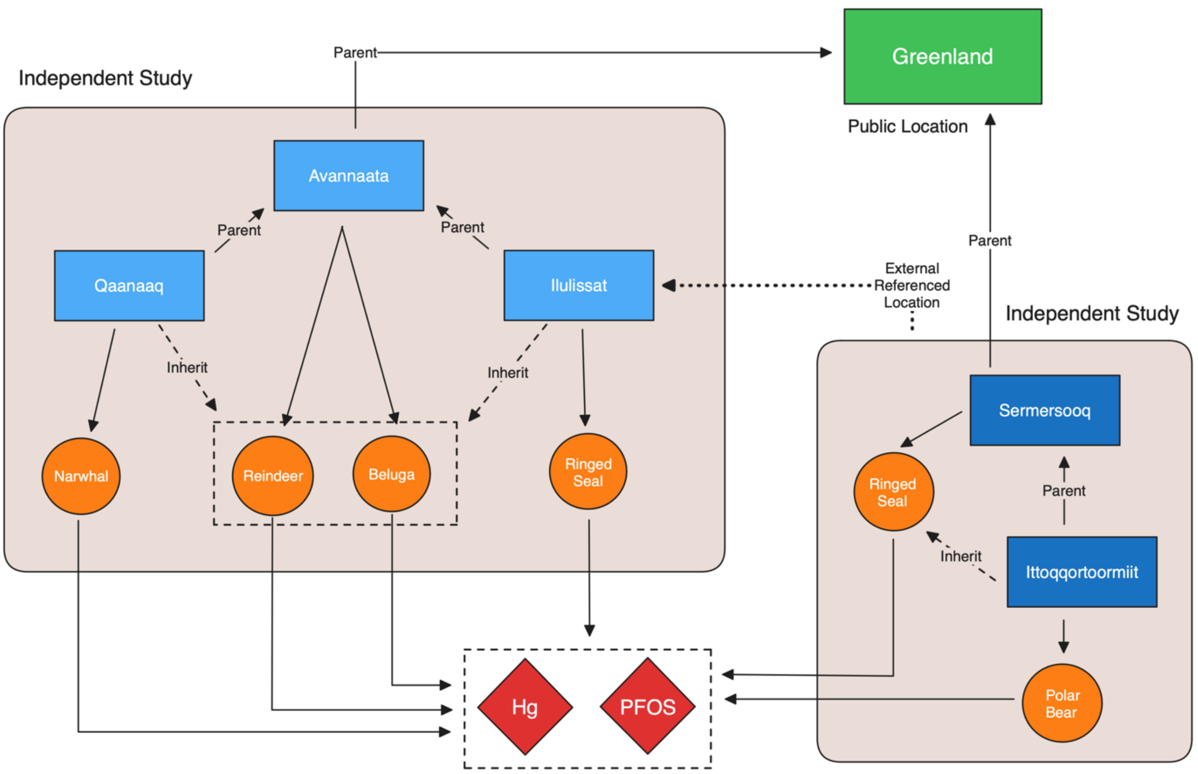


Figure 5 Visual representation of studies, locations, species, and contaminants relationships. Two independent studies reference various locations. Child locations inherit species from their parents, and a single location can be reused by more than one study. Each species defines its contaminant tissue loads separately. Shapes represent different study components; Large boxes: studies; Small boxes: locations; Circles: species; Rhombuses: contaminants. Arrows indicate the type of relationship between each component; Solid: direct relationship; Dashed: inherited components; Dotted: external reference from another study.

3.2.4 User Data Collections

Individual user profiles, dietary intake, and contaminant exposure data are stored in the database. Their relation to research studies is based on a subscription model whereby users become study participants by joining a public study of interest. At this time, the frontend apps in this project are not publicly available for users to subscribe to the studies. However, images of a mobile app in current development have been provided as examples of the GUI design and functionality (Figure 6). Once users subscribe to a study, their dietary data associated to the study becomes available to its researchers, for as long as that subscription is maintained, even after the study runs its course. Additional user data information includes the name, email address, age, sex, or pregnancy status (Figure S13).

Dietary information is divided into two parts. The first part is the *Diet* collection, which stores species consumption from direct user input. It includes all relevant information about the intake, such as the location and species names, date of intake, consumed tissue, additional processing (e.g., frozen, fermented, raw), and the intake amount (Figure S14). In addition, references to the diet owner and source species documents in the database are also included. This semi-linked schema of atomic intake entries creates data redundancy, ensures document independence from the source study, and treats its data as an entity fully owned by the user that originated it.

The second part is stored in the Exposure collection. Each document describes the exposure of a single tissue and contaminant, generated automatically after a diet entry is created by the user (Figure S14). References to the source dietary entry and specific tissue identifiers are included, so the exposure document only exists insofar as the diet entry does. Segregating intake and exposure collections enables running independent search queries, simplifies the exposure computation process, which can be run asynchronously, and allows to recreate the data in case of corruption or loss.

3.3 Application Programming Interface

The MongoDB query language (MQL) provides an expressive syntax to search document collections without being restricted to a preestablished database schema. This is because the document model is polymorphic by design and allows each document to self-describe its shape. This platform follows a well-described schema and API implementation that evolved from the development process (Figure 3; Figure S4). However, researchers using the platform do not need to strictly adhere to or have extensive knowledge of the database schema to compose their queries.

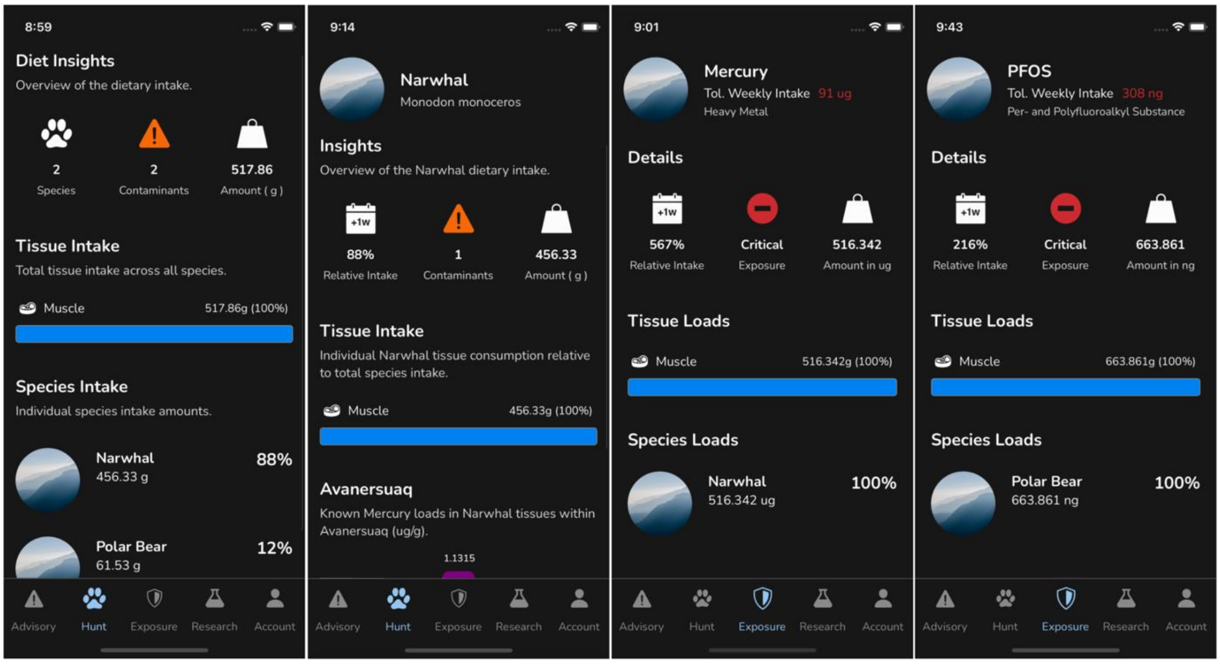
The platform API provides a programmatic way to access user dietary data. Every collection exposes a REST endpoint, akin to a website URL, that instead of returning HTML, sends a JSON response via HTTP (Figure S16). This standard response can be deserialized by bioinformatics scripts or other software to process and analyze the data or compose an interactive GUI. In addition, a GraphQL endpoint is also exposed, along with a Playground UI to experiment with queries (Figure S17). The GraphQL language allows the network request to specify the exact shape of the data to retrieve, while also leveraging schema introspection to automatically self-document available queries and mutations.

Beyond the default functionality provided by the framework, we configured two additional endpoints in the *Diet* and *Exposure* collections that leverage MongoDB’s aggregation pipeline (Figure S18). These endpoints are designed to process all diet or exposure entries within an arbitrary date range and then output a summary of tissue amounts or contaminant loads, respectively. The JSON response can be used in the frontend to efficiently display the details of a user’s dietary intake and contaminant exposure within the specified date range (Figure 6). Additional endpoints with a higher degree of customization can be added on demand as the platform matures and new use cases are requested by the users.

The API enables software interoperability, facilitates reproducibility, and allows the composition of automated workflows. Moreover, custom applications, such as the companion mobile app, require an API to interact with the database in a controlled and safe manner. To this end, the access control rules present in the admin interface are also in effect for the API, defining who and in what circumstances can request data.

3.4 Mobile Apps

Collecting and monitoring dietary intake and exposure data requires developing a public frontend application that can be installed in client devices or served via a browser interface to access the backend services (database, CMS, API). The ubiquitous availability of consumer smartphone devices provides an opportunity to develop a mobile app that targets the two main operating systems (OS) in the market, Android (Google) and iOS (Apple), with the potential to expand to web browsers and desktop environments.



8:59

Diet Insights

Overview of the dietary intake.

2 Species

2 Contaminants

517.86 Amount (g)

Tissue Intake

Total tissue intake across all species.

Muscle 517.86g (100%)

Species Intake

Individual species intake amounts.

Narwhal 456.33 g 88%

Polar Bear 61.53 g 12%

9:14

Narwhal

Monodon monoceros

Insights

Overview of the Narwhal dietary intake.

88% Relative Intake

1 Contaminants

456.33 Amount (g)

Tissue Intake

Individual Narwhal tissue consumption relative to total species intake.

Muscle 456.33g (100%)

Avanersuaq

Known Mercury loads in Narwhal tissues within Avanersuaq (ug/g).

1.1315

9:01

Mercury

Tol. Weekly Intake 91 ug

Heavy Metal

Details

567% Relative Intake

Critical Exposure

516.342 Amount in ug

Tissue Loads

Muscle 516.342g (100%)

Species Loads

Narwhal 516.342 ug 100%

9:43

PFOS

Tol. Weekly Intake 308 ng

Per- and Polyfluoroalkyl Substance

Details

216% Relative Intake

Critical Exposure

663.861 Amount in ng

Tissue Loads

Muscle 663.861g (100%)

Species Loads

Polar Bear 663.861 ng 100%

Figure 6 A currently in-development mobile app prototype for users to monitor dietary intake and contaminant exposure. Data from a hypothetical user consuming narwhal and polar bear meat at both study locations. Four screens, from left to right: 1) Dietary intake overview; 2) Narwhal dietary intake; 3) Hg exposure details; and 4) PFOS exposure details.

This consumer-grade app should provide the functionality needed to sign up and sign in for the platform, log new dietary intake entries, and visualize exposure for specific contaminants, species, and tissues within concrete date ranges (Figure 6). In addition, it should allow users to subscribe to available research studies, granting access to their species and locations, and receive questionnaires that target their demographics. Moreover, a home screen should display study results, relevant news, and public advisory.

3.5 Exposure Data Validation

For the purposes of presenting and discussing exposure results in this thesis, the data for each species and contaminant of interest in the original studies (Dietz et al., 2018; Sonne et al., 2023) has been extracted and further analyzed. Additional figures are used to argue the relevancy of their results in the context of the digital platform. This was done to accurately represent the dietary exposure of Inuit populations in the Greenlandic locations of Avanersuaq and Ittoqoortoormiit. When appropriate, results from the internal dietary exposure calculations in the simulated population of the platform will be contrasted with the original study results. In the future, the validation of the *Arctic Hunter* platform should be done via one or more pilot studies.

3.5.1 Mercury Exposure in Avanersuaq

The first study (Dietz et al., 2018) took place in the old Greenlandic county of Avanersuaq. In the present day, it spans the septentrional area of the Avannaata and Qeqertalik municipalities of Northwest and Northeast Greenland, respectively (Figure S1). The largest settlement in the study area, Qaanaaq, with a population of 630, is also the northernmost settlement in the country and the Avannaata *kommunia* (Grønlands Statistik, 2023).

The authors initially identified Hg exposure of the Inughuit of Avanersuaq as the highest reported in Greenland, exceeding the concentrations of other indigenous and non-indigenous populations by 5- to 50-fold. To derive dietary intake and contaminant exposure, they combined data on hunted species taken from *Piniarneq* 1993-2013 datasets, wildlife contaminant loads from studies in the region during 1984-2015, and their own sampling conducted during 2015 and 2017 (Dietz et al., 2018). The results showed that provisional tolerable monthly (PTMI) and yearly (PTYI) intakes were exceeded by 7- and 11-fold, respectively.

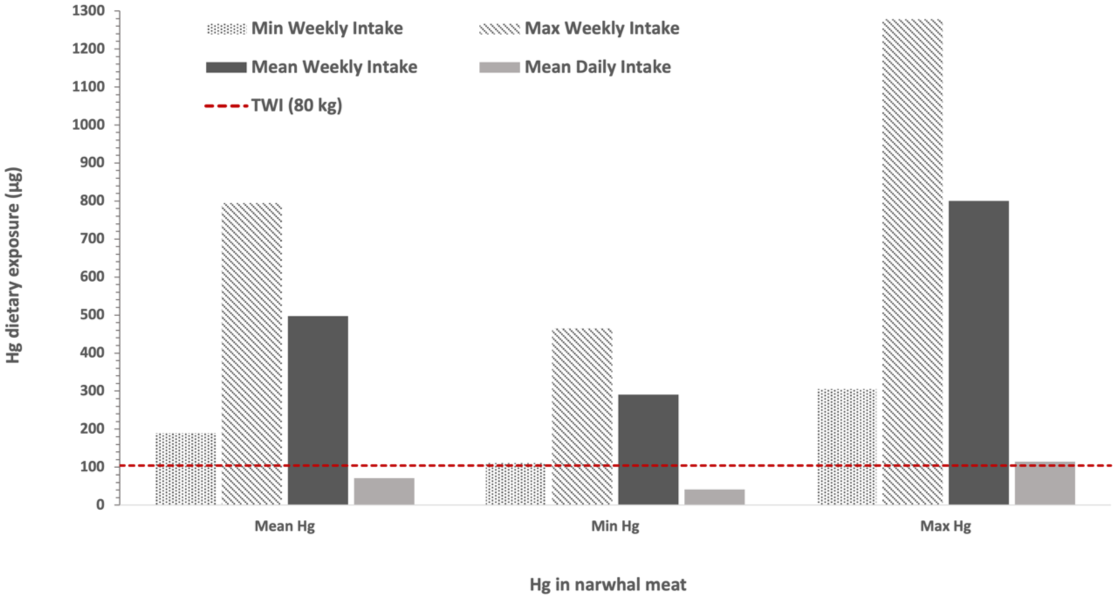


Figure 7 Hg exposure from narwhal meat intake in Avanersuaq. Groups of bars represent a category of Hg concentrations in narwhal meat, from left to right: Mean, 1.1315 µg/g; Min, 0.662 µg/g; Max, 1.82 µg/g. Individual bars represent meat intake values, from left to right: Min weekly, 167.62g; Max weekly, 702.18g; Mean weekly, 439.65g; Mean daily, 62.81g. For comparison, a single meal is approximately 200g of meat. Values derived from yearly intake during 1993-2013 by Dietz et al., 2018.

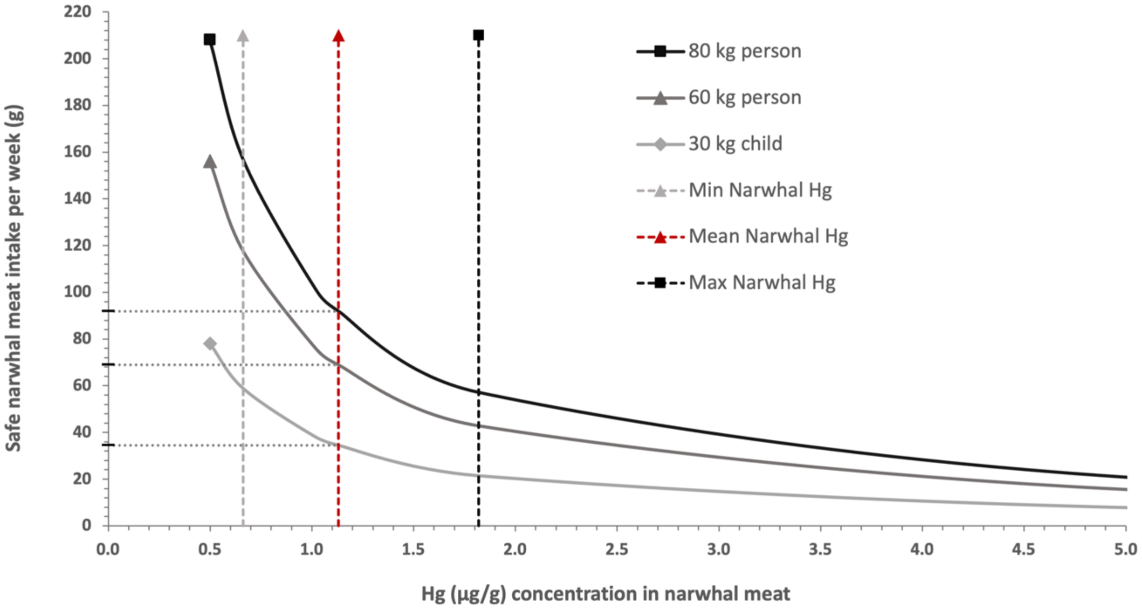


Figure 8 Safe narwhal meat intake as a function of its Hg concentration. The dashed lines show that safe Hg exposure from mean narwhal loads is exceeded at approximately 1.15g meat per kilogram of the consumer's body weight. Min, 0.662 µg/g; Mean, 1.1315 µg/g; Max, 1.82 µg/g.

This Hg exposure was largely driven by the high consumption of narwhal meat (439.65g mean intake, Figure 7), with an extremely pronounced peak during the summer harvest season (Figure S2). In particular, the mean weekly narwhal intake accounted for a 1.82- to 7.64-fold (189.66-794.52 μg) Hg excess compared to the TWI of an 80kg consumer (Figure 7). These numbers were consistent with the simulated dietary exposure in the digital platform, which resulted in a mean weekly Hg exposure for the Avanersuaq population 4.73 times higher (492.31μg Hg) than the TWI of an 80kg consumer. Moreover, because TWI is expressed as a function of the consumer's weight, a dynamic safe intake limit can be computed from their body mass (Figure 8). In this case, a single gram of narwhal meat would account for 87% of the TWI (1.1315 μg/g), setting the maximum safe intake at 92g of meat for an 80kg person (80/0.87).

3.5.2 PFAS exposure in Ittoqoortoormiit

The second study (Sonne et al., 2023) took place in the area of Ittoqqortoormiit, a coastal settlement in the Sermersooq municipality (Figure S1), with a population of 353 and located in the heart of the East Greenland Atlantic coast (Grønlands Statistik, 2023).

In this study, the authors identified East Greenland Inuit populations at high risk of PFAS exposure, reporting blood serum concentrations up to 5-fold higher than any other documented non-occupational exposure in populations worldwide. To derive dietary intake and PFAS exposure, they took blood serum concentration samples (n = 22) and administered FFQs (n = 14, subset) to subsistence and non-subsistence hunters in 2015. A Monte Carlo simulation (k = 5000) was run to upscale these sample sizes. In addition, they analyzed muscle tissue samples from polar bears (n = 30) and ringed seals (n = 17) hunted during 2018-2019. Finally, they conducted a literature search of cross-sectional and cohort PFAS studies published between 2000-2021 to assess PFAS exposure worldwide. The results estimated that 86% of the Ittoqoortoormiit population was at the most severe (>31.9 ng/mL) of the EFSA’s exposure risk categories (Sonne et al., 2023).

PFAS exposure from whole-year polar bear consumption alone, dominated by PFOS, exceeded the recommended TWI. Mean weekly polar bear meat intake was estimated at 64.23g, contributing to a 0.53- to 3.06-fold (183.37-1078.67 ng) excess PFOS compared to the TWI of an 80kg consumer (Figure 9). A single gram of polar bear meat would constitute 245% of the TWI (Figure 10), setting the weekly safe intake limit at 32.63g meat consumption for an 80kg person (80/2.45). In the platform simulation, the resulting mean weekly PFOS dietary exposure for the Ittoqoortoormiit population was 1.80 times (633.76 ng PFOS) higher than the TWI of an 80kg person.

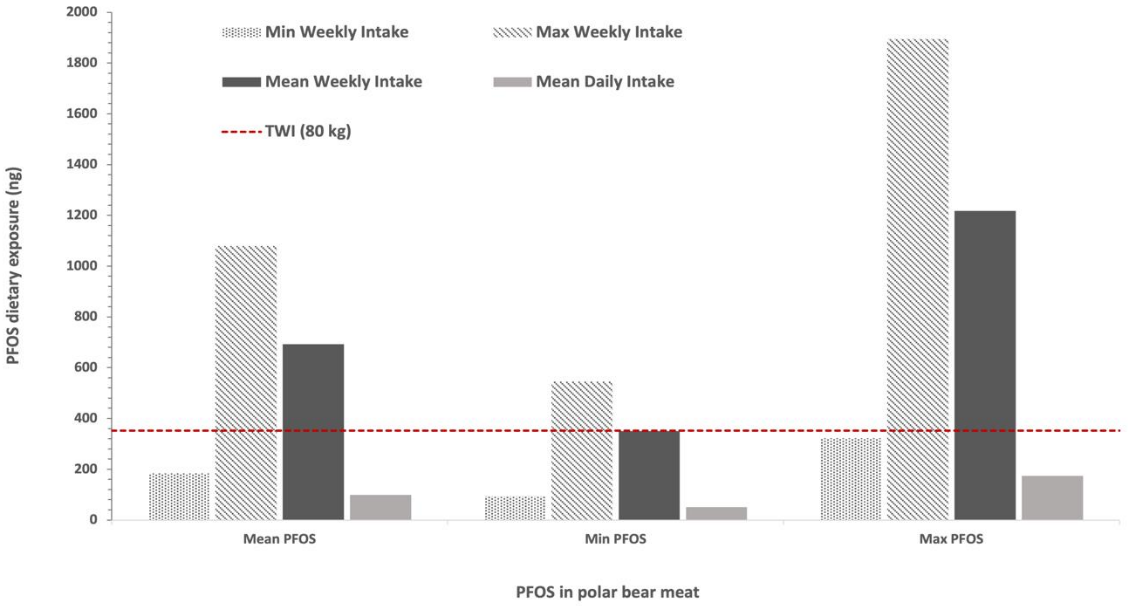


Figure 9 PFOS exposure from polar bear meat intake in Ittoqqortoormiit. Each group of bars represents a category of PFOS concentrations in polar bear meat, from left to right: Mean, 10.79 ng/g; Min, 5.45 ng/g; Max, 18.95 ng/g. Individual bars represent meat intake values, from left to right: Min Weekly, 17g; Max weekly, 100g; Mean weekly, 64.23g; Mean daily, 9.18g. In comparison, a single meal accounts for approximately 200g of meat. Values derived from weekly intake during 2015 by Sonne et al., 2023.

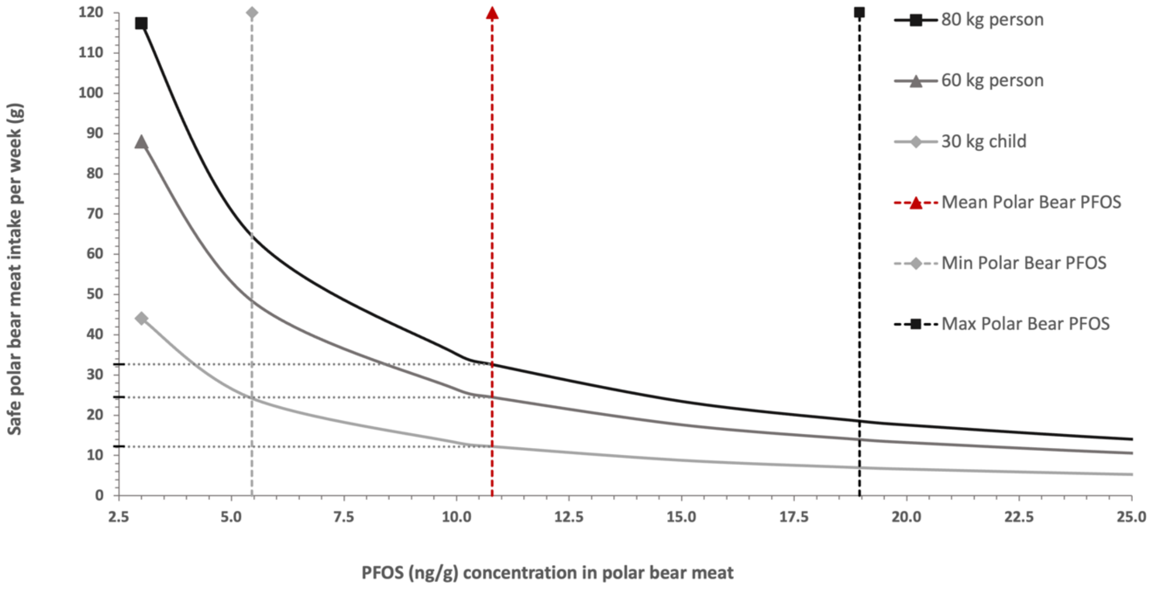


Figure 10 Safe polar bear meat intake as a function of its PFOS concentration. The dashed lines show that safe PFOS exposure from mean polar bear loads is exceeded at approximately 0.41g of meat per kilogram of the consumer's body weight. Min, 5.45 ng/g; Mean, 10.79 ng/g; Max, 18.95 ng/g.

4 Discussion

The following discussion is structured in two interconnected sections. The first section analyzes dietary exposure in Inuit populations using the results from Dietz et al. (2018) and Sonne et al. (2023), while extending their findings using the literature to encompass a broad range of dimensions, including dietary intake patterns, contaminant levels, geographic and temporal variability, and societal impacts on food security. The second section examines current dietary data collection methods, strategies, and challenges within the same multidimensional framework. It also introduces various applications of the *Arctic Hunter* platform, clarifying how it can overcome existing limitations, enhance data collection capabilities, and expand the scale of future exposure monitoring efforts.

4.1 Dimensions of Contaminant Exposure

The degree to which Inuit populations are exposed to dietary contaminants is contingent on the consumption of concrete species and tissues, the levels of contaminants within these tissues, and the variability of these levels in the locations studied. Furthermore, traditional food availability depends on harvest activities and, therefore, also on both seasonal and geographical availability. In addition, imported food consumption is an inextricable part of the dual Inuit food system derived from colonial influence and thus shaped by societal factors that may narrow or broaden the range of dietary choices.

4.1.1 Dietary Intake

North and East Greenland Inuit populations have been consistently identified as being at the highest risk of dietary exposure in the Arctic (AMAP, 2021a, 2021b). Indeed, Dietz et al. (2018) and Sonne et al. (2023) reported substantial intake amounts of two highly relevant contaminants, Hg and PFAS, respectively. Avanersuaq narwhal dietary intake alone accounted for a mean Hg exposure of 21.96 g year^{-1}, about 4.78 times higher than the TWI of an 80kg adult population, a value that increases to a staggering 12.76-fold Hg excess for 30kg children (Dietz et al., 2018). In Ittoqoortoormiit, polar bear dietary intake estimates accounted for a PFOS exposure of 12.61 mg year^{-1}, or 1.97 times higher than the TWI of an 80kg adult population, which again increases to a 5.25-fold PFOS excess for 30kg children (Sonne et al., 2023).

The elevated Hg exposure was compounded by its relatively high loads in narwhal meat, together with the large proportion of this species in the diet (439.65 g week^{-1}; Figure 7), which largely surpassed the safe weekly consumption amount (1.15g/kg bw; Figure 8). Conversely, PFOS exposure from polar bear intake was driven by the extremely high concentrations of this contaminant in the meat, which significantly lowered the weekly safe consumption limit (0.41 g/kg bw; Figure 10) to a point where even a moderate meat intake (64.23 g week^{-1}; Figure 9) would double the TWI of an 80kg adult.

As large as these exposure results may appear, they do not account for the many species that compose the traditional Inuit diet. In Avanersuaq, the same study found that tissue consumption from whale (beluga, narwhal), seal (ringed, bearded, hooded, harp), and several marine bird (glaucous gull, kittiwake, black guillemot) species all significantly contributed to dietary Hg loads, elevating the Hg influx to 46 g year^{-1}, doubling the 21.96 g year^{-1} narwhal-only exposure seen before (Dietz et al., 2018). In Ittoqoortoormiit, Sonne et al. (2023) revealed a higher mean consumption of ringed seal meat (140.50 g week^{-1}) compared to polar bear meat (64.23 g week^{-1}), which also contributed to an overall PFAS exposure well over the EFSA's TWI in a large portion of the population (66%). Moreover, total PFAS exposure was much greater when the other congeners (PFOA, PFHxS, PFNA) in the study were considered. To date, Sonne et al. (2023) stands out as the only recent PFOS study detailing tissue intake amounts of Arctic species together with their associated exposure in Inuit populations.

In Nunavut, Canada, an earlier study analyzed PFAS loads in animal samples collected between 1997-1998 (Ostertag et al., 2009), then matched this data with highly detailed dietary intake derived from 24-hour recalls conducted during 1997-2000 (Kuhnlein et al., 2000). Based on the intake frequency for each species and tissue, the authors estimated that the top contributors to overall PFAS exposure in the population were caribou meat (43-75%), beluga *muktuk*, and arctic char, accounting for a mean daily PFOS intake (1.3-3.2 ng/g kg bw) around 2-5 times higher than the EFSA's TWI. In general, high PFAS exposure was due to either large dietary intake or the consumption of tissues with exceptionally high loads (Ostertag et al., 2009).

A large-scale data collection initiative covering a number of villages and towns across North, West, South, and East Greenland, analyzed dietary intake and blood Hg levels from Inuit (n = 2600) during 2005-2008 (Jeppesen et al., 2012). The results showed that intake of meat, blubber, and *muktuk* tissues from ringed seal (46.9 g day^{-1}) and whale (27.6 g day^{-1}) species, including beluga and narwhal, were the major contributors to whole blood Hg levels (21.1 μg/L). The same study also measured relatively large intakes of other species in the traditional diet, including polar bear, terrestrial game, birds (aggregated mean: 168.5, SD: 144.2; g day^{-1}), and fish (61.2 g day^{-1}), but did not report significant associations with Hg intake in those cases.

In the Canadian Arctic, yearly surveys conducted during 2007-2008 (Laird et al., 2013) found ringed seal liver to be the major contributor to dietary Hg intake (32.7 g liver week^{-}

^{1}, 4.7 µg/kg Hg; 59% Hg), together with beluga (126.9 g week^{-1}; 0.68 µg/kg Hg; 8.5% Hg) and narwhal (50.7 g week^{-1}; 0.28 µg/kg Hg; 3.5% Hg) *muktuk*, as well as meat from ringed seal (148 g week^{-1}; 0.31 µg/kg Hg; 4% Hg), beluga (25.3 g week^{-1}; 1.2% Hg), caribou (731 g week^{-1}; 3.8% Hg), and arctic char (378 g week^{-1}; 8.4% Hg). These items comprised the majority of the traditional food intake (79%) and Hg exposure (>90%).

In Nunavut, a study conducted on children from three regions during 2007-2008 (Tian et al., 2011) estimated a mean weekly MeHg dietary intake 1.82-times (2.37 µg/kg bw) greater than the EFSA's TWI, the majority of which (>95%) originated from the consumption of beluga (12.95 g day^{-1}; 33.37%) and narwhal (8.95 g day^{-1}; 25.90%) *muktuk*, ringed seal liver (0.23 g day^{-1}; 14.71%) and meat (5.75 g day^{-1}; 4.59%), various fish (13.04 g day^{-1}; 10.60%), and caribou meat (31.14 g day^{-1}; 6.02%). Furthermore, Hg concentrations in children's hair positively correlated with blood Hg levels in the adults of the same household, indicating a shared food Hg source.

These studies represent patterns of dietary exposure along a spectrum defined by two different endpoints: amount of tissue intake and amount of tissue loads. It is a highly relevant pattern to consider when designing food substitution intervention programmes (Calder et al., 2019). As such, a larger and more frequent intake of tissues with low to moderate contaminant loads, like reindeer meat or narwhal and beluga muktuk (Laird et al., 2013; Tian et al., 2011), can still compound to similar or even greater exposure levels than from consuming highly contaminated tissues, including polar bear meat (Sonne et al., 2023) or ringed seal liver (Laird et al., 2013). This is also clearly observed by comparing (Figure S3) intake and exposure in Dietz et al. (2018) and Sonne et al. (2023).

4.1.2 Species and Tissue Loads

Comprehensive Arctic wildlife exposure studies in the last four decades have consistently documented concerning Hg concentrations in high trophic marine mammal predators (Dietz et al., 2022, 2018). In Greenland, average median liver Hg levels ranged from elevated in bearded seal, harp seal, and ringed seal, to very high in hooded seal, polar bear, harbor porpoise, and narwhal (Table S1). Moreover, as previously mentioned, significant Hg loads were detected in the meat of these species (Table S1), becoming a large source of Hg exposure in Northern Inuit populations (Dietz et al., 2018). In Canada, liver Hg concentrations in polar bear, ringed seal, and beluga, as well as in bearded seal meat, were also high and consistent with the observations in Greenland (Table S1). While clear geographical Hg distribution patterns are not immediately apparent, particularly high Hg concentrations have been consistently observed in North and East Greenland regions, including Qaanaaq and Ittoqqortoormiit (Table S2), as well as specific locations in

Northwest Canada, such as the Beaufort Sea (Table S3). Establishing temporal exposure patterns from this cross-sectional data alone would be challenging, as the availability of these species depends on environmental and ecosystem dynamics not reflected here (Dietz et al., 2018; Flora et al., 2018).

In terrestrial ecosystems (Table S4), studies in Greenland from 2008-2009 reported Hg loads in reindeer kidney, liver, and muscle generally lower than in the marine mammals (Gamberg et al., 2016). These concentrations were similar to those in previous studies at these locations (Aastrup et al., 2000). In Canada, early studies during 1995 to 2002 (Elkin and Bethke, 1995; Robillard et al., 2002) documented similar caribou muscle Hg loads, but comparatively higher in kidney and liver (Table S5). However, later observations spanning from 1991 to 2016 have reported lower kidney Hg concentrations (Gamberg et al., 2020).

PFAS exposure has also been extensively studied in Arctic marine mammal species (Muir et al., 2019). In Greenland, studies during 2016-2019 reported PFOS concentrations ranging from very high to extreme in orca liver, ringed seal liver, polar bear meat, and polar bear liver (Table S6). Indeed, as previously mentioned, the high PFOS exposure in meat from polar bear and ringed seal observed in Ittoqqortoormiit may have been a significant driver of dietary exposure (Sonne et al., 2023). In Canada, wildlife studies during 1999 to 2003 (Kelly et al., 2009; Martin et al., 2004) also reported extreme PFOS loads in polar bear liver, as well as high in beluga liver, beluga blood, and ringed seal liver (Table S6). In those studies, liver PFOS concentrations accounted for the majority of PFAS loads in polar bear (75-85%) and beluga (40%). However, beluga meat and blubber concentrations were comparatively lower (Kelly et al., 2009). In Svalbard, studies conducted during 1997-2014 on polar bears also found large PFOS concentrations (196.7-237 ng/g ww) in their plasma (Routti et al., 2017; Tartu et al., 2017). Though it is important to note that polar bear liver is not part of the Inuit diet due to its high Vitamin A toxicity (Dietz et al., 2018), it is still a relevant indicator of exposure in this species.

In terrestrial environments, recent observations in Canada (Muir et al., 2019) revealed low PFOS concentrations in caribou liver, kidney, and meat (Table S7). Interestingly, as previously mentioned, early studies in Nunavut reported comparatively higher PFOS loads in caribou liver and meat foods, driving PFOS exposure in the population (Ostertag et al., 2009). In Greenland, caribou liver PFAS loads were also relatively low. In general, reindeer PFOS loads across all regions were reportedly much lower than in marine mammals.

These results show common patterns in the contaminant distribution among different species. Indeed, marine mammal predators generally have higher loads than terrestrial species (Dietz et al., 2022; Muir et al., 2019). However, geographical and tissue-specific variability is sufficient that a thorough investigation of Inuit dietary exposure may require complementary wildlife sampling in proximity to the studied populations. Moreover, temporal patterns are difficult to elucidate from cross-sectional studies scattered across many locations, underlining the importance of continuous wildlife exposure observations.

4.1.3 Regional and Temporal Variability

Geographical and temporal variations in dietary intake patterns can have large effects on differential contaminant exposure. Dietz et al. (2018) observed temporal changes in the amounts of harvested species and derived Hg intake from 1993 to 2013. Reported catches for species like beluga or walrus decreased significantly (4-11% year^{-1}), whereas others like reindeer and harp seal increased (8-14% year^{-1}). Hg intake from Narwhal meat showed a pronounced peak from June to August (+237%), coinciding with the summer harvest season (Figure S2). Bearded and ringed seal Hg intake also increased markedly during the May to October (+75%) and September to December (+47%) periods, respectively, presumably due to greater consumption of these species.

Sonne et al. (2023) collected human blood serum samples to measure PFAS loads in September, potentially underestimating exposure during the polar bear and ringed seal spring harvest season, when meat consumption is expected to be greater. In addition, wildlife samples were taken from January to July, which may have led to discrepancies between their reported loads and the human measurements done in September. Interestingly, median plasma PFOS levels reported by Tartu et al. (2017) in Svalbard were higher in September (23.8%) than in April, which would further support these potential measurement discrepancies. However, considering there was a 3-year interval between the human and wildlife sample collection (Sonne et al., 2023), the effects of seasonal variability in this instance would be hard to determine.

Birth cohort studies across various towns and villages in Greenland have found substantial regional differences in dietary intake and contaminant exposure. A study on Greenlandic pregnant women in 2015 (Knudsen et al., 2015) found a greater intake of traditional food in the North and East regions compared to the others, especially for marine mammals (+27%). In addition, East Greenland also had a higher consumption of imported meat (+86%) than other regions. Results that were consistent with significantly elevated Hg (6.97 μg/L North; 7.74 μg/L East) and PFOS (17.1 ng/mL North; 24.6 ng/mL East) blood serum levels previously reported at those locations (Long et al., 2015), the latter above the critical serum concentration for immune-suppression effects (Schrenk et al., 2020).

A follow-up study during 2019-2020 in the same cohort (Wielsøe et al., 2022), which included their born children of 3-5 years of age, again showed positive associations between higher blood serum PFAS concentrations and consumption of marine mammals, seabirds, and fish, as well as negative associations with imported food consumption. However, overall PFAS concentrations, including PFOS (mean 7.27 ng/mL), were now lower than in the previous study (Long et al., 2015), attributed to decreasing contaminant loads in ringed seal and polar bear tissues (Wielsøe et al., 2022).

In Canada, temporal trends from 1992-2017 showed there had been a significant decrease in whole blood Hg levels (65%) in the Nunavik Inuit population, associated with a large reduction (71%) in marine dietary intake (Adamou et al., 2020). Similarly, PFOS exposure in pregnant women during 2004-2017 decreased significantly (64%), reportedly as a result of regulations, whereas concentrations of non-regulated PFAS congeners increased (19%). Moreover, PFOS exposure was 1.8 times higher than overall Canadian levels (Caron-Beaudoin et al., 2020). In the previously discussed study on children in Nunavut (Tian et al., 2011), the reported Hg intakes represented a significant decrease (30%) in comparison to MeHg levels reported 20 years earlier by the same authors (Chan et al., 1995), also attributed to a decrease in traditional food consumption. Furthermore, regional differences in MeHg concentrations were 4.0 and 1.8 times greater in the children of Baffin Island than those in the Central Arctic and Kivalliq regions, respectively (Tian et al., 2011).

These dynamic patterns of temporal and geographical variations can be the result of changes in species loads and dietary composition due to regulations (Caron-Beaudoin et al., 2020), differences in species availability (Dietz et al., 2018), or a reduced traditional diet intake in favor of more imported foods (Adamou et al., 2020; Wielsøe et al., 2022). Capturing this complexity using cross-sectional and cohort data from literature reviews and peer communications (Dietz et al., 2019, 2018; Muir et al., 2019; Sonne et al., 2023), while useful to produce a more comprehensive overview of dietary exposure, can be challenging and inferences need to be made to address information gaps.

4.1.4 Dietary Transition and Food Security

The duality of the Inuit food system encompasses implications related to the availability, access, and utilization of resources that guarantee stability in all aspects of food security (Shafiee et al., 2022). These four fundamental pillars of food security are at the balance between the consumption of traditional and imported foods and the different demographic factors that characterize the Inuit society. A society undergoing a dietary and identity transition that is central to every study on contaminant exposure.

In Greenland, a study by Pars et al. (2001) identified country-wide trends favoring the consumption of imported foods (40-75%) over the traditional diet (2-21%). In addition, it was established that Inuit in villages consumed more country food than in towns, and North Greenlanders consumed more country food than in the South. Regional differences in the consumption of species were also observed in East Greenland, including a greater intake of seal meat but a lower intake of whale and terrestrial animals, compared to other regions (Pars et al., 2001).

In Nunavut, Canada, a series of studies during 2013-2014 revealed that while certain traditional foods like caribou, *muktuk*, or seal remained a popular choice, the consumption frequency of imported foods was much higher, especially NNDFs and carbohydrates, together with a low vegetable and fruit intake (Sheehy et al., 2014, 2013). Indeed, in the Canadian Inuit Nunangat, steady decreases of Inuit participation in harvesting activities have been reported from 2006 (70%) to 2017 (56%), a change most prevalent in women (Kumar et al., 2019). When asked about the causes, not having enough time (33%) or money for equipment and supplies (29%) were the top reasons, and employed individuals were twice as likely to hunt, fish, or trap. Interestingly, a large proportion of Inuit harvested for their own use (91%), to share with the community (61%), or for cultural reasons (54%), whereas only a minority did so to supplement their income (14%).

Modeling the intake of country and imported foods together with contaminant exposure is relevant to issue advisory or design intervention programmes. A previous Canadian study from 2007-2008 estimated that substitution of ringed seal liver with other traditional foods would decrease Hg intake by 58%, while still maintaining a consistent Se and n-3 PUFAs nutrient intake (Laird et al., 2013). Another study targeting MeHg exposure in Labrador Inuit, estimated that replacing traditional foods with store-bought alternatives would increase cardiovascular risk and reduce vitamin A and n-3 PUFA intake by up to 70% per capita, while not achieving a net improvement in neuro-developmental impacts (Calder et al., 2019). In contrast, substituting high MeHg country food intake with locally caught Atlantic salmon (*Salmo salar*) would lead to significantly better outcomes, underlining the importance of preserving a traditional diet when designing intervention programmes.

A comprehensive study by Long et al. (2023) in three municipalities of East Greenland, which included Ittoqoortoormiit, reported much higher consumption of Greenlandic food (75% vs 40%) than imported food (15% vs 60%) in this location. PFAS exposure was significantly higher (2.67-3.34 times) and polar bear intake was associated with elevated PFAS serum loads. In addition, there were significant correlations between plasma n-3/n-6 ratios, an indicator of marine food intake, and PFAS and heavy metal levels, including Hg, highlighting the marine diet as a source of both contaminants and essential fatty acids

(Long et al., 2023). In the West, recent data from Nuuk, Sisimiut, and Ilulissat municipalities show similar ratios of imported (76%) to country food (14%) consumption (Wielsøe et al., 2022). Interestingly, imported meat intake was negatively associated with PFAS exposure, even though it is an important source of these contaminants in the countries of origin (Wielsøe et al., 2022).

In this regard, some studies from previous decades in Greenland have shown very little influence (1%) of the awareness of contaminant exposure on the choice to consume country food, partially attributed to a lack of public advisory or "less attention" in the news (Pars et al., 2001). This starkly contrasts with more recent reports from North Greenland's Qaanaaq, where hunters avoid specific hunting groups due to fear of contamination (Dietz et al., 2018) or perceive a higher vulnerability to disease and illness (Hastrup et al., 2016). In Canada, studies in Nunavik also reported that a significant portion of the population (33%) limited the intake of country food due to exposure risks (Little et al., 2021).

Various demographics and socioeconomic factors have been associated with dietary intake patterns and participation in harvesting activities (Arriagada and Bleakney, 2019; Kumar et al., 2019). A generational gap, sex differences, indigenous upbringing, financial status, or lifestyle habits are all relevant in relation to dietary choice and food security (Bjerregaard and Mulvad, 2012; Pars et al., 2001; Wielsøe et al., 2022). However, each study presents a different perspective on such preferences.

According to Pars et al. (2001), traditional food consumption has different connotations in villages and towns. In villages, it is not something to be bought but a culture to inherit, a signifier of position as well as the ability to hunt and share. In towns, traditional food consumption is a symbol of status and appreciation of Inuit culture, something that can be bought in food stores. Therefore, access to this type of food depends on either participation in harvest activities, or being financially sound enough to purchase it. Accordingly, its high price in towns (42.8%) and being difficult to obtain in villages (59.3%) were described as major reasons for lack of access to country food. In younger generations (52.2%) a desire for variation in the diet was more important (Pars et al., 2001).

Wielsøe et al. (2022) used a comprehensive modeling approach to find associations between socioeconomic and lifestyle factors, and dietary intake patterns. Higher education level, personal and household income, and a healthy lifestyle were positively associated with a traditional diet rich in Greenlandic fish or terrestrial animals, as well as the consumption of more expensive imported foods, like fruits and vegetables. In contrast, lower income, lack of education, smoking history, and alcohol intake were all correlated with a higher intake of fast food and carbohydrates. Furthermore, age was correlated with a greater consumption of healthy foods and a traditional diet, as opposed to a higher fast food and sugar intake by the younger population. These results are consistent with previous observations over a broader distribution of Inuit in Greenland (Bjerregaard and Mulvad, 2012), which placed a significantly higher traditional food consumption in older age groups (60+; 28.3%) compared to younger individuals (18-24; 12.8%).

4.2 Exposure Monitoring

The multidimensionality of dietary exposure discussed in the previous sections presents a complex challenge to accurately assess the exposure risks faced by Arctic indigenous populations. Given the number of factors that need to be controlled and the technical difficulties that arise when studying dietary exposure, a digital platform connecting scientists and indigenous users can offer a more flexible approach to data collection than traditional analog or hybrid methods. A platform that can produce continuous dietary intake observations and higher data resolution, both required to effectively issue public advisory, design intervention programmes, or provide reasonable means for self-monitoring exposure, while intuitively accounting for socioeconomic realities, temporal and geographical variability, and the dynamic nature of contaminant exposure.

4.2.1 Dietary Intake

Analog dietary data collection strategies involve the use of FFQs and 24-hour recalls. In Sonne et al. (2023), a subsample of the study participants completed an FFQ detailing the species and tissues consumed, as well as the month of intake. In this instance, amounts were determined as the number of meals, ranging from 1-3 (<200g, 200-600g, >600g, respectively). In contrast, Dietz et al. (2018) leveraged data within the *Piniarneq* database, which contains self-reported hunter statistics of harvested species, to derive an approximate meat intake (30% of the hunted game weight) of 500 g day^{-1} per person, or 155 t year^{-1} for the whole Avanersuaq population.

In many instances, the administration of FFQs is done in person (Calder et al., 2019; Laird et al., 2013), often by the same healthcare professionals responsible for sample collection (Knudsen et al., 2015; Wielsøe et al., 2021). Different strategies can be applied to measure dietary intake amounts, including recall interviews (Tian et al., 2011), photos of serving sizes (Bjerregaard and Mulvad, 2012; Caron-Beaudoin et al., 2020; Jeppesen et al., 2012), three-dimensional food models (Johnson et al., 2009; Sharma, 2010), or derive them from frequency responses (Wielsøe et al., 2021). However, all these methods suffer from some measure of recall bias or estimation error, with the best results being achieved when participants can define their own portion sizes (Cade et al., 2002).

These cross-sectional dietary intake inferences may not provide sufficient measurement resolution to monitor exposure or the effectiveness of intervention programmes. This issue could be ameliorated using a personal mobile phone device to input daily intake amounts in real-time (Figure 6), providing a continuous stream of dietary data information. This method allows for the generation of intake time series for whole populations, as is usually required in research studies, as well as specific individuals. This latter use case is useful for self-monitoring, enabling study participants to follow the toxicological research without altering the outcome, or adjust their intake appropriately during intervention programmes. Moreover, it opens the possibility of using image recognition and detection techniques powered by artificial intelligence (AI), which could potentially automate this task and consistently produce more accurate results. Then, from the reported intake, individual exposure entries can be created for each contaminant, species, and tissue (Figure S14), providing the necessary granularity to conduct thorough toxicological investigations.

Seasonal length is another parameter usually considered to compute dietary intake (Bjerregaard and Mulvad, 2012; Calder et al., 2019; Caron-Beaudoin et al., 2020; Jeppesen et al., 2012; Munch-Andersen et al., 2012), as it can lead to confounding results if inferences are made over out-of-season periods (Cade et al., 2002). In addition, modifications made to the FFQs during the study period can lead to an eventual exclusion of some food items from the analyses (Knudsen et al., 2015), underlining the limitation of analog methods to include new requirements retroactively. Moreover, food storage and processing, potential sources of contaminant and nutrient intake variability, are rarely documented (Caron-Beaudoin et al., 2020; Jeppesen et al., 2012; Ostertag et al., 2009; Tian et al., 2011).

The iterative nature of software-driven data collection also allows for fast adaptation to new requirements from either the scientific or indigenous communities. Well-known paradigms of feature-driven development can be used to add support for additional demographics or study parameters, even retroactively, with minimal effort. For example, app versions can be made mandatory for users, and the same versioning approach could be applied to study management, prompting participants to update specific dietary entries. Adjusting ongoing study parameters with additional information, though necessarily done with careful consideration of the potential effects on the results, is simplified from a centralized admin UI, such as the one proposed in this platform.

As previously reported, contaminant concentrations tend to correlate within household members (Tian et al., 2011). However, capturing individual member exposure at a large scale may be desirable but difficult due to the practical limitations of administering FFQs and in-person interviews. There have been instances in which only one member was questioned about the dietary preferences, then household intake frequency and amounts inferred from this data (Sheehy et al., 2013). The proposed approach in this thesis increases the resolution of the data by using personal apps, allowing for a fine-grained analysis of intake within a single household, thus being able to differentiate further other factors, such as individual age, gender, or intake time.

4.2.2 Contaminant Loads

Common toxicity patterns are shared among many species in the traditional Inuit diet, but the relevancy of each contaminant is dependent on the concrete species, tissues, and locations studied (AMAP, 2021a; Basu et al., 2022). This complexity is unavoidable and creates additional challenges when designing an appropriate diet composition. Culturally appropriate FFQs must include food items tailored for the studied population (Cade et al., 2002), human or wildlife samples often need to be collected in geographical and temporal proximity to the study location and duration (Jeppesen et al., 2012; Long et al., 2023; Sonne et al., 2023; Wielsøe et al., 2022), and exposure risk levels exist under different state regulations (Basu et al., 2022; Bjerregaard and Mulvad, 2012; Schrenk et al., 2020).

In Sonne et al. (2023), blood serum samples were collected from ringed seals and polar bears hunted during 2018-2019, several years after the human data collection took place. Moreover, participant blood samples were collected outside of the harvest season for these species. In Dietz et al. (2018), human exposure was derived from the estimated meat intake reported in the *Piniarneq* database and species loads extracted from the literature. In other studies, blood serum contaminant concentrations have also been analyzed, but complementary measurements of species loads are rarely done and, therefore, only discussed via literature review (Adamou et al., 2020; Caron-Beaudoin et al., 2020; Long et al., 2023, 2015; Turgeon O'Brien et al., 2012; Wielsøe et al., 2022). Moreover, while tissue intake amounts are usually derived from FFQs, the specific numbers are seldom documented (Caron-Beaudoin et al., 2020; Long et al., 2023, 2015; Wielsøe et al., 2022).

The system proposed in this platform is a first step towards addressing some of these limitations. A study network architecture allows for the decoupling of species and dietary intake analyses as two distinct patterns, while still enabling individual research studies to benefit from a complete data integration. By facilitating app users to self-monitor dietary intake and exposure (Figure 6), researchers focusing on wildlife loads can reach these participants to access their data for specific periods, then integrate it with the wildlife sample data. Furthermore, public locations ensure a stream of dietary intake information from users even when not currently participating in any studies, allowing for asynchronous data integration. Conversely, studies aiming to provide a unique perspective on dietary patterns alone can easily leverage the existing species and tissue loads in the platform, either from public locations or other collaborating studies. Networking dietary and species exposure observations provides a more complete view of how both human and wildlife exposure progress over time and space and enables future cross-disciplinary studies to access this higher-resolution information in further collaborative analyses (Figure 5).

4.2.3 Regional and Temporal Variability

Regional and seasonal variability is contingent on the geographical, cultural, and temporal scale investigated. Capturing relevant parameters for these additional dimensions is challenging, requires careful consideration of the data used, and often compromises need to be made to overcome practical limitations related to the scope of the investigation.

Dietz et al. (2018) derived temporal intake data from 1993 to 2013 from the *Piniarneq* database, while inferring species Hg loads from literature published at discrete points within this period. This allowed for a comprehensive Hg influx modeling at the whole population level but was limited by the cross-sectional nature of the data. Sonne et al. (2023) conducted a worldwide comparison of human PFAS serum loads using cross-sectional and cohort studies from 2000-2021. Leveraging existing literature in combination with their own sampling data, contextualized an otherwise local risk assessment within the larger planetary context.

In Greenland, sub-studies within the ACCEPT (Adaptation to Climate Change, Environmental Pollution, and Dietary Transition) programme administered FFQs designed for the Greenlandic population, but they were shared among regions, lacked seasonal availability data, or were unable to cover more remote locations (Knudsen et al., 2015; Wielsøe et al., 2021). In addition, unbalanced population numbers meant dietary exposure results were unlikely to capture statistics from underrepresented segments of the population, such as those in older age groups or living in villages (Wielsøe et al., 2022).

Capturing temporal variability, for example in cohorts, requires strict selection criteria in the initial and follow-up studies, which may encompass specific age ranges, indigenous upbringing, current residence in concrete territories, or pregnancy and birth outcome requirements (Caron-Beaudoin et al., 2020; Knudsen et al., 2015; Long et al., 2015; Wielsøe et al., 2021). Furthermore, continuous monitoring via the administration of FFQs and biological sample collection is expensive and impractical. Thus, cross-sectional data is used to infer continuous intake and exposure (Adamou et al., 2020; Wielsøe et al., 2022).

The platform architecture presented in this thesis proposes a hierarchical relationship between study design, location parameters, and species data, that references a common set of contaminants of interest (Figure 5). Each location contains a unique set of species that individually define their contaminant tissue loads. Furthermore, any location can hierarchically be linked to another parent location. Public locations provide baseline geographical information with current data on species loads, whereas individual research studies add a temporal context and increase geographical resolution. Thus, every recorded dietary exposure is explicitly linked to a geographical and temporal interval, represented by the locations and duration in the parent study, respectively. This approach is complementary and similar to literature reviews but creates a centralized source of information intended to leverage network effects for this specific use case.

While still a work in progress, in the future, this system could serve as the basis for a public network of highly specific studies for other research projects to build upon. In this scenario, any researcher could design a new study that leverages already collected data to produce a novel interpretation from a new geographical and temporal perspective.

4.2.4 Dietary Transition and Food Security

As previously mentioned, the consumption of traditional country food by the Inuit society is deeply integrated within their cultural identity and influenced by socioeconomic status, lifestyle choices, and other demographic factors. Likewise, the dietary balance between traditional and imported food intake is an important covariate of these same variables. Consequently, toxicological studies frequently focus on modeling dietary preferences and exposure in terms of their relationships with several key variables, such as education level, financial stability, marital status, age, pregnancy status, or ethnic background.

FFQs are commonly used to document details of animal- and plant-based consumption of country foods, as well as the intake and nutritional properties of imported products. To facilitate dietary analysis, traditional country foods can be further classified based on the species consumed (e.g., marine mammals, seabirds), the methods of food processing (e.g., dried fish, fermented meat or *igunaq*), or their plant-based origin (e.g., berries). Similarly, imported products can be categorized by their nutritional characteristics, such as meat, carbohydrates, fruits, vegetables, fast food, and sweets and snacks (Caron-Beaudoin et al., 2020; Knudsen et al., 2015; Wielsøe et al., 2021).

Previous research has extensively analyzed the impact of socioeconomic factors on various outcomes. Metrics of financial stability include employment or student status, direct measures of personal and household income (Wielsøe et al., 2022, 2021), or indirect indicators, such as housing conditions and household composition (Arriagada and Bleakney, 2019; Caron-Beaudoin et al., 2020). Other commonly considered demographic variables include age, sex, pregnancy history, marital status (e.g., widowed, divorced), or educational achievements, which may range from primary school completion to college education and graduation (Caron-Beaudoin et al., 2020; Wielsøe et al., 2022). Furthermore, when studying indigenous populations, the family's ethnic background and proportion of time lived in predominantly indigenous areas are also profiled (Wielsøe et al., 2022, 2021). Lifestyle factors, such as physical activity (e.g., sports, harvest activities), body mass index (BMI), weight categories (e.g., overweight, underweight), and substance use (e.g., smoking, alcohol, or narcotics), are also recorded in these studies as potential confounding factors (Long et al., 2023; Wielsøe et al., 2022, 2021).

Collecting data for this type of parameter is cumbersome and usually involves filling out multiple questionnaires (Sharma, 2010). In addition, it requires specific consent, assessment of potential privacy concerns, and approval by the appropriate scientific commissions (Long et al., 2023; Wielsøe et al., 2022). Moreover, participants may be less inclined to respond to some of these questions (Johnson et al., 2009; Knudsen et al., 2015; Wielsøe et al., 2022), which may preclude them from further inclusion.

To address these concerns, I propose two different strategies for data collection. The first is including basic demographic information in the user profile, including age, weight, and optionally pregnancy status, which are all highly relevant to produce automated advisory and self-monitoring exposure. This approach has the additional benefit of streamlining the signing-up process into the platform. Moreover, it signals to the user that respect for privacy is at the forefront of this initiative, so only the minimum set of personal data fields is requested to provide effective advisory services. In the second strategy, additional socioeconomic and lifestyle parameters, which may be deemed more invasive, can be collected from complementary questionnaires supported via study forms (Figure S8).

Because both intake data and form submissions are uniquely linked to specific study participants within the platform, complete demographic and lifestyle profiles can be constructed for each individual and then investigated in the context of intake and exposure patterns. Furthermore, analytics services can enrich this data with detailed usage patterns, which can help discover potential errors and biases during dietary input. However, it is important that personal data always be treated within the established ethical and legal boundaries. Participation in a study follows a strictly opt-in model, a conscious effort from the participant to collaborate in research initiatives. Data protection measures must always be in effect, transparency should be the singular principle that defines community interactions, and personal ownership of the data must supersede any other motivations.

4.3 Conclusions and Further Development

I have presented a digital platform with the goal of enhancing scientific research, while in parallel providing indigenous communities with the fundamental tools for self-monitoring dietary exposure. Existing platforms provide the scientific community with all necessary instruments to conduct research, including training and outreach. However, they fall short of engaging the broader community, those who stand to benefit most from research outcomes. Conversely, indigenous toxicological research efforts in both past and ongoing initiatives have shown similar goals, but to my knowledge, none of them have fully leveraged the power of digital technologies to create a real-time collaborative network between the scientific and indigenous communities.

This platform offers researchers a compelling approach to community involvement, critical for large-scale data collection. For community members, it provides intuitive access to research findings, enabling them to apply new insights to their daily lives, an essential ingredient for successful crowdsourcing. By connecting these two points, highly relevant goals like promoting Inuit leadership or furthering inter-institutional collaboration are automatically brought to the forefront of the conversation. This initial strategy borrows the same sharing principle that characterizes Inuit tradition. Researchers design dietary exposure studies across geographical locations, sharing their species data with the community for immediate access. In exchange, the community contributes the usage of these resources, enriching the overall data pool under a trust-based agreement with clear temporal boundaries.

Future growth of the platform should encompass an expansion in scope and feature development to maintain engagement and attract developer support. To this end, an open-source foundation, adherence to industry standards for cross-platform applications, and strict data privacy compromises are essential to make the platform uniquely identifiable, trackable over time, and continuously evolving. In a subsequent public release, the goal is to include a broader range of geographical locations, more species and tissues, and a wider spectrum of contaminants. User demands, either via direct feedback or indirectly through analytics, will guide the introduction of new features, such as targeting specific demographic groups, aligning with international exposure regulations, or incorporating mechanisms for effective communication between communities and authorities.

Finally, it is important to underscore the potential role of AI in this context. The AI revolution in early 2023 has set the stage for disruptive interactions across various sectors. As the complexity of planetary systems and our understanding grows, traditional analyses alone will become inadequate. AI can bridge this gap between complex data and user comprehension, consistently collect data, summarize results, generate visualizations, and provide advice tailored to individual community members. This represents a vision of many specialized AI agents working in concert to assist users in understanding their dietary intake and exposure patterns. Indeed, this integration will require the high-quality data sovereignty that arises from the collaborative efforts of scientific and indigenous communities.

5 References

Aastrup, P., Riget, F., Dietz, R., Asmund, G., 2000. Lead, zinc, cadmium, mercury, selenium and copper in Greenland caribou and reindeer (Rangifer tarandus). Sci. Total Environ. 245, 149–159. https://doi.org/10.1016/S0048-9697(99)00440-4

Adamou, T.Y., Riva, M., Muckle, G., Laouan Sidi, E.A., Lemire, M., Ayotte, P., 2020. Blood mercury and plasma polychlorinated biphenyls concentrations in pregnant Inuit women from Nunavik: Temporal trends, 1992–2017. Sci. Total Environ. 743, 140495. https://doi.org/10.1016/j.scitotenv.2020.140495

Ahrens, L., Rakovic, J., Ekdahl, S., Kallenborn, R., 2023. Environmental distribution of per- and polyfluoroalkyl substances (PFAS) on Svalbard: Local sources and long-range transport to the Arctic. Chemosphere 345, 140463. https://doi.org/10.1016/j.chemosphere.2023.140463

AMAP, 2021a. AMAP Assessment 2021: Human Health in the Arctic. Arctic Monitoring and Assessment Programme (AMAP), Oslo.

AMAP, 2021b. AMAP Assessment 2021: Mercury in the Arctic. Arctic Monitoring and Assessment Programme (AMAP), Oslo.

Andersen, A.O., Flora, J.K., Johansen, K.L., Heide-Jørgensen, M.P., Mosbech, A., 2017. Piniariarneq: From interdisciplinary research towards a new resource management.

Armitage, J.M., MacLeod, M., Cousins, I.T., 2009. Comparative Assessment of the Global Fate and Transport Pathways of Long-Chain Perfluorocarboxylic Acids (PFCAs) and Perfluorocarboxylates (PFCs) Emitted from Direct Sources. Environ. Sci. Technol. 43, 5830–5836. https://doi.org/10.1021/es900753y

Arriagada, P., Bleakney, A., 2019. Inuit participation in the wage and land-based economies in Inuit Nunangat. Stat. Can. 17.

Basu, N., Abass, K., Dietz, R., Krümmel, E., Rautio, A., Weihe, P., 2022. The impact of mercury contamination on human health in the Arctic: A state of the science review. Sci. Total Environ. 831, 154793. https://doi.org/10.1016/j.scitotenv.2022.154793

Bjerregaard, P., Dahl-Petersen, I.K., 2010. Sundhedsundersøgelsen i Avanersuaq 2010.

Bjerregaard, P., Mulvad, G., 2012. The best of two worlds: how the Greenland Board of Nutrition has handled conflicting evidence about diet and health. Int. J. Circumpolar Health 71, 10.3402/ijch.v71i0.18588. https://doi.org/10.3402/ijch.v71i0.18588

Brase, R.A., Mullin, E.J., Spink, D.C., 2021. Legacy and Emerging Per- and Polyfluoroalkyl Substances: Analytical Techniques, Environmental Fate, and Health Effects. Int. J. Mol. Sci. 22, 995. https://doi.org/10.3390/ijms22030995

Buck, R.C., Franklin, J., Berger, U., Conder, J.M., Cousins, I.T., de Voogt, P., Jensen, A.A., Kannan, K., Mabury, S.A., van Leeuwen, S.P., 2011. Perfluoroalkyl and polyfluoroalkyl substances in the environment: Terminology, classification, and origins. Integr. Environ. Assess. Manag. 7, 513–541. https://doi.org/10.1002/ieam.258

Cade, J., Thompson, R., Burley, V., Warm, D., 2002. Development, validation and utilisation of food-frequency questionnaires - a review. Public Health Nutr. 5, 567–587. https://doi.org/10.1079/PHN2001318

Calder, R.S.D., Bromage, S., Sunderland, E.M., 2019. Risk tradeoffs associated with traditional food advisories for Labrador Inuit. Environ. Res. 168, 496–506. https://doi.org/10.1016/j.envres.2018.09.005

Camacho, C., Boratyn, G.M., Joukov, V., Vera Alvarez, R., Madden, T.L., 2023. ElasticBLAST: accelerating sequence search via cloud computing. BMC Bioinformatics 24, 117. https://doi.org/10.1186/s12859-023-05245-9

Caron-Beaudoin, É., Ayotte, P., Blanchette, C., Muckle, G., Avard, E., Ricard, S., Lemire, M., 2020. Perfluoroalkyl acids in pregnant women from Nunavik (Quebec, Canada): Trends in exposure and associations with country foods consumption. Environ. Int. 145, 106169. https://doi.org/10.1016/j.envint.2020.106169

Chan, H.M., Kim, C., Khoday, K., Receveur, O., Kuhnlein, H.V., 1995. Assessment of dietary exposure to trace metals in Baffin Inuit food. Environ. Health Perspect. 103, 740–746. https://doi.org/10.1289/ehp.95103740

Dastoor, A., Ryzhkov, A., Durnford, D., Lehnherr, I., Steffen, A., Morrison, H., 2015. Atmospheric mercury in the Canadian Arctic. Part II: Insight from modeling. Sci. Total Environ. 509–510, 16–27. https://doi.org/10.1016/j.scitotenv.2014.10.112

Di Nisio, A., Rocca, M.S., De Toni, L., Sabovic, I., Guidolin, D., Dall'Acqua, S., Acquasaliente, L., De Filippis, V., Plebani, M., Foresta, C., 2020. Endocrine disruption of vitamin D activity by perfluoro-octanoic acid (PFOA). Sci. Rep. 10, 16789. https://doi.org/10.1038/s41598-020-74026-8

Dietz, R., Desforges, J.-P., Rigét, F.F., Aubail, A., Garde, E., Ambus, P., Drimmie, R., Heide-Jørgensen, M.P., Sonne, C., 2021. Analysis of narwhal tusks reveals lifelong feeding ecology and mercury exposure. Curr. Biol. 31, 2012-2019.e2. https://doi.org/10.1016/j.cub.2021.02.018

Dietz, R., Letcher, R.J., Aars, J., Andersen, M., Boltunov, A., Born, E.W., Ciesielski, T.M., Das, K., Dastnai, S., Derocher, A.E., Desforges, J.-P., Eulaers, I., Ferguson, S., Hallanger, I.G., Heide-Jørgensen, M.P., Heimbürger-Boavida, L.-E., Hoekstra, P.F., Jenssen, B.M., Kohler, S.G., Larsen, M.M., Lindstrøm, U., Lippold, A., Morris, A., Nabe-Nielsen, J., Nielsen, N.H., Peacock, E., Pinzone, M., Rigét, F.F., Rosing-Asvid, A., Routti, H., Siebert, U., Stenson, G., Stern, G., Strand, J., Søndergaard, J., Treu, G., Víkingsson, G.A., Wang, F., Welker, J.M., Wiig, Ø., Wilson, S.J., Sonne, C., 2022. A risk assessment review of mercury exposure in Arctic marine and terrestrial mammals. Sci. Total Environ. 829, 154445. https://doi.org/10.1016/j.scitotenv.2022.154445

Dietz, R., Letcher, R.J., Desforges, J.-P., Eulaers, I., Sonne, C., Wilson, S., Andersen-Ranberg, E., Basu, N., Barst, B.D., Bustnes, J.O., Bytingsvik, J., Ciesielski, T.M., Drevnick, P.E., Gabrielsen, G.W., Haarr, A., Hylland, K., Jenssen, B.M., Levin, M., McKinney, M.A., Nørregaard, R.D., Pedersen, K.E., Provencher, J., Styrishave, B., Tartu, S., Aars, J., Ackerman, J.T., Rosing-Asvid, A., Barrett, R., Bignert, A., Born, E.W., Branigan, M., Braune, B., Bryan, C.E., Dam, M., Eagles-Smith, C.A., Evans, M., Evans, T.J., Fisk, A.T., Gamberg, M., Gustavson, K., Hartman, C.A., Helander, B., Herzog, M.P., Hoekstra, P.F., Houde, M., Hoydal, K., Jackson, A.K., Kucklick, J., Lie, E., Loseto, L., Mallory, M.L., Miljeteig, C., Mosbech, A., Muir, D.C.G., Nielsen, S.T., Peacock, E., Pedro, S., Peterson, S.H., Polder, A., Rigét, F.F., Roach, P., Saunes, H., Sinding, M.-H.S., Skaare, J.U., Søndergaard, J., Stenson, G., Stern, G., Treu, G., Schuur, S.S., Víkingsson, G., 2019. Current state of knowledge on biological effects from contaminants on arctic wildlife and fish. Sci. Total Environ. 696, 133792. https://doi.org/10.1016/j.scitotenv.2019.133792

Dietz, R., Mosbech, A., Flora, J., Eulaers, I., 2018. Interactions of climate, socio-economics, and global mercury pollution in the North Water. Ambio 47, 281–295. https://doi.org/10.1007/s13280-018-1033-z

Dietz, R., Riget, F., Born, E.W., 2000. An assessment of selenium to mercury in Greenland marine animals. Sci. Total Environ. 245, 15–24. https://doi.org/10.1016/S0048-9697(99)00430-1

Dietz, R., Sonne, C., Basu, N., Braune, B., O'Hara, T., Letcher, R.J., Scheuhammer, T., Andersen, M., Andreasen, C., Andriashek, D., Asmund, G., Aubail, A., Baagøe, H., Born, E.W., Chan, H.M., Derocher, A.E., Grandjean, P., Knott, K., Kirkegaard, M., Krey, A., Lunn, N., Messier, F., Obbard, M., Olsen, M.T., Ostertag, S., Peacock, E., Renzoni, A., Rigét, F.F., Skaare, J.U., Stern, G., Stirling, I., Taylor, M., Wiig, Ø., Wilson, S., Aars, J., 2013. What are the toxicological effects of mercury in Arctic biota? Sci. Total Environ. 443, 775–790. https://doi.org/10.1016/j.scitotenv.2012.11.046

Durnford, D., Dastoor, A., Figueras-Nieto, D., Ryjkov, A., 2010. Long range transport of mercury to the Arctic and across Canada. Atmospheric Chem. Phys. 10, 6063–6086. https://doi.org/10.5194/acp-10-6063-2010

EFSA, 2020. Risk to human health related to the presence of perfluoroalkyl substances in food | EFSA [WWW Document]. URL https://www.efsa.europa.eu/en/efsajournal/pub/6223 (accessed 1.17.24).

EFSA, 2012. Scientific Opinion on the risk for public health related to the presence of mercury and methylmercury in food. EFSA J. 10, 2985. https://doi.org/10.2903/j.efsa.2012.2985

Elkin, B.T., Bethke, R.W., 1995. Environmental contaminants in caribou in the Northwest Territories, Canada. Sci. Total Environ. 160–161, 307–321. https://doi.org/10.1016/0048-9697(95)04365-8

Evich, M.G., Davis, M.J.B., McCord, J.P., Acrey, B., Awkerman, J.A., Knappe, D.R.U., Lindstrom, A.B., Speth, T.F., Tebes-Stevens, C., Strynar, M.J., Wang, Z., Weber, E.J., Henderson, W.M., Washington, J.W., 2022. Per- and polyfluoroalkyl substances in the environment. Science 375, eabg9065. https://doi.org/10.1126/science.abg9065

Fenton, S.E., Ducatman, A., Boobis, A., DeWitt, J.C., Lau, C., Ng, C., Smith, J.S., Roberts, S.M., 2021. Per- and Polyfluoroalkyl Substance Toxicity and Human Health Review: Current State of Knowledge and Strategies for Informing Future Research. Environ. Toxicol. Chem. 40, 606–630. https://doi.org/10.1002/etc.4890

Flora, J., Johansen, K.L., Grønnow, B., Andersen, A.O., Mosbech, A., 2018. Present and past dynamics of Inughuit resource spaces. Ambio 47, 244–264. https://doi.org/10.1007/s13280-018-1039-6

Gamberg, M., Cuyler, C., Wang, X., 2016. Contaminants in two West Greenland caribou populations. Sci. Total Environ. 554–555, 329–336. https://doi.org/10.1016/j.scitotenv.2016.02.154

Gamberg, M., Pratte, I., Brammer, J., Cuyler, C., Elkin, B., Gurney, K., Kutz, S., Larter, N.C., Muir, D., Wang, X., Provencher, J.F., 2020. Renal trace elements in barren-ground caribou subpopulations: Temporal trends and differing effects of sex, age and season. Sci. Total Environ. 724, 138305. https://doi.org/10.1016/j.scitotenv.2020.138305

Grønlands Statistik, 2023. Kalaallit Nunaanni Kisitsisit 2023 [WWW Document]. URL https://stat.gl/publ/kl/GF/2023/pdf/Kalaallit%20Nunaanni%20Kisitsisit%202023.pdf (accessed 1.17.24).

Harrow, J., Drysdale, R., Smith, A., Repo, S., Lanfear, J., Blomberg, N., 2021. ELIXIR: providing a sustainable infrastructure for life science data at European scale. Bioinformatics 37, 2506–2511. https://doi.org/10.1093/bioinformatics/btab481

Hastrup, K., Rieffestahl, A.M., Olsen, A., 2016. Food Security: Health and Environmental Concerns in the North. Food Secur.

Hong, Y.-S., Kim, Y.-M., Lee, K.-E., 2012. Methylmercury Exposure and Health Effects. J. Prev. Med. Pub. Health 45, 353–363. https://doi.org/10.3961/jpmph.2012.45.6.353

ICES, 2024. Database on the Marine Environment (DOME). [WWW Document]. ICES Cph. Den. URL https://www.ices.dk/data/data-portals/Pages/DOME.aspx (accessed 2.20.24).

Inuit Tapiriit Kanatami, 2021. Inuit Nunangat Food Security Strategy. Inuit Tapiriit Kanatami.

Jeppesen, C., Eika Jørgensen, M., Bjerregaard, P., 2012. Assessment of consumption of marine food in Greenland by a food frequency questionnaire and biomarkers. Int. J. Circumpolar Health 71, 18361. https://doi.org/10.3402/ijch.v71i0.18361

Jiskra, M., Sonke, J.E., Obrist, D., Bieser, J., Ebinghaus, R., Myhre, C.L., Pfaffhuber, K.A., Wängberg, I., Kyllönen, K., Worthy, D., Martin, L.G., Labuschagne, C., Mkololo, T., Ramonet, M., Magand, O., Dommergue, A., 2018. A vegetation control on seasonal variations in global atmospheric mercury concentrations. Nat. Geosci. 11, 244–250. https://doi.org/10.1038/s41561-018-0078-8

Joerss, H., Xie, Z., Wagner, C.C., von Appen, W.-J., Sunderland, E.M., Ebinghaus, R., 2020. Transport of Legacy Perfluoroalkyl Substances and the Replacement Compound HFPO-DA through the Atlantic Gateway to the Arctic Ocean—Is the Arctic a Sink or a Source? Environ. Sci. Technol. 54, 9958–9967. https://doi.org/10.1021/acs.est.0c00228

Johnson, J.S., Nobmann, E.D., Asay, E., Lanier, A.P., 2009. Developing a validated Alaska Native food frequency questionnaire for western Alaska, 2002–2006. Int. J. Circumpolar Health 68, 99–108. https://doi.org/10.3402/ijch.v68i2.18319

Kelly, B.C., Ikonomou, M.G., Blair, J.D., Surridge, B., Hoover, D., Grace, R., Gobas, F.A.P.C., 2009. Perfluoroalkyl Contaminants in an Arctic Marine Food Web: Trophic Magnification and Wildlife Exposure. Environ. Sci. Technol. 43, 4037–4043. https://doi.org/10.1021/es9003894

Kenny, T., 2017. The Inuit Food System: Ecological, Economic, and Environmental Dimensions of the Nutrition Transition. https://doi.org/10.20381/RUOR-20437

Kenny, T.-A., Fillion, M., Simpkin, S., Wesche, S.D., Chan, H.M., 2018. Caribou (Rangifer tarandus) and Inuit Nutrition Security in Canada. EcoHealth 15, 590–607. https://doi.org/10.1007/s10393-018-1348-z

Kenny, T.-A., Hu, X.F., Jamieson, J.A., Kuhnlein, H.V., Wesche, S.D., Chan, H.M., 2019. Potential impact of restricted caribou (Rangifer tarandus) consumption on anemia prevalence among Inuit adults in northern Canada. BMC Nutr. 5, 30. https://doi.org/10.1186/s40795-019-0292-9

Khan, B., Burgess, R.M., Cantwell, M.G., 2023. Occurrence and Bioaccumulation Patterns of Per- and Polyfluoroalkyl Substances (PFAS) in the Marine Environment. ACS EST Water 3, 1243–1259. https://doi.org/10.1021/acsestwater.2c00296

Kim, S., Chen, J., Cheng, T., Gindulyte, A., He, J., He, S., Li, Q., Shoemaker, B.A., Thiessen, P.A., Yu, B., Zaslavsky, L., Zhang, J., Bolton, E.E., 2023. PubChem 2023 update. Nucleic Acids Res. 51, D1373–D1380. https://doi.org/10.1093/nar/gkac956

King, M., Smith, A., Gracey, M., 2009. Indigenous health part 2: the underlying causes of the health gap. The Lancet 374, 76–85. https://doi.org/10.1016/S0140-6736(09)60827-8

Knudsen, A.-K.S., Long, M., Pedersen, H.S., Bonefeld-Jørgensen, E.C., 2015. Lifestyle, reproductive factors and food intake in Greenlandic pregnant women: The ACCEPT – sub-study. Int. J. Circumpolar Health 74, 29469. https://doi.org/10.3402/ijch.v74.29469

Kuhnlein, H., Receveur, O., Chan, L., Loring, E., 2000. Assessment of Dietary Benefit/Risk in Inuit Communities.

Kumar, M.B., Furgal, C., Hutchinson, P., Roseboroug, W., Kootoo-Chiarello, S., 2019. Harvesting activities among First Nations people living off reserve, Métis and Inuit (2001-2017): Time trends, barriers and associated factors.

Laird, B.D., Goncharov, A.B., Egeland, G.M., Man Chan, H., 2013. Dietary Advice on Inuit Traditional Food Use Needs to Balance Benefits and Risks of Mercury, Selenium, and n3 Fatty Acids. J. Nutr. 143, 923–930. https://doi.org/10.3945/jn.112.173351

Larter, N.C., Macdonald, C.R., Elkin, B.T., Wang, X., Harms, N.J., Gamberg, M., Muir, D.C.G., 2016. Cadmium and other elements in tissues from four ungulate species from the Mackenzie Mountain region of the Northwest Territories, Canada. Ecotoxicol. Environ. Saf. 132, 9–17. https://doi.org/10.1016/j.ecoenv.2016.05.018

Larter, N.C., Nagy, J.A., 2000. A comparison of heavy metal levels in the kidneys of High Arctic and mainland caribou populations in the Northwest Territories of Canada. Sci. Total Environ. 246, 109–119. https://doi.org/10.1016/S0048-9697(99)00418-0

Ling, A.L., 2024. Estimated scale of costs to remove PFAS from the environment at current emission rates. Sci. Total Environ. 918, 170647. https://doi.org/10.1016/j.scitotenv.2024.170647

Little, M., Hagar, H., Zivot, C., Dodd, W., Skinner, K., Kenny, T.-A., Caughey, A., Gaupholm, J., Lemire, M., 2021. Drivers and health implications of the dietary transition among Inuit in the Canadian Arctic: a scoping review. Public Health Nutr. 24, 2650–2668. https://doi.org/10.1017/S1368980020002402

Little, M., Winters, N., Achouba, A., Magesky, A., Ayotte, P., Palliser, T., Naylor, A., Jararuse, W., Lemire, M., 2023. Weaving together Inuit knowledge and western science: a mixed-methods case study of *qilalugaq* (beluga whale) in Quaqtaq, Nunavik. Arct. Sci. as-2022-0039. https://doi.org/10.1139/as-2022-0039

Long, M., Knudsen, A.-K.S., Pedersen, H.S., Bonefeld-Jørgensen, E.C., 2015. Food intake and serum persistent organic pollutants in the Greenlandic pregnant women: The ACCEPT sub-study. Sci. Total Environ. 529, 198–212. https://doi.org/10.1016/j.scitotenv.2015.05.022

Long, M., Sonne, C., Dietz, R., Bossi, R., Jørgensen, N., Olsen, T.I., Bonefeld-Jørgensen, E.C., 2023. Diet, lifestyle and contaminants in three east Greenland Inuit municipalities. Chemosphere 344, 140368. https://doi.org/10.1016/j.chemosphere.2023.140368

Martin, J.W., Smithwick, M.M., Braune, B.M., Hoekstra, P.F., Muir, D.C.G., Mabury, S.A., 2004. Identification of Long-Chain Perfluorinated Acids in Biota from the Canadian Arctic. Environ. Sci. Technol. 38, 373–380. https://doi.org/10.1021/es034727+

Mistry, J., Chuguransky, S., Williams, L., Qureshi, M., Salazar, G.A., Sonnhammer, E.L.L., Tosatto, S.C.E., Paladin, L., Raj, S., Richardson, L.J., Finn, R.D., Bateman, A., 2021. Pfam: The protein families database in 2021. Nucleic Acids Res. 49, D412–D419. https://doi.org/10.1093/nar/gkaa913

Muir, D., Bossi, R., Carlsson, P., Evans, M., De Silva, A., Halsall, C., Rauert, C., Herzke, D., Hung, H., Letcher, R., Rigét, F., Roos, A., 2019. Levels and trends of poly- and perfluoroalkyl substances in the Arctic environment – An update. Emerg. Contam. 5, 240–271. https://doi.org/10.1016/j.emcon.2019.06.002

Munch-Andersen, T., Olsen, D.B., Søndergaard, H., Daugaard, JensR., Bysted, A., Christensen, D.L., Saltin, B., Helge, JørnW., 2012. Metabolic profile in two physically active Inuit groups consuming either a western or a traditional Inuit diet. Int. J. Circumpolar Health 71, 17342. https://doi.org/10.3402/ijch.v71i0.17342

NILU, 2024. EBAS: a database to handle, store and disseminate atmospheric composition data generated by international and national frameworks like long-term monitoring programmes and research projects. [WWW Document]. EBAS. URL https://ebas.nilu.no (accessed 1.16.24).

Obrist, D., Agnan, Y., Jiskra, M., Olson, C.L., Colegrove, D.P., Hueber, J., Moore, C.W., Sonke, J.E., Helmig, D., 2017. Tundra uptake of atmospheric elemental mercury drives Arctic mercury pollution. Nature 547, 201–204. https://doi.org/10.1038/nature22997

Olker, J.H., Elonen, C.M., Pilli, A., Anderson, A., Kinziger, B., Erickson, S., Skopinski, M., Pomplun, A., LaLone, C.A., Russom, C.L., Hoff, D., 2022. The ECOTOXicology Knowledgebase: A Curated Database of Ecologically Relevant Toxicity Tests to Support Environmental Research and Risk Assessment. Environ. Toxicol. Chem. 41, 1520–1539. https://doi.org/10.1002/etc.5324

Olson, C., Jiskra, M., Biester, H., Chow, J., Obrist, D., 2018. Mercury in Active-Layer Tundra Soils of Alaska: Concentrations, Pools, Origins, and Spatial Distribution. Glob. Biogeochem. Cycles 32, 1058–1073. https://doi.org/10.1029/2017GB005840

Olson, C.L., Jiskra, M., Sonke, J.E., Obrist, D., 2019. Mercury in tundra vegetation of Alaska: Spatial and temporal dynamics and stable isotope patterns. Sci. Total Environ. 660, 1502–1512. https://doi.org/10.1016/j.scitotenv.2019.01.058

Ostertag, S.K., Tague, B.A., Humphries, M.M., Tittlemier, S.A., Chan, H.M., 2009. Estimated dietary exposure to fluorinated compounds from traditional foods among Inuit in Nunavut, Canada. Chemosphere 75, 1165–1172. https://doi.org/10.1016/j.chemosphere.2009.02.053

Pakseresht, M., Sharma, S., 2010. Validation of a quantitative food frequency questionnaire for Inuit population in Nunavut, Canada. J. Hum. Nutr. Diet. 23, 67–74. https://doi.org/10.1111/j.1365-277X.2010.01104.x

Pars, T., Osler, M., Bjerregaard, P., 2001. Contemporary Use of Traditional and Imported Food among Greenlandic Inuit. ARCTIC 54, 22–31. https://doi.org/10.14430/arctic760

Paysan-Lafosse, T., Blum, M., Chuguransky, S., Grego, T., Pinto, B.L., Salazar, G.A., Bileschi, M.L., Bork, P., Bridge, A., Colwell, L., Gough, J., Haft, D.H., Letunić, I., Marchler-Bauer, A., Mi, H., Natale, D.A., Orengo, C.A., Pandurangan, A.P., Rivoire, C., Sigrist, C.J.A., Sillitoe, I., Thanki, N., Thomas, P.D., Tosatto, S.C.E., Wu, C.H., Bateman, A., 2023. InterPro in 2022. Nucleic Acids Res. 51, D418–D427. https://doi.org/10.1093/nar/gkac993

Pickard, H.M., Criscitiello, A.S., Spencer, C., Sharp, M.J., Muir, D.C.G., De Silva, A.O., Young, C.J., 2017. Continuous Non-Marine Inputs of Per- and Polyfluoroalkyl Substances to the High Arctic: A Multi-Decadal Temporal Record (preprint). Clouds and Precipitation/Field Measurements/Troposphere/Chemistry (chemical composition and reactions). https://doi.org/10.5194/acp-2017-1009

Re3data.Org, 2016. Norwegian Polar Data Centre 399 datasets. https://doi.org/10.17616/R3B94H

Research Council of Norway, 2024. Research in Svalbard [WWW Document]. URL https://www.researchinsvalbard.no/ (accessed 1.16.24).

Rice, D.C., 2004. The US EPA reference dose for methylmercury: sources of uncertainty. Environ. Res., An Ecosystem Approach to Health Effects of Mercury in the St. Lawrence Great Lakes 95, 406–413. https://doi.org/10.1016/j.envres.2003.08.013

Robillard, S., Beauchamp, G., Paillard, G., Bélanger, D., 2002. Levels of Cadmium, Lead, Mercury and 137caesium in Caribou (*Rangifer tarandus*) Tissues from Northern Québec. ARCTIC 55, 1–9. https://doi.org/10.14430/arctic686

Routti, H., Aars, J., Fuglei, E., Hanssen, L., Lone, K., Polder, A., Pedersen, Å.Ø., Tartu, S., Welker, J.M., Yoccoz, N.G., 2017. Emission Changes Dwarf the Influence of Feeding Habits on Temporal Trends of Per- and Polyfluoroalkyl Substances in Two Arctic Top Predators. Environ. Sci. Technol. 51, 11996–12006. https://doi.org/10.1021/acs.est.7b03585

Rusell, D.E., Gunn, A., Kutz, S., 2018. Migratory Tundra Caribou and Wild Reindeer [in Arctic Report Card 2018]. National Oceanic and Atmospheric Administration (NOAA).

Ryman, T.K., Austin, M.A., Hopkins, S., Philip, J., O'Brien, D., Thummel, K., Boyer, B.B., 2014. Using exploratory factor analysis of FFQ data to identify dietary patterns among Yup'ik people. Public Health Nutr. 17, 510–518. https://doi.org/10.1017/S1368980012005411

Ryman, T.K., Boyer, B.B., Hopkins, S., Philip, J., Beresford, S.A.A., Thompson, B., Heagerty, P.J., Pomeroy, J.J., Thummel, K.E., Austin, M.A., 2015. Associations between diet and cardiometabolic risk among Yup'ik Alaska Native people using food frequency questionnaire dietary patterns. Nutr. Metab. Cardiovasc. Dis. 25, 1140–1145. https://doi.org/10.1016/j.numecd.2015.08.003

Schrenk, D., Bignami, M., Bodin, L., Chipman, J.K., del Mazo, J., Grasl-Kraupp, B., Hogstrand, C., Hoogenboom, L. (Ron), Leblanc, J.-C., Nebbia, C.S., Nielsen, E., Ntzani, E., Petersen, A., Sand, S., Vleminckx, C., Wallace, H., Barregård, L., Ceccatelli, S., Cravedi, J.-P., Halldorsson, T.I., Haug, L.S., Johansson, N., Knutsen, H.K., Rose, M., Roudot, A.-C., Van Loveren, H., Vollmer, G., Mackay, K., Riolo, F., Schwerdtle, T., 2020. Risk to human health related to the presence of perfluoroalkyl substances in food. EFSA J. 18, e06223. https://doi.org/10.2903/j.efsa.2020.6223

Schuster, P.F., Schaefer, K.M., Aiken, G.R., Antweiler, R.C., Dewild, J.F., Gryziec, J.D., Gusmeroli, A., Hugelius, G., Jafarov, E., Krabbenhoft, D.P., Liu, L., Herman-Mercer, N., Mu, C., Roth, D.A., Schaefer, T., Striegl, R.G., Wickland, K.P., Zhang, T., 2018. Permafrost Stores a Globally Significant Amount of Mercury. Geophys. Res. Lett. 45, 1463–1471. https://doi.org/10.1002/2017GL075571

Shafiee, M., Keshavarz, P., Lane, G., Pahwa, P., Szafron, M., Jennings, D., Vatanparast, H., 2022. Food Security Status of Indigenous Peoples in Canada According to the 4 Pillars of Food Security: A Scoping Review. Adv. Nutr. 13, 2537–2558. https://doi.org/10.1093/advances/nmac081

Sharma, S., 2010. Assessing diet and lifestyle in the Canadian Arctic Inuit and Inuvialuit to inform a nutrition and physical activity intervention programme. J. Hum. Nutr. Diet. Off. J. Br. Diet. Assoc. 23 Suppl 1, 5–17. https://doi.org/10.1111/j.1365-277X.2010.01093.x

Sharma, S., Hopping, B.N., Roache, C., Sheehy, T., 2013. Nutrient intakes, major food sources and dietary inadequacies of Inuit adults living in three remote communities in Nunavut, Canada. J. Hum. Nutr. Diet. 26, 578–586. https://doi.org/10.1111/jhn.12091

Sheehy, T., Kolahdooz, F., Roache, C., Sharma, S., 2014. Changing Dietary Patterns in the Canadian Arctic: Frequency of Consumption of Foods and Beverages by Inuit in Three Nunavut Communities. Food Nutr. Bull. 35, 244–252. https://doi.org/10.1177/156482651403500211

Sheehy, T., Roache, C., Sharma, S., 2013. Eating habits of a population undergoing a rapid dietary transition: portion sizes of traditional and non-traditional foods and beverages consumed by Inuit adults in Nunavut, Canada. Nutr. J. 12, 70. https://doi.org/10.1186/1475-2891-12-70

Simmons-Willis, T.A., Koh, A.S., Clarkson, T.W., Ballatori, N., 2002. Transport of a neurotoxicant by molecular mimicry: the methylmercury-L-cysteine complex is a substrate for human L-type large neutral amino acid transporter (LAT) 1 and LAT2. Biochem. J. 367, 239–246. https://doi.org/10.1042/BJ20020841

Sonne, C., Desforges, J.-P., Gustavson, K., Bossi, R., Bonefeld-Jørgensen, E.C., Long, M., Rigét, F.F., Dietz, R., 2023. Assessment of exposure to perfluorinated industrial substances and risk of immune suppression in Greenland and its global context: a mixed-methods study. Lancet Planet. Health 7, e570–e579. https://doi.org/10.1016/S2542-5196(23)00106-7

Sonne, C., Dietz, R., Jenssen, B.M., Lam, S.S., Letcher, R.J., 2021. Emerging contaminants and biological effects in Arctic wildlife. Trends Ecol. Evol. 36, 421–429. https://doi.org/10.1016/j.tree.2021.01.007

Statistics Canada, 2020. Aboriginal Peoples Survey [WWW Document]. URL https://www150.statcan.gc.ca/n1/en/catalogue/89-653-X

Steffen, A., Lehnherr, I., Cole, A., Ariya, P., Dastoor, A., Durnford, D., Kirk, J., Pilote, M., 2015. Atmospheric mercury in the Canadian Arctic. Part I: A review of recent field measurements. Sci. Total Environ. 509–510, 3–15. https://doi.org/10.1016/j.scitotenv.2014.10.109

Stock, N.L., Furdui, V.I., Muir, D.C.G., Mabury, S.A., 2007. Perfluoroalkyl Contaminants in the Canadian Arctic: Evidence of Atmospheric Transport and Local Contamination. Environ. Sci. Technol. 41, 3529–3536. https://doi.org/10.1021/es062709x

Tartu, S., Bourgeon, S., Aars, J., Andersen, M., Lone, K., Jenssen, B.M., Polder, A., Thiemann, G.W., Torget, V., Welker, J.M., Routti, H., 2017. Diet and metabolic state are the main factors determining concentrations of perfluoroalkyl substances in female polar bears from Svalbard. Environ. Pollut. 229, 146–158. https://doi.org/10.1016/j.envpol.2017.04.100

The Galaxy Community, 2022. The Galaxy platform for accessible, reproducible and collaborative biomedical analyses: 2022 update. Nucleic Acids Res. 50, W345–W351. https://doi.org/10.1093/nar/gkac247

The Gene Ontology Consortium, Aleksander, S.A., Balhoff, J., Carbon, S., Cherry, J.M., Drabkin, H.J., Ebert, D., Feuermann, M., Gaudet, P., Harris, N.L., Hill, D.P., Lee, R., Mi, H., Moxon, S., Mungall, C.J., Muruganugan, A., Mushayahama, T., Sternberg, P.W., Thomas, P.D., Van Auken, K., Ramsey, J., Siegele, D.A., Chisholm, R.L., Fey, P., Aspromonte, M.C., Nugnes, M.V., Quaglia, F., Tosatto, S., Giglio, M., Nadendla, S., Antonazzo, G., Attrill, H., dos Santos, G., Marygold, S., Strelets, V., Tabone, C.J., Thurmond, J., Zhou, P., Ahmed, S.H., Asanitthong, P., Luna Buitrago, D., Erdol, M.N., Gage, M.C., Ali Kadhum, M., Li, K.Y.C., Long, M., Michalak, A., Pesala, A., Pritazahra, A., Saverimuttu, S.C.C., Su, R., Thurlow, K.E., Lovering, R.C., Logie, C., Oliferenko, S., Blake, J., Christie, K., Corbani, L., Dolan, M.E., Drabkin, H.J., Hill, D.P., Ni, L., Sitnikov, D., Smith, C., Cuzick, A., Seager, J., Cooper, L., Elser, J., Jaiswal, P., Gupta, P., Jaiswal, P., Naithani, S., Lera-Ramirez, M., Rutherford, K., Wood, V., De Pons, J.L., Dwinell, M.R., Hayman, G.T., Kaldunski, M.L., Kwitek, A.E., Laulederkind, S.J.F., Tutaj, M.A., Vedi, M., Wang, S.-J., D'Eustachio, P., Aimo, L., Axelsen, K., Bridge, A., Hyka-Nouspikel, N., Morgat, A., Aleksander, S.A., Cherry, J.M., Engel, S.R., Karra, K., Miyasato, S.R., Nash, R.S., Skrzypek, M.S., Weng, S., Wong, E.D., Bakker, E., Berardini, T.Z., Reiser, L., Auchincloss, A., Axelsen, K., Argoud-Puy, G., Blatter, M.-C., Boutet, E., Breuza, L., Bridge, A., Casals-Casas, C., Coudert, E., Estreicher, A., Livia Famiglietti, M., Feuermann, M., Gos, A., Gruaz-Gumowski, N., Hulo, C., Hyka-Nouspikel, N., Jungo, F., Le Mercier, P., Lieberherr, D., Masson, P., Morgat, A., Pedruzzi, I., Pourcel, L., Poux, S., Rivoire, C., Sundaram, S., Bateman, A., Bowler-Barnett, E., Bye-A-Jee, H., Denny, P., Ignatchenko, A., Ishtiaq, R., Lock, A., Lussi, Y., Magrane, M., Martin, M.J., Orchard, S., Raposo, P., Speretta, E., Tyagi, N., Warner, K., Zaru, R., Diehl, A.D., Lee, R., Chan, J., Diamantakis, S., Raciti, D., Zarowiecki, M., Fisher, M., James-Zorn, C., Ponferrada, V., Zorn, A., Ramachandran, S., Ruzicka, L., Westerfield, M., 2023. The Gene Ontology knowledgebase in 2023. Genetics 224, iyad031. https://doi.org/10.1093/genetics/iyad031

The UniProt Consortium, 2023. UniProt: the Universal Protein Knowledgebase in 2023. Nucleic Acids Res. 51, D523–D531. https://doi.org/10.1093/nar/gkac1052

Tian, W., Egeland, G.M., Sobol, I., Chan, H.M., 2011. Mercury hair concentrations and dietary exposure among Inuit preschool children in Nunavut, Canada. Environ. Int. 37, 42–48. https://doi.org/10.1016/j.envint.2010.05.017

Turgeon O'Brien, H., Blanchet, R., Gagné, D., Lauzière, J., Vézina, C., Vaissière, É., Ayotte, P., Déry, S., 2012. Exposure to Toxic Metals and Persistent Organic Pollutants in Inuit Children Attending Childcare Centers in Nunavik, Canada. Environ. Sci. Technol. 46, 4614–4623. https://doi.org/10.1021/es203622v

UNEP, 2022. Stockholm Convention on Persistent Organic Pollutants.

Varshavsky, J., Reade, A., Kwiatkowski, C., Merced-Nieves, F.M., Cavalier, H., Schultz, K., Wolffe, T., Pelch, K.E., 2022. The PFAS-Tox Database: A systematic evidence map of health studies on per- and polyfluoroalkyl substances. ISEE Conf. Abstr. 2022. https://doi.org/10.1289/isee.2022.P-0026

Wang, Z., DeWitt, J.C., Higgins, C.P., Cousins, I.T., 2017. A Never-Ending Story of Per- and Polyfluoroalkyl Substances (PFASs)? Environ. Sci. Technol. 51, 2508–2518. https://doi.org/10.1021/acs.est.6b04806

Wania, F., 2007. A Global Mass Balance Analysis of the Source of Perfluorocarboxylic Acids in the Arctic Ocean. Environ. Sci. Technol. 41, 4529–4535. https://doi.org/10.1021/es070124c

Wielsøe, M., Berthelsen, D., Mulvad, G., Isidor, S., Long, M., Bonefeld-Jørgensen, E.C., 2021. Dietary habits among men and women in West Greenland: follow-up on the ACCEPT birth cohort. BMC Public Health 21, 1426. https://doi.org/10.1186/s12889-021-11359-7

Wielsøe, M., Long, M., Bossi, R., Vorkamp, K., Bonefeld-Jørgensen, E.C., 2022. Persistent organic pollutant exposures among Greenlandic adults in relation to lifestyle and diet: New data from the ACCEPT cohort. Sci. Total Environ. 827, 154270. https://doi.org/10.1016/j.scitotenv.2022.154270

Wilkinson, M.D., Dumontier, M., Aalbersberg, Ij.J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., da Silva Santos, L.B., Bourne, P.E., Bouwman, J., Brookes, A.J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C.T., Finkers, R., Gonzalez-Beltran, A., Gray, A.J.G., Groth, P., Goble, C., Grethe, J.S., Heringa, J., 't Hoen, P.A.C., Hooft, R., Kuhn, T., Kok, R., Kok, J., Lusher, S.J., Martone, M.E., Mons, A., Packer, A.L., Persson, B., Rocca-Serra, P., Roos, M., van Schaik, R., Sansone, S.-A., Schultes, E., Sengstag, T., Slater, T., Strawn, G., Swertz, M.A., Thompson, M., van der Lei, J., van Mulligen, E., Velterop, J., Waagmeester, A., Wittenburg, P., Wolstencroft, K., Zhao, J., Mons, B., 2016. The FAIR Guiding Principles for scientific data management and stewardship. Sci. Data 3, 160018. https://doi.org/10.1038/sdata.2016.18

Williams, A.J., Grulke, C.M., Edwards, J., McEachran, A.D., Mansouri, K., Baker, N.C., Patlewicz, G., Shah, I., Wambaugh, J.F., Judson, R.S., Richard, A.M., 2017. The CompTox Chemistry Dashboard: a community data resource for environmental chemistry. J. Cheminformatics 9, 61. https://doi.org/10.1186/s13321-017-0247-6

Wishart, D.S., Feunang, Y.D., Guo, A.C., Lo, E.J., Marcu, A., Grant, J.R., Sajed, T., Johnson, D., Li, C., Sayeeda, Z., Assempour, N., Iynkkaran, I., Liu, Y., Maciejewski, A., Gale, N., Wilson, A., Chin, L., Cummings, R., Le, D., Pon, A., Knox, C., Wilson, M., 2018. DrugBank 5.0: a major update to the DrugBank database for 2018. Nucleic Acids Res. 46, D1074–D1082. https://doi.org/10.1093/nar/gkx1037

Yamashita, M., Yamashita, Y., Suzuki, T., Kani, Y., Mizusawa, N., Imamura, S., Takemoto, K., Hara, T., Hossain, M.A., Yabu, T., Touhata, K., 2013. Selenoneine, a novel selenium-containing compound, mediates detoxification mechanisms against methylmercury accumulation and toxicity in zebrafish embryo. Mar. Biotechnol. N. Y. N 15, 559–570. https://doi.org/10.1007/s10126-013-9508-1

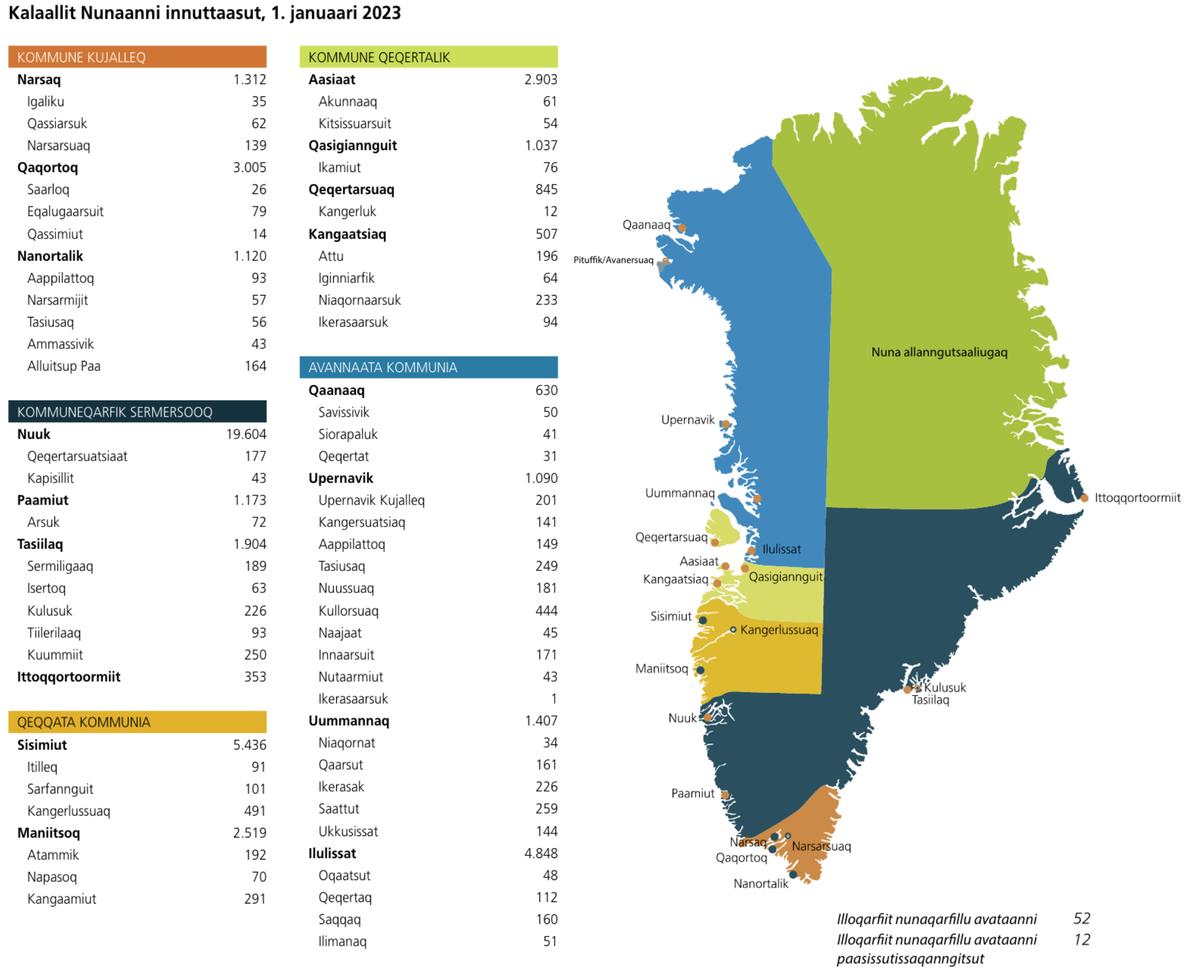
Yuan, D., Ahamed, A., Burgin, J., Cummins, C., Devraj, R., Gueye, K., Gupta, D., Gupta, V., Haseeb, M., Ihsan, M., Ivanov, E., Jayathilaka, S., Kadhirvelu, V.B., Kumar, M., Lathi, A., Leinonen, R., McKinnon, J., Meszaros, L., O'Cathail, C., Ouma, D., Paupério, J., Pesant, S., Rahman, N., Rinck, G., Selvakumar, S., Suman, S., Sunthornyotin, Y., Ventouratou, M., Vijayaraja, S., Waheed, Z., Woollard, P., Zyoud, A., Burdett, T., Cochrane, G., 2024. The European Nucleotide Archive in 2023. Nucleic Acids Res. 52, D92–D97. https://doi.org/10.1093/nar/gkad1067

Zdrazil, B., Felix, E., Hunter, F., Manners, E.J., Blackshaw, J., Corbett, S., de Veij, M., Ioannidis, H., Lopez, D.M., Mosquera, J.F., Magarinos, M.P., Bosc, N., Arcila, R., Kizilören, T., Gaulton, A., Bento, A.P., Adasme, M.F., Monecke, P., Landrum, G.A., Leach, A.R., 2024. The ChEMBL Database in 2023: a drug discovery platform spanning multiple bioactivity data types and time periods. Nucleic Acids Res. 52, D1180–D1192. https://doi.org/10.1093/nar/gkad1004

Zhang, Y., Song, Z., Huang, S., Zhang, P., Peng, Y., Wu, P., Gu, J., Dutkiewicz, S., Zhang, H., Wu, S., Wang, F., Chen, L., Wang, S., Li, P., 2021. Global health effects of future atmospheric mercury emissions. Nat. Commun. 12, 3035. https://doi.org/10.1038/s41467-021-23391-7

6 Appendix

6.1 Appendix A – Data Selection



Kalaallit Nunaanni innuttaasut, 1. januaari 2023

KOMMUNE KUJALLEQ	
Narsaq	1.312
Igaliku	35
Qassiarsuk	62
Narsarsuaq	139
Qaqortoq	3.005
Saarloq	26
Eqalugaarsuit	79
Qassimiut	14
Nanortalik	1.120
Aappilattoq	93
Narsarmijit	57
Tasiusaq	56
Ammassivik	43
Alluitsup Paa	164

KOMMUNEQARFIK SERMERSOOQ	
Nuuk	19.604
Qeqertarsuatsiaat	177
Kapisillit	43
Paamiut	1.173
Arsuk	72
Tasiilaq	1.904
Sermiligaaq	189
Isertoq	63
Kulusuk	226
Tiilerilaaq	93
Kuummiit	250
Ittoqqortoormiit	353

QEQQATA KOMMUNIA	
Sisimiut	5.436
Itilleq	91
Sarfannguit	101
Kangerlussuaq	491
Maniitsoq	2.519
Atammik	192
Napasoq	70
Kangaamiut	291

KOMMUNE QEQERTALIK	
Aasiaat	2.903
Akunnaaq	61
Kitsissuarsuit	54
Qasigiannguit	1.037
Ikamiut	76
Qeqertarsuaq	845
Kangerluk	12
Kangaatsiaq	507
Attu	196
Iginniarfik	64
Niaqornaarsuk	233
Ikerasaarsuk	94

AVANNAATA KOMMUNIA	
Qaanaaq	630
Savissivik	50
Siorapaluk	41
Qeqertat	31
Upernavik	1.090
Upernavik Kujalleq	201
Kangersuatsiaq	141
Aappilattoq	149
Tasiusaq	249
Nuussuaq	181
Kullorsuaq	444
Naajaat	45
Innaarsuit	171
Nutaarmiut	43
Ikerasaarsuk	1
Uummannaq	1.407
Niaqornat	34
Qaarsut	161
Ikerasak	226
Saattut	259
Ukkusissat	144
Ilulissat	4.848
Oqaatsut	48
Qeqertaq	112
Saqqaq	160
Ilimanaq	51

Illoqarfiit nunaqarfillu avataanni	*52*
Illoqarfiit nunaqarfillu avataanni paasissutissaqanngitsut	*12*

Figure S1 Administrative regions of Greenland and most relevant settlements. The legacy region of Avanersuaq mentioned in this manuscript covers the North portion of the Avannaata and Qeqertalik regions. From Grønlands Statistik, 2023.

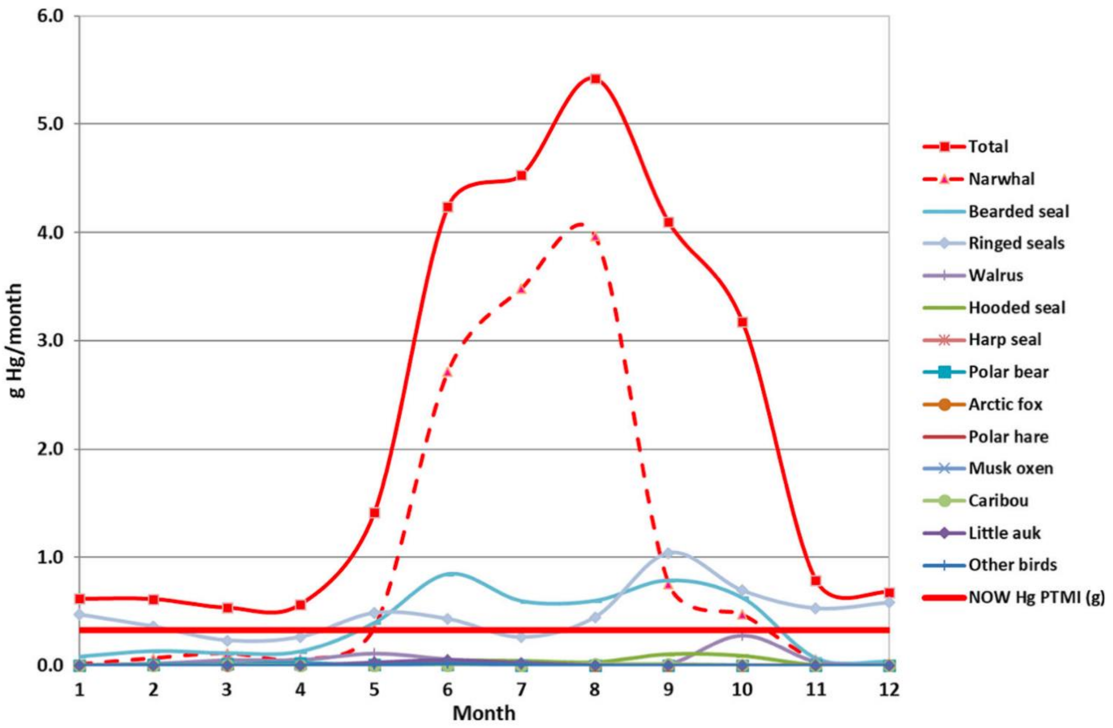


Figure S2 Derived Hg intake from different species in Avanersuaq. Each line represents a different species. A significant peak due to large narwhal intake occurs during the months of June-August. The solid red line indicates provisional tolerable monthly intake (PTMI) for the whole North Water Polynya (NOW) population, derived from the EFSA TWI (1.3 µg/kg bw). From Dietz et al., 2018.

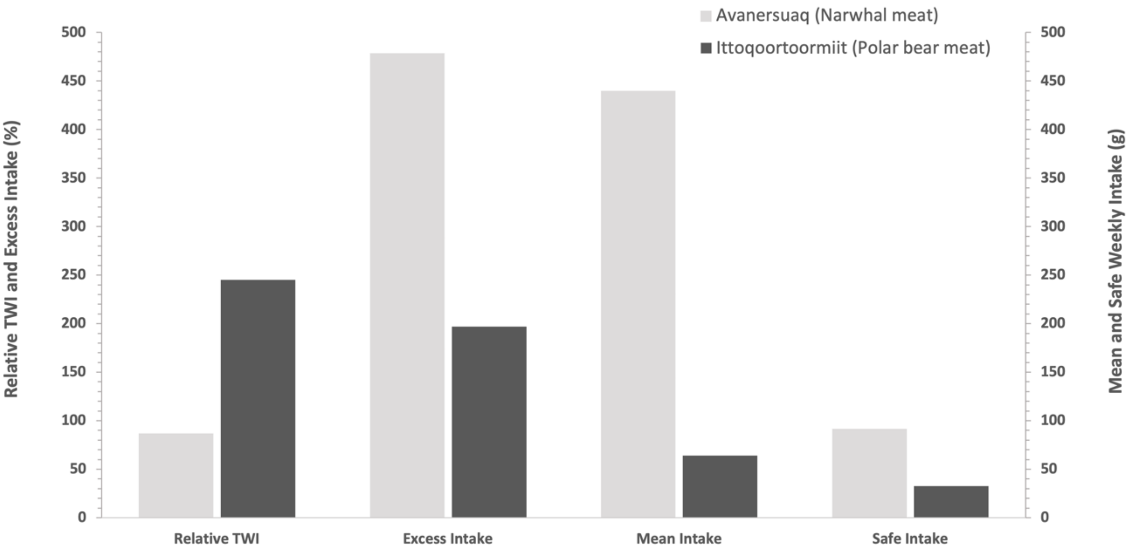


*Figure S3 Dietary intake versus contaminant loads comparison in Avanersuaq and Ittoqoortoormiit. **Relative TWI** is the proportion of contaminant in 1 gram of meat over the TWI. **Excess Intake** is the proportion of mean weekly intake over the safe weekly intake amount of the relevant species. Avanersuaq: high intake with moderate loads pattern. Ittoqoortoormiit: moderate intake with high loads pattern. Data from Dietz et al., 2018 and Sonne et al., 2023.*

Table S1 Summarized liver and meat Hg exposure in Artic marine mammal species from Canada and Greenland. Meat concentrations are provided for comparison and correspond to a different sampling period.

Species	**Location**	**Sampling**		**Hg (µg/g ww)**			**References**
		Year	*N*	*Liver* [a]	*N*	*Meat* [b]	
Polar bear	Greenland	2000-2018	217	24.41	36	0.057	Dietz et al., 2018, 2022
	Canada	2006-2017	249	40.89			Dietz et al., 2022
Bearded seal	Greenland	2015	6	1.82			Dietz et al., 2022
	Canada	1973-1974	58			0.310	Dietz et al., 2018
Harp seal	Greenland	2001-2018	85	2.3	70	0.323	Dietz et al., 2018, 2022
Hooded seal	Greenland	2000-2018	127	48.37	45	0.548	Dietz et al., 2018, 2022
Ringed seal	Greenland	2000-2018	610	5.37	14	0.241	Dietz et al., 2018, 2022
	Canada	2000-2018	1069	8.32			Dietz et al., 2022
Beluga	Canada	2001-2017	636	10.73	24	0.576	Dietz et al., 2018, 2022
Harbor porpoise	Greenland	1998-2018	76	17.60	40	0.587	Dietz et al., 2018, 2022
Narwhal	Greenland	2010-2015	42	11.57	66	1.132	Dietz et al., 2018, 2022

[a] Liver loads include individuals from all age groups (adult, subadult, juvenile, yearling). Brackets: adults only.

[b] Greenland muscle loads obtained in 1984-2015 from Dietz et al. (2018) and personal communication.

Table S2 Liver Hg exposure in Artic marine mammal species at various geographical and temporal intervals in Greenland. Concentrations are averaged median values from Dietz et al., 2022.

Species	**Location** [a]	**Sampling**		**Hg (µg/g ww)**	**References**
		Year	*N*	*Liver* [a]	
Polar bear	Qaanaaq (North)	2000-2013	6	45.34	Dietz et al., 2022
	Davis Strait	2000-2018	6	28.85	Dietz et al., 2022
	Ittoqoortoormiit	2000-2018	205	15.96	Dietz et al., 2022
Bearded seal	Ittoqoortoormiit	2015	6	1.82	Dietz et al., 2022
Harp seal	Davis Strait	2005-2009	20	6.49	Dietz et al., 2022
	Ittoqoortoormiit	2015	6	0.78	Dietz et al., 2022
	Greenland Sea	2001-2018	59	0.585	Dietz et al., 2022
Hooded seal	Davis Strait	2000-2015	21	78.90	Dietz et al., 2022
	Ittoqoortoormiit	2015	5	23.06	Dietz et al., 2022
	Greenland Sea	2002-2019	101	39.43	Dietz et al., 2022
Ringed seal	Qaanaaq (North)	2004-2018	246	4.52	Dietz et al., 2022
	Qeqertarsuaq	2000-2015	203	0.92	Dietz et al., 2022
	Ittoqoortoormiit	2000-2018	161	7.71	Dietz et al., 2022
Harbor porpoise	Danish Straits	1998-2018	34	13.59	Dietz et al., 2022
	Maniitsoq (South)	2009	42	5.0	Dietz et al., 2022
Narwhal	Qaanaaq (North)	2010-2015	20	15.76	Dietz et al., 2022
	Ittoqoortoormiit	2015	22	7.39	Dietz et al., 2022

[a] Locations are sorted, for each species, from West to East based on their approximate longitude.

[b] Liver loads include individuals from all age groups (adult, subadult, juvenile, yearling).

Table S3 Liver Hg exposure in marine mammal species at various geographical and temporal intervals in Canada. Concentrations are averaged median values from Dietz et al., 2022.

Species	**Location** [a]	**Sampling**		**Hg (µg/g ww)**	**References**
		Year	*N*	*Liver* [a]	
Polar bear	Beaufort Sea	2001-2017	17	95.41	Dietz et al., 2022
	Gulf of Boothia	2007	6	60.77	Dietz et al., 2022
	Jones Sound	2007-2008	11	67.16	Dietz et al., 2022
	Hudson Bay	2006-2017	203	7.79	Dietz et al., 2022
	Baffin Bay	2007-2008	12	49.47	Dietz et al., 2022
Ringed seal	Beaufort Sea	2001-2017	103	18.84	Dietz et al., 2022
	Sachs Harbor	2001-2017	83	35.55	Dietz et al., 2022
	Gjoahaven	2004-2009	31	4.65	Dietz et al., 2022
	Resolute	2000-2017	154	7.24	Dietz et al., 2022
	Arctic Bay	2000-2009	59	4.60	Dietz et al., 2022
	Hudson Bay	2006-2017	245	9.98	Dietz et al., 2022
	Grise Fjord	2003-2008	50	8.35	Dietz et al., 2022
	Inukjuaq	2002-2007	37	2.89	Dietz et al., 2022
	Pond Inlet	2000-2009	29	5.36	Dietz et al., 2022
	Kangiqsujuaq	2002	9	1.30	Dietz et al., 2022
	Quaqtaq	2002	14	5.35	Dietz et al., 2022
	Kangiqsualujjuaq	2002	4	4.82	Dietz et al., 2022
	Pangniertung	2002-2011	48	2.37	Dietz et al., 2022
	Qikiqtarjuaq	2005	26	6.44	Dietz et al., 2022
	Labrador Sea	2005-2018	99	4.66	Dietz et al., 2022
Beluga	Beaufort Sea	2001-2017	412	14.95	Dietz et al., 2022
	Hudson Bay	2002-2016	181	9.06	Dietz et al., 2022
	Cumberland Sound	2002-2010	43	8.18	Dietz et al., 2022

[a] Locations are sorted, for each species, from West to East based on their approximate longitude.

[b] Liver loads include individuals from all age groups (adult, subadult, juvenile, yearling).

Table S4 Hg exposure in kidney, liver, and muscle from different reindeer herds in Greenland. Table adapted from unpublished work by Velasco, 2022 (AT-330).

Herd Location	**Sampling**			**Hg (µg/g dw)**			**Reference**
	Season	*Year*	*N*	*Kidney*	*Liver*	*Muscle*	
Kangerlussuaq	Mar	2009	41	1.21	0.24	0.02	Gamberg et al., 2016
Akia	Mar-Apr	2008	40	2.22	0.46	0.05	Gamberg et al., 2016
Kangerlussuaq	Nov	1996	23		0.143[a]	0.016[a]	Aastrup et al., 2000
	Mar	1997	24		0.222[a]	0.039[a]	
Akia	Nov	1996	24		0.426[a]	0.118[a]	Aastrup et al., 2000
	Mar	1997	25		0.963[a]	0.039[a]	
Itinnera	Sep	1995	6		0.175[a]	0.012[a]	Aastrup et al., 2000
	Sep	1996	7		0.243[a]	0.012[a]	
	Sep	1997	10		0.204[a]	0.024[a]	
Isortoq	Mar	1995	15		2.212[a]	0.169[a]	Aastrup et al., 2000

[a] Derived dry weight concentrations using the moisture factors in the reference publication. Liver: 3.58; Muscle: 3.93.

Table S5 Hg exposure in kidney, liver, and muscle from different caribou herds in Canada. Table adapted from unpublished work by Velasco, 2022 (AT-330).

Herd Location [a]	**Sampling**			**Hg (µg/g dw)**			**Reference**
	Season	*Year*	*N*	*Kidney*	*Liver*	*Muscle*	
Porcupine	All	1991-2016	509	1.65			Gamberg et al., 2020
Cape Bathurst	All	1994-2000	11	6.80			Gamberg et al., 2020
Bluenose	Mar-Sep	2005-2013	38	4.15			Gamberg et al., 2020
Bathurst	All	1992-2009	108	3.05			Gamberg et al., 2020
Beverly	Mar-Sep	1994-2014	67	6.70			Gamberg et al., 2020
Qamanirjuaq	All	1992-2016	130	9.40			Gamberg et al., 2020
Baffin Island	Mar-Sep	1992-1999	43	6.85			Gamberg et al., 2020
Mackenzie Mountains	Sep-Dec	2010-2013	36	0.84[c]		0.02[c]	Larter et al., 2016
Leaf River	Dec-May	1994-1996	264	6.51[bd]	2.46[bd]	0.11[bd]	Robillard et al., 2002
Torngat Mountains	Dec-May	1994-1996	53	2.78[bd]	1.46[bd]	0.08[bd]	Robillard et al., 2002
Banks Island	Sep-Nov	1991	20	5.43			Larter and Nagy, 2000
Bluenose	Feb	1995	20	10.45			Larter and Nagy, 2000
Bathurst	Jul- Sep	1992	20	2.76[c]	0.55[c]		Elkin and Bethke, 1995
Arviat	Apr	1992	10	14.14[c]	3.14[c]		Elkin and Bethke, 1995
Southampton	Nov	1991	10	10.94[c]			Elkin and Bethke, 1995
Cape Dorset	Apr	1992	10	6.59[c]	1.53[c]		Elkin and Bethke, 1995
Kimmirut	Apr	1992	10	13.14[c]	2.19[c]		Elkin and Bethke, 1995

[a] Locations are sorted both chronologically and geographically from West to East.

[b] Averaged concentrations from adult and cub samples.

[c] Derived dry weight concentrations using the moisture values provided in the reference.

[d] Derived dry weight concentrations using organ values in Northern Quebec from Crête et al., 1989.

Table S6 Summarized mean PFOS exposure in liver, meat, blood, and blubber from Arctic marine mammal species in Canada and Greenland.

Species	**Location**	**Sampling**		**PFOS [a]**				**References**
		Year	*N*	*Blood*	*Blubber*	*Liver*	*Meat*	
Polar bear	Greenland	2006-2019	241	128.0	15.4	2.6 [b]	13.35	Muir et al., 2019 Sonne et al., 2023
	Canada	2002	7			3.1 [b]		Martin et al., 2004
Ringed seal	Greenland	1984-2019	54			64.0	5.21	Muir et al., 2019 Sonne et al., 2023
	Canada	2009-2013	119			14.52		Muir et al., 2019
Beluga	Canada	1999-2003	55	12.15	2.23	32.35	1.18	Muir et al., 2019
Orca	Greenland	2012-2013	6			237.0		Muir et al., 2019

[a] Loads include linear and branched PFOS. All concentrations except for those marked as (b) are given in ng/g ww.

[b] Extreme liver PFOS load given in µg/g ww.

Table S7 Mean PFOS exposure in kidney, liver, and meat from different caribou/reindeer herds in Canada and Greenland.

Herd Location [a]	**Sampling**		**PFOS (ng/g ww)**			**References**
	Year	*N*	*Kidney*	*Liver*	*Meat*	
Porcupine	2007-2008	30	0.02	0.645		Muir et al., 2019
Bathurst	2008	16		2.18	0.08	Muir et al., 2019
Qamanirjuaq	2006-2008	21	0.04	1.81		Muir et al., 2019
Nunavut	1997-1998	4		3.85		Ostertag et al., 2009
South Greenland	2008	10		[b] 1.27		Muir et al., 2019

[a] Locations are sorted from West to East.

[b] Loads are of branched PFOS.

6.2 Appendix B – Database Schema

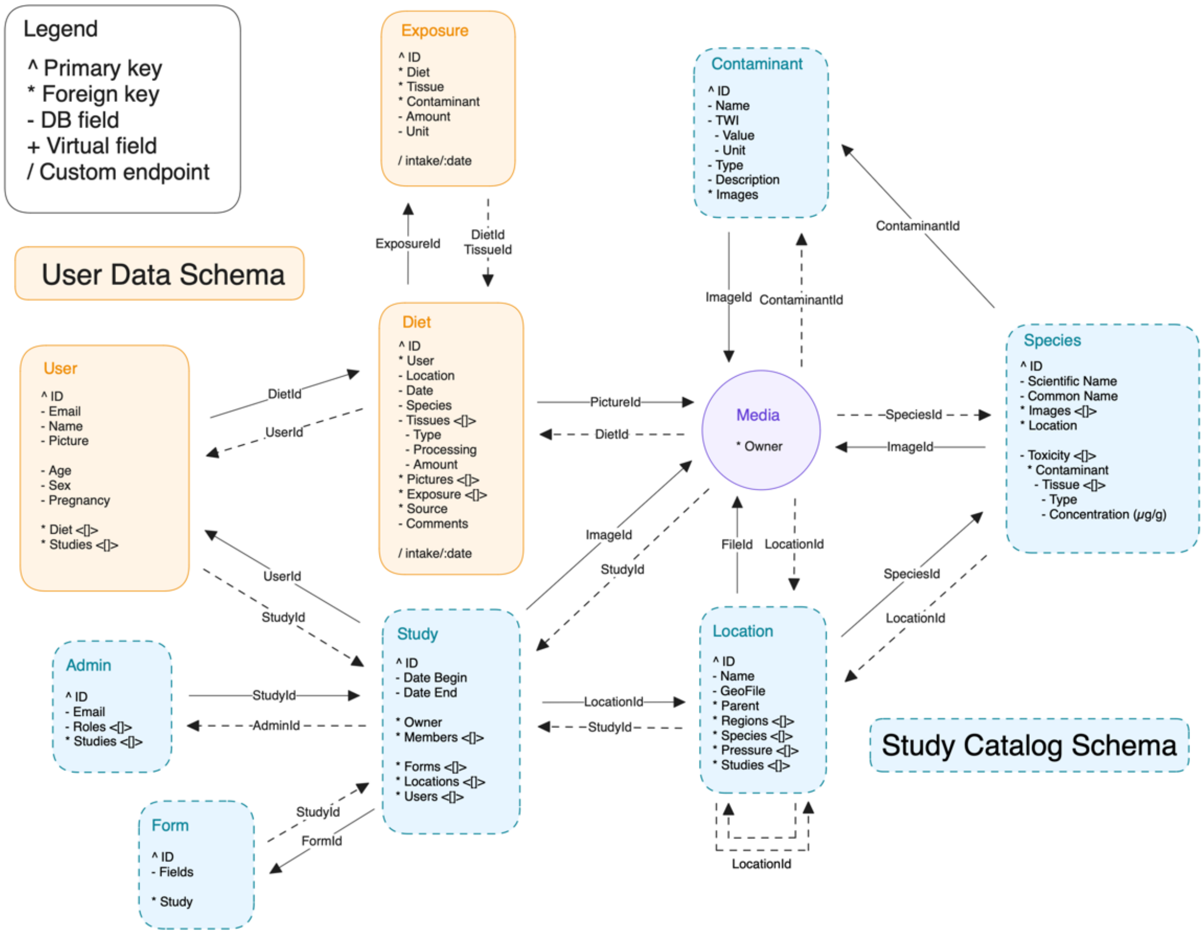
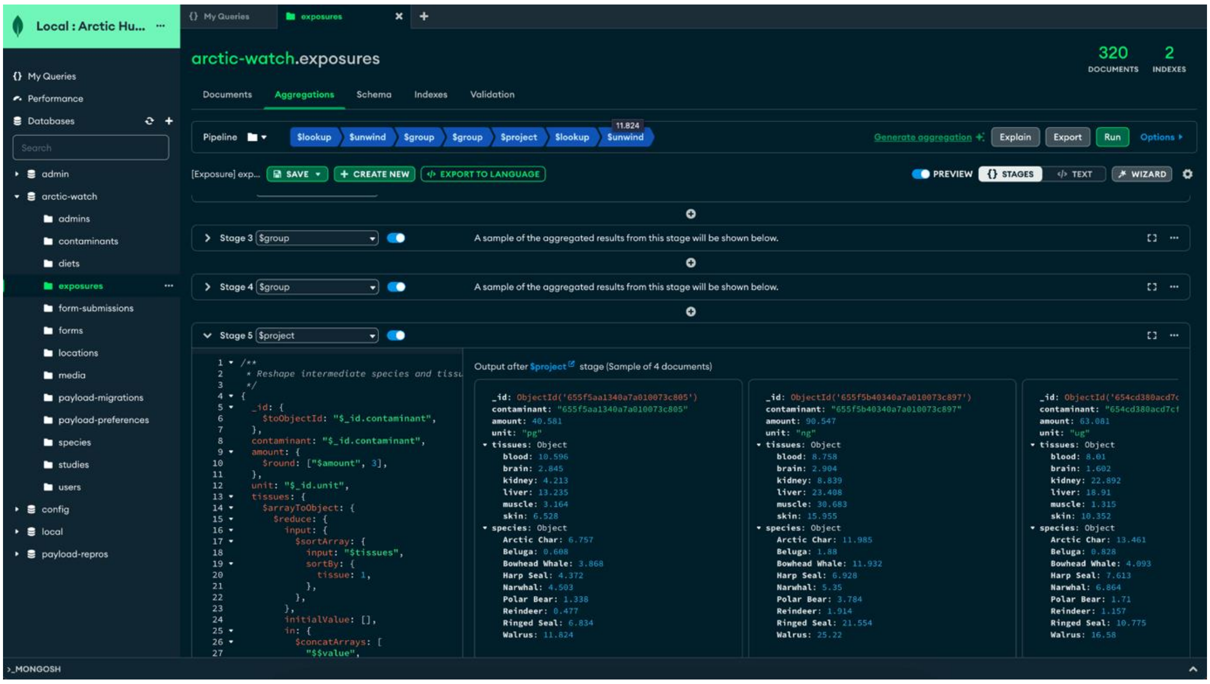


Figure S4 Database schema. Boxes represent document collections; Solid: User Data; Dashed: Study Catalog. Arrows indicate relationships via primary and foreign keys; Solid: primary relation; Dashed: reverse relation. Shapes signify the data storage solution; Box: MongoDB; Circle: Object Storage. Symbols indicate specific field properties from the document perspective; Caret (^): primary key; Asterisk (*): foreign document key; Dash (-): regular document field; Plus (+): virtual field; Slash (/): custom endpoint.



A sample of the aggregated results from this stage will be shown below.

A sample of the aggregated results from this stage will be shown below.

```
/**
 * Reshape intermediate species and tissu
 */
{
  _id: {
    $toObjectId: "$_id.contaminant",
  },
  contaminant: "$_id.contaminant",
  amount: {
    $round: ["$amount", 3],
  },
  unit: "$_id.unit",
  tissues: {
    $arrayToObject: {
      $reduce: {
        input: {
          $sortArray: {
            input: "$tissues",
            sortBy: {
              tissue: 1,
            },
          },
        },
        initialValue: [],
        in: {
          $concatArrays: [
            "$$value",
```

Output after $project stage (Sample of 4 documents)

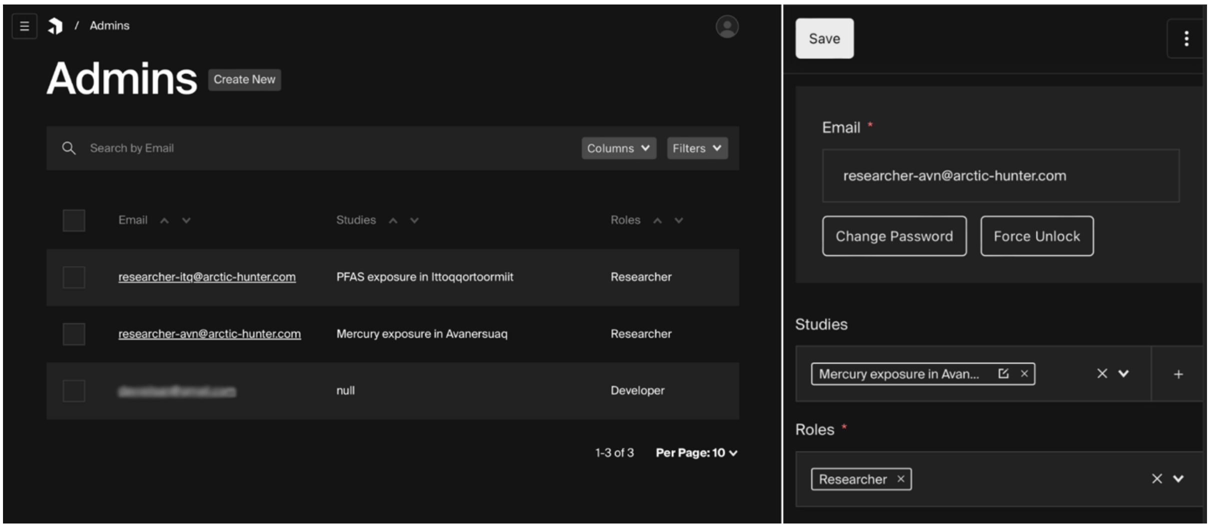
```
_id: ObjectId('655f5aa1340a7a010073c805')
contaminant: "655f5aa1340a7a010073c805"
amount: 40.581
unit: "pg"
▾ tissues: Object
   blood: 10.596
   brain: 2.845
   kidney: 4.213
   liver: 13.235
   muscle: 3.164
   skin: 6.528
▾ species: Object
   Arctic Char: 6.757
   Beluga: 0.608
   Bowhead Whale: 3.868
   Harp Seal: 4.372
   Narwhal: 4.503
   Polar Bear: 1.338
   Reindeer: 0.477
   Ringed Seal: 6.834
   Walrus: 11.824
```

```
_id: ObjectId('655f5b40340a7a010073c897')
contaminant: "655f5b40340a7a010073c897"
amount: 90.547
unit: "ng"
▾ tissues: Object
   blood: 8.758
   brain: 2.904
   kidney: 8.839
   liver: 23.408
   muscle: 30.683
   skin: 15.955
▾ species: Object
   Arctic Char: 11.985
   Beluga: 1.88
   Bowhead Whale: 11.932
   Harp Seal: 6.928
   Narwhal: 5.35
   Polar Bear: 3.784
   Reindeer: 1.914
   Ringed Seal: 21.554
   Walrus: 25.22
```

```
_id: ObjectId('654cd380acd7c
contaminant: "654cd380acd7c
amount: 63.081
unit: "ug"
▾ tissues: Object
   blood: 8.01
   brain: 1.602
   kidney: 22.892
   liver: 18.91
   muscle: 1.315
   skin: 10.352
▾ species: Object
   Arctic Char: 13.461
   Beluga: 0.828
   Bowhead Whale: 4.093
   Harp Seal: 7.613
   Narwhal: 6.864
   Polar Bear: 1.71
   Reindeer: 1.157
   Ringed Seal: 10.775
   Walrus: 16.58
```

Figure S5 Compass application user interface. The main area shows the various stages of an aggregation pipeline to search and process dietary exposure data. On the left, a navigation drawer allows to select database collections. A tab system at the top efficiently separates workspaces. An AI supports generation of new queries as well as explaining existing pipelines. A different dataset with additional species is used in this example, using randomized daily intake patterns, to better showcase the summarization of contaminant loads.

6.3 Appendix C – Content Management System



Email	Studies	Roles
researcher-itq@arctic-hunter.com	PFAS exposure in Ittoqqortoormiit	Researcher
researcher-avn@arctic-hunter.com	Mercury exposure in Avanersuaq	Researcher
[redacted]	null	Developer

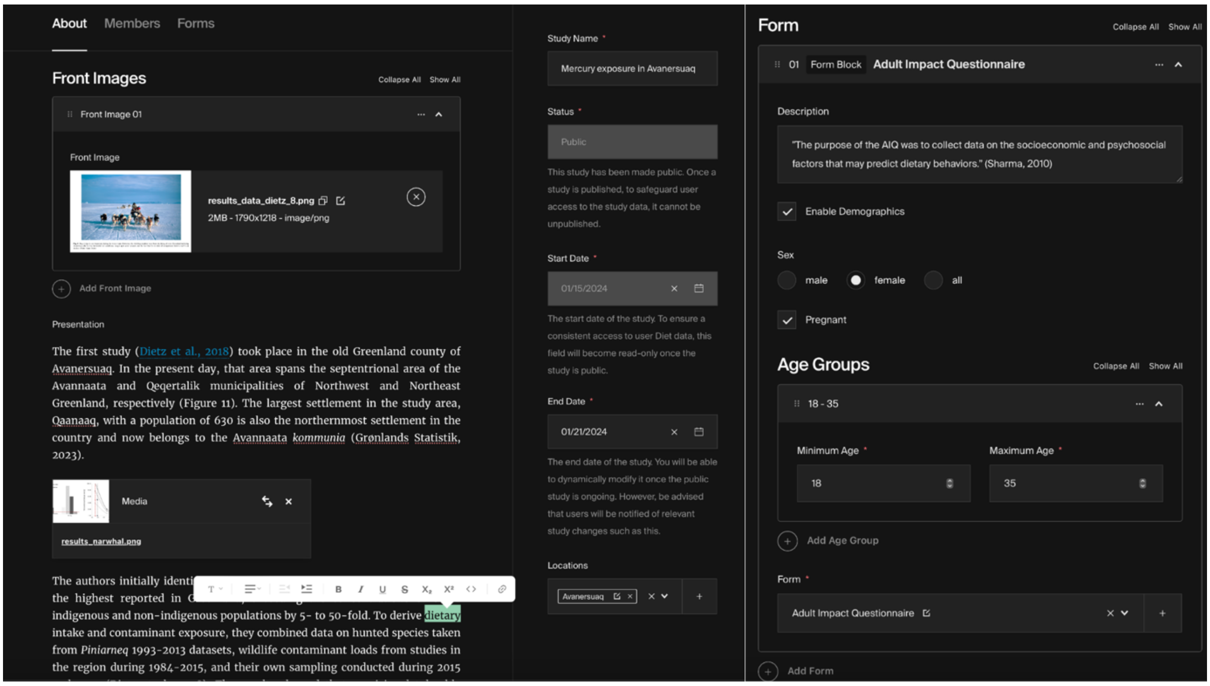
1-3 of 3 Per Page: 10

Email *: researcher-avn@arctic-hunter.com

Studies: Mercury exposure in Avan...

Roles *: Researcher

Figure S6 *Admin collection. Left: admins list view. Right: researcher profile with email, study membership, and database roles fields.*



results_data_dietz_8.png
2MB - 1790x1218 - image/png

Presentation

The first study (Dietz et al., 2018) took place in the old Greenland county of Avanersuaq. In the present day, that area spans the septentrional area of the Avannaata and Qeqertalik municipalities of Northwest and Northeast Greenland, respectively (Figure 11). The largest settlement in the study area, Qaanaaq, with a population of 630 is also the northernmost settlement in the country and now belongs to the Avannaata *kommunia* (Grønlands Statistik, 2023).

results_narwhal.png

The authors initially identi

the highest reported in G

indigenous and non-indigenous populations by 5- to 50-fold. To derive dietary intake and contaminant exposure, they combined data on hunted species taken from *Piniarneq* 1993-2013 datasets, wildlife contaminant loads from studies in the region during 1984-2015, and their own sampling conducted during 2015

Study Name *: Mercury exposure in Avanersuaq

Status *: Public

This study has been made public. Once a study is published, to safeguard user access to the study data, it cannot be unpublished.

Start Date *: 01/15/2024

The start date of the study. To ensure a consistent access to user Diet data, this field will become read-only once the study is public.

End Date *: 01/21/2024

The end date of the study. You will be able to dynamically modify it once the public study is ongoing. However, be advised that users will be notified of relevant study changes such as this.

Locations: Avanersuaq

01 Form Block Adult Impact Questionnaire

Description: "The purpose of the AIQ was to collect data on the socioeconomic and psychosocial factors that may predict dietary behaviors." (Sharma, 2010)

☑ Enable Demographics

Sex: ○ male ● female ○ all

☑ Pregnant

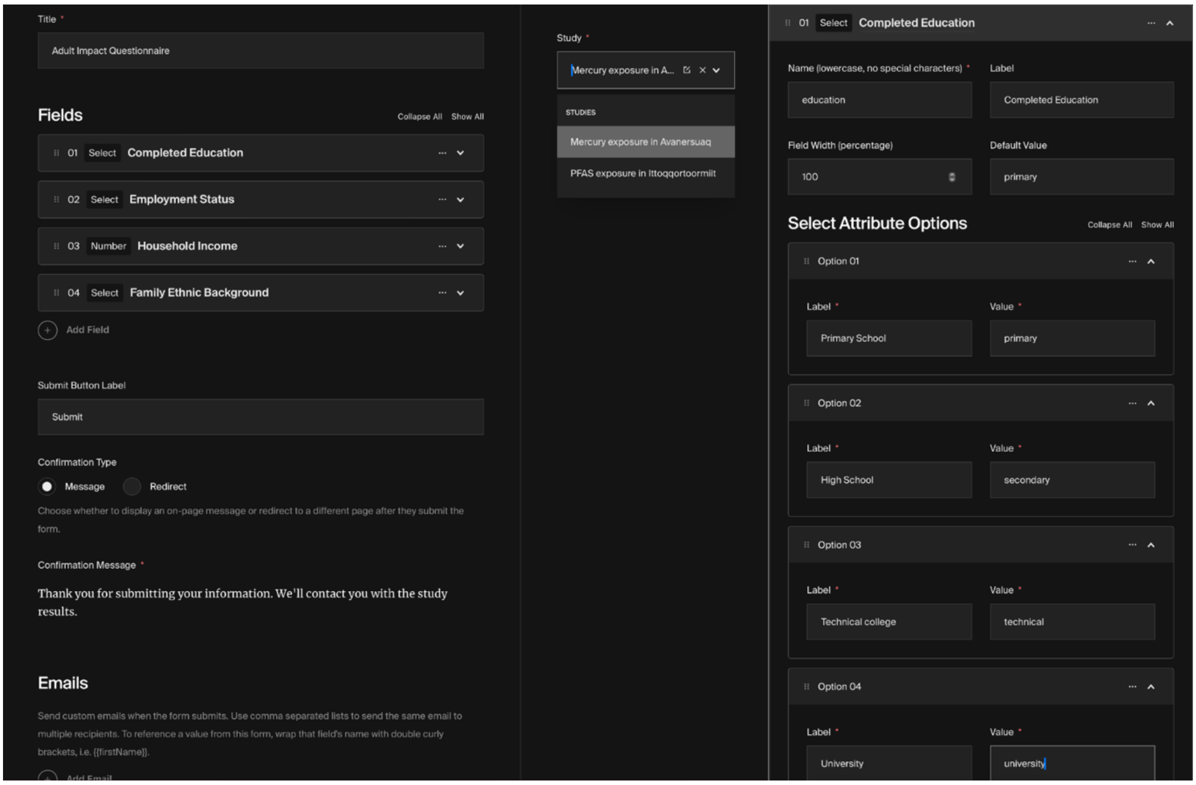
18 - 35

Minimum Age *: 18

Maximum Age *: 35

Form *: Adult Impact Questionnaire

Figure S7 *Study document interface. Left: custom study description and cover images; the side column displays study name, visibility status, duration, and locations. Right: questionnaire activation with custom title, description, and target demographics.*



Title *: Adult Impact Questionnaire

01 Select Completed Education
02 Select Employment Status
03 Number Household Income
04 Select Family Ethnic Background

Submit Button Label: Submit

Confirmation Type: ● Message ○ Redirect

Choose whether to display an on-page message or redirect to a different page after they submit the form.

Confirmation Message *: Thank you for submitting your information. We'll contact you with the study results.

Send custom emails when the form submits. Use comma separated lists to send the same email to multiple recipients. To reference a value from this form, wrap that field's name with double curly brackets, i.e. {{firstName}}.

Study *: Mercury exposure in A...

Mercury exposure in Avanersuaq
PFAS exposure in Ittoqqortoormiit

01 Select Completed Education

Name (lowercase, no special characters) *: education
Label: Completed Education
Field Width (percentage): 100
Default Value: primary

Option 01 — Label *: Primary School; Value *: primary
Option 02 — Label *: High School; Value *: secondary
Option 03 — Label *: Technical college; Value *: technical
Option 04 — Label *: University; Value *: university

Figure S8 Creation of a new Form collection document. Left: questionnaire title, fields, confirmation message or redirect, emails, and currently assigned study. Right: customization options for a field of type select.

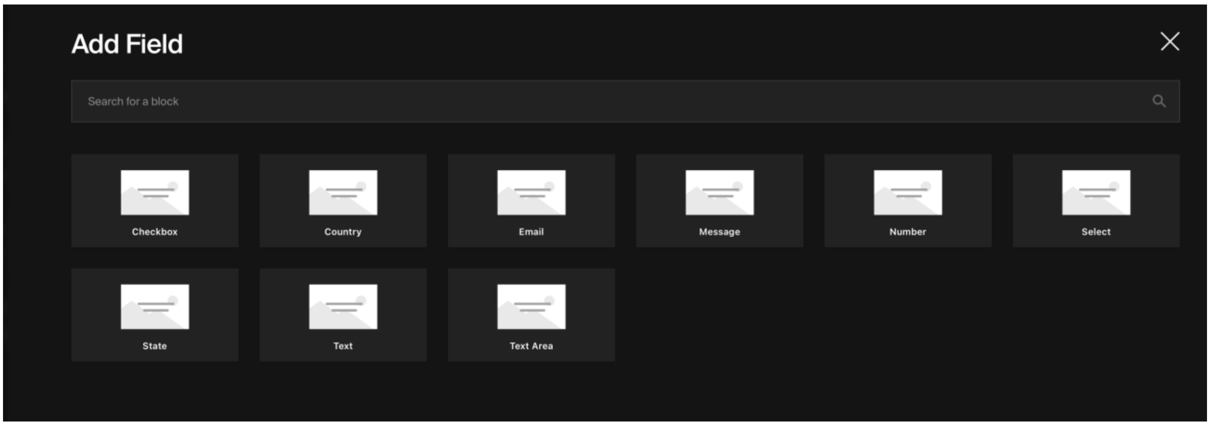
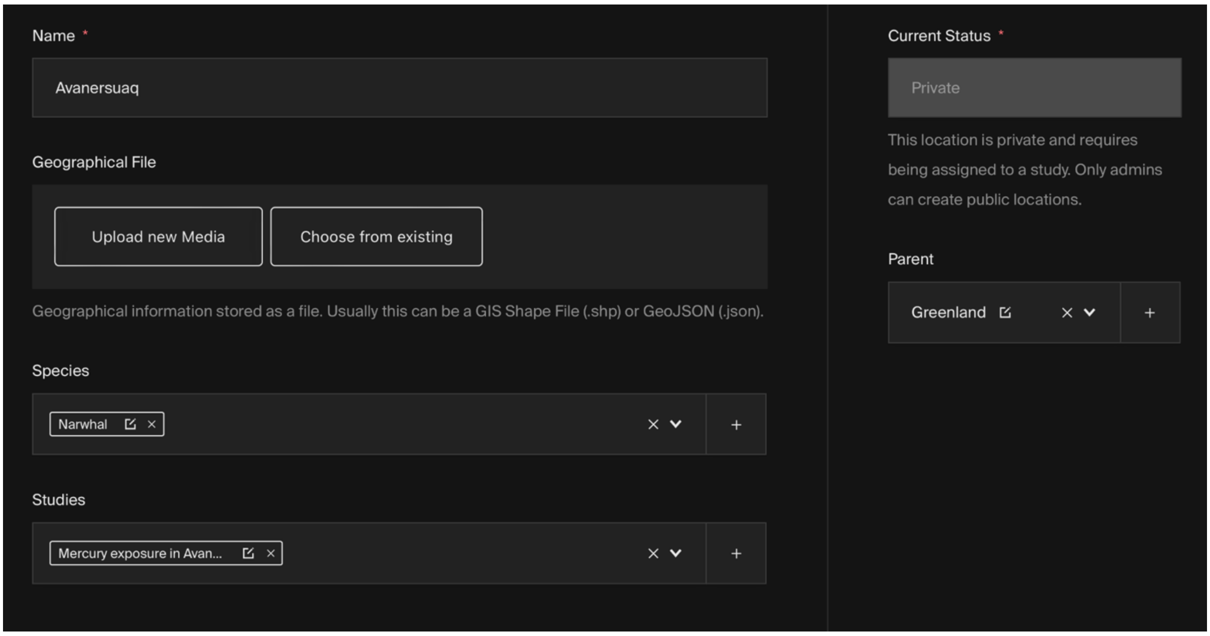


Figure S9 Available form fields. A search bar allows to quickly search for a specific form field component. Currently, nine basic types are available.



Name *

Avanersuaq

Geographical File

Geographical information stored as a file. Usually this can be a GIS Shape File (.shp) or GeoJSON (.json).

Species

Narwhal

Studies

Mercury exposure in Avan...

Current Status *

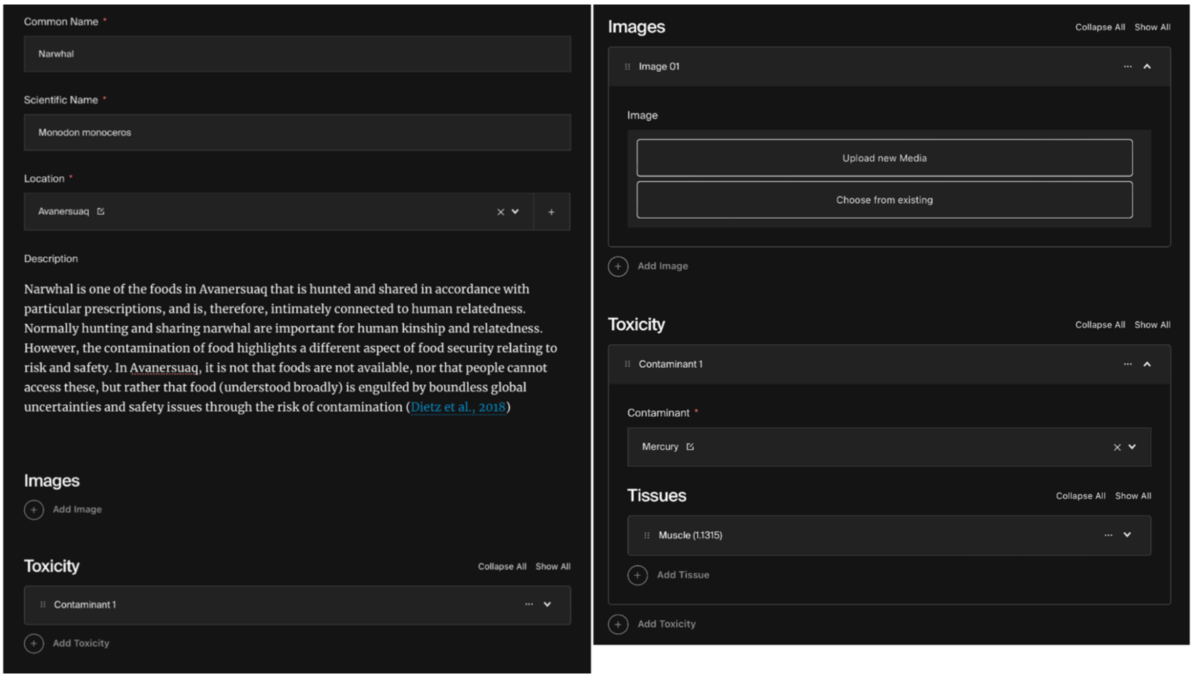
Private

This location is private and requires being assigned to a study. Only admins can create public locations.

Parent

Greenland

Figure S10 Location collection document. The main area shows the location name, species, and assigned study. A GIS file can be uploaded to support geospatial features in the frontend. The right-side area displays the location visibility status and parent region.



Common Name *

Narwhal

Scientific Name *

Monodon monoceros

Location *

Avanersuaq

Description

Narwhal is one of the foods in Avanersuaq that is hunted and shared in accordance with particular prescriptions, and is, therefore, intimately connected to human relatedness. Normally hunting and sharing narwhal are important for human kinship and relatedness. However, the contamination of food highlights a different aspect of food security relating to risk and safety. In Avanersuaq, it is not that foods are not available, nor that people cannot access these, but rather that food (understood broadly) is engulfed by boundless global uncertainties and safety issues through the risk of contamination (Dietz et al., 2018)

Images

Toxicity

Contaminant 1

Images

Image 01

Image

Toxicity

Contaminant 1

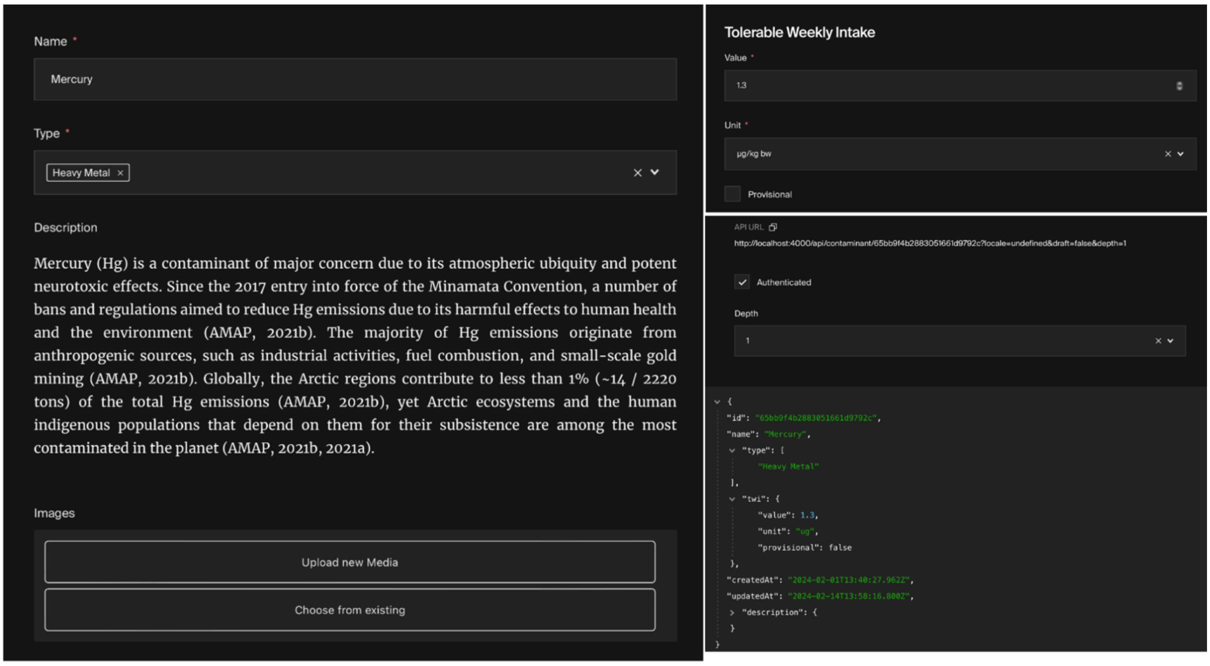
Contaminant *

Mercury

Tissues

Muscle (1.1315)

Figure S11 Species collection document. Left: common and scientific names, assigned location, and description. Right: tissue loads and optional images.



Name *

Mercury

Type *

Heavy Metal

Description

Mercury (Hg) is a contaminant of major concern due to its atmospheric ubiquity and potent neurotoxic effects. Since the 2017 entry into force of the Minamata Convention, a number of bans and regulations aimed to reduce Hg emissions due to its harmful effects to human health and the environment (AMAP, 2021b). The majority of Hg emissions originate from anthropogenic sources, such as industrial activities, fuel combustion, and small-scale gold mining (AMAP, 2021b). Globally, the Arctic regions contribute to less than 1% (~14 / 2220 tons) of the total Hg emissions (AMAP, 2021b), yet Arctic ecosystems and the human indigenous populations that depend on them for their subsistence are among the most contaminated in the planet (AMAP, 2021b, 2021a).

Images

Tolerable Weekly Intake

Value *

1.3

Unit *

μg/kg bw

☐ Provisional

API URL

http://localhost:4000/api/contaminant/65bb9f4b2883051661d9792c?locale=undefined&draft=false&depth=1

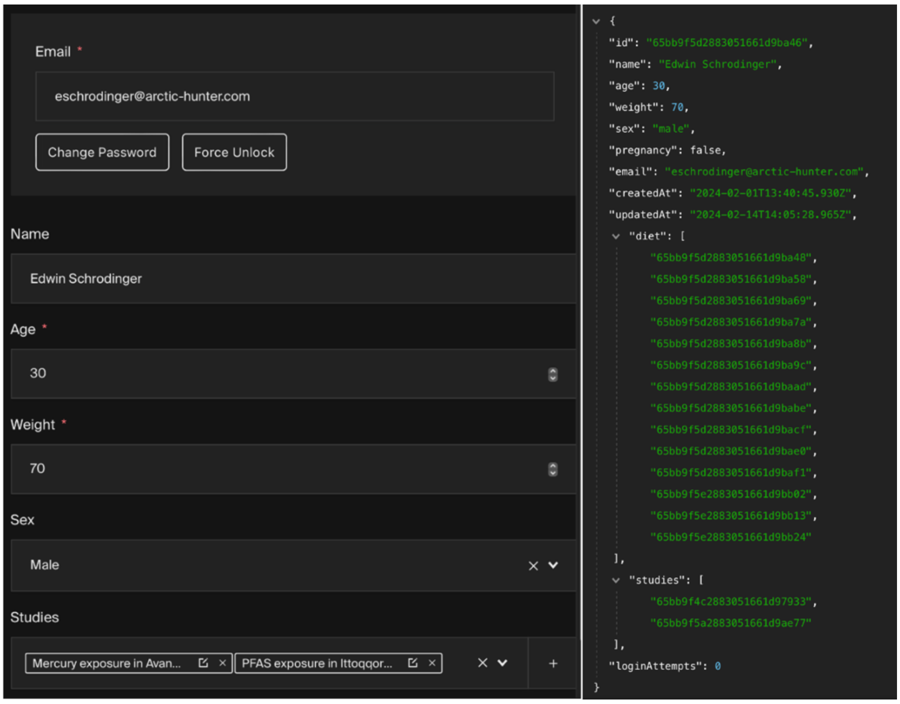
☑ Authenticated

Depth

1

```
{
  "id": "65bb9f4b2883051661d9792c",
  "name": "Mercury",
  "type": [
      "Heavy Metal"
  ],
  "twi": {
      "value": 1.3,
      "unit": "ug",
      "provisional": false
  },
  "createdAt": "2024-02-01T13:40:27.962Z",
  "updatedAt": "2024-02-14T13:58:16.800Z",
  > "description": {
  }
}
```

Figure S12 Contaminant collection document. Left: contaminant name, type, description, and optional media. Top-Right: TWI value and unit. Bottom-Right: API response view.



Email *

eschrodinger@arctic-hunter.com

Name

Edwin Schrodinger

Age *

30

Weight *

70

Sex

Male

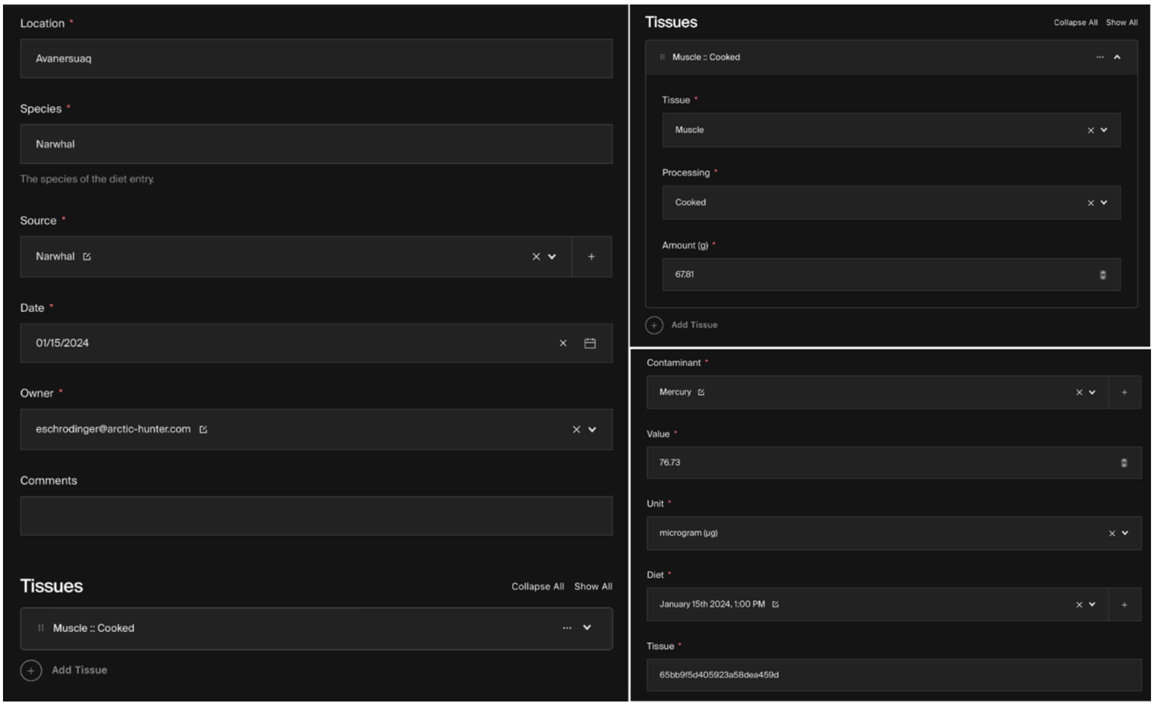
Studies

Mercury exposure in Avan...

PFAS exposure in Ittoqqor...

```
{
  "id": "65bb9f5d2883051661d9ba46",
  "name": "Edwin Schrodinger",
  "age": 30,
  "weight": 70,
  "sex": "male",
  "pregnancy": false,
  "email": "eschrodinger@arctic-hunter.com",
  "createdAt": "2024-02-01T13:40:45.930Z",
  "updatedAt": "2024-02-14T14:05:28.965Z",
  "diet": [
      "65bb9f5d2883051661d9ba48",
      "65bb9f5d2883051661d9ba58",
      "65bb9f5d2883051661d9ba69",
      "65bb9f5d2883051661d9ba7a",
      "65bb9f5d2883051661d9ba8b",
      "65bb9f5d2883051661d9ba9c",
      "65bb9f5d2883051661d9baad",
      "65bb9f5d2883051661d9babe",
      "65bb9f5d2883051661d9bacf",
      "65bb9f5d2883051661d9bae0",
      "65bb9f5d2883051661d9baf1",
      "65bb9f5e2883051661d9bb02",
      "65bb9f5e2883051661d9bb13",
      "65bb9f5e2883051661d9bb24"
  ],
  "studies": [
      "65bb9f4c2883051661d97933",
      "65bb9f5a2883051661d9ae77"
  ],
  "loginAttempts": 0
}
```

Figure S13 User collection document. Left: name, email address, age, sex, and subscribed studies. Right: API response view.



Location *

Avanersuaq

Species *

Narwhal

The species of the diet entry.

Source *

Narwhal

Date *

01/15/2024

Owner *

eschrodinger@arctic-hunter.com

Comments

Tissues

Muscle :: Cooked

Tissues

Muscle :: Cooked

Tissue *

Muscle

Processing *

Cooked

Amount (g) *

67.81

Contaminant *

Mercury

Value *

76.73

Unit *

microgram (µg)

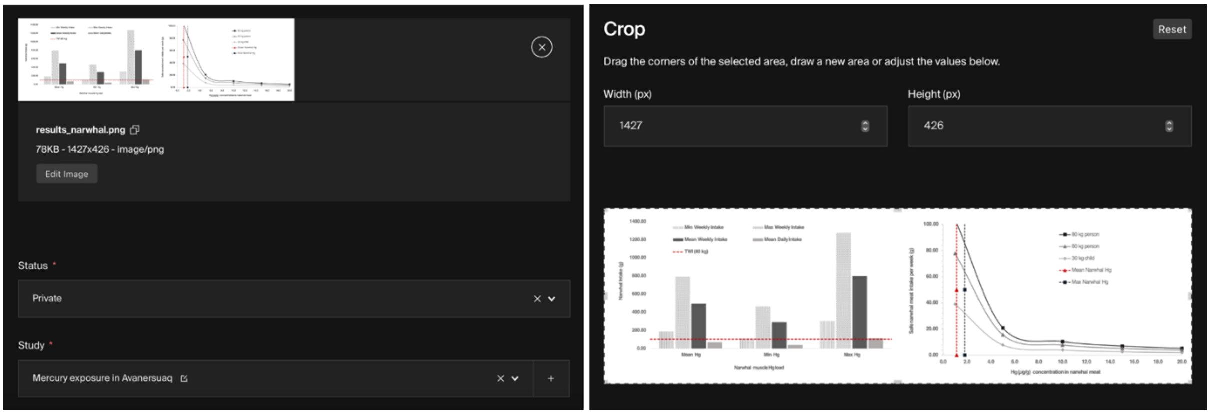
Diet *

January 15th 2024, 1:00 PM

Tissue *

65bb9f5d405923a58dea459d

Figure S14 Diet and Exposure collection documents. Left) dietary intake data fields: location, species, date, owner, optional comments. Top-Right) consumed tissues details: tissue type, processing, and intake amount in grams. Bottom-Right) associated exposure entry: contaminant name, intake amount and unit, source diet document and tissue identifier.



results_narwhal.png

78KB - 1427x426 - image/png

Status *

Private

Study *

Mercury exposure in Avanersuaq

Crop

Drag the corners of the selected area, draw a new area or adjust the values below.

Width (px)

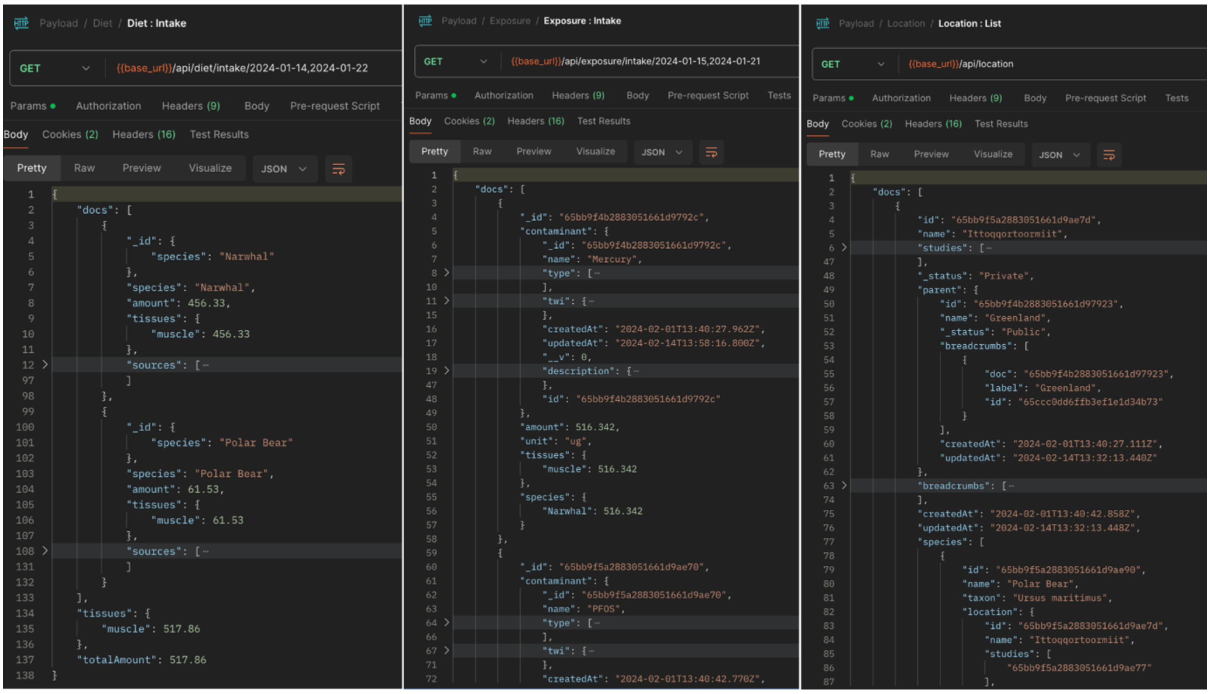
1427

Height (px)

426

Figure S15 Media collection document. Left: Uploaded PNG image, visibility status, and assigned study. Right: photo editing options.

6.4 Appendix D – Application Programming Interface



GET {{base_url}}/api/diet/intake/2024-01-14,2024-01-22

```
{
    "docs": [
        {
            "_id": {
                "species": "Narwhal"
            },
            "species": "Narwhal",
            "amount": 456.33,
            "tissues": {
                "muscle": 456.33
            },
            "sources": [⋯
            ]
        },
        {
            "_id": {
                "species": "Polar Bear"
            },
            "species": "Polar Bear",
            "amount": 61.53,
            "tissues": {
                "muscle": 61.53
            },
            "sources": [⋯
            ]
        }
    ],
    "tissues": {
        "muscle": 517.86
    },
    "totalAmount": 517.86
}
```

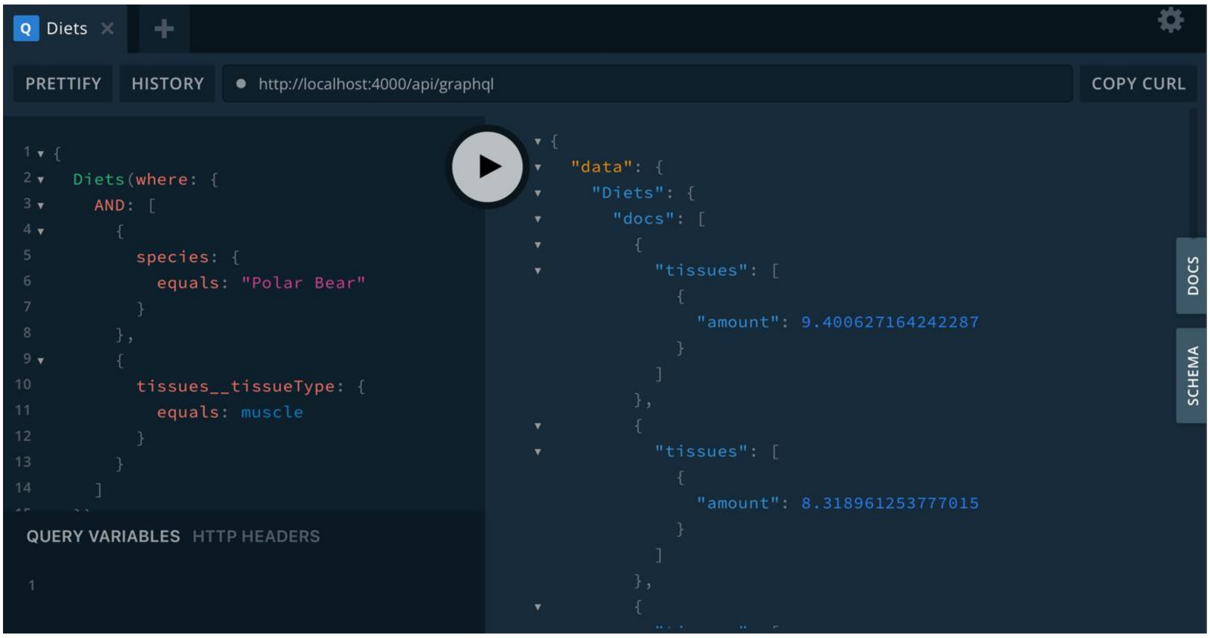
GET {{base_url}}/api/exposure/intake/2024-01-15,2024-01-21

```
{
    "docs": [
        {
            "_id": "65bb9f4b2883051661d9792c",
            "contaminant": {
                "_id": "65bb9f4b2883051661d9792c",
                "name": "Mercury",
                "type": [⋯
                ],
                "twi": {⋯
                },
                "createdAt": "2024-02-01T13:40:27.962Z",
                "updatedAt": "2024-02-14T13:58:16.800Z",
                "__v": 0,
                "description": {⋯
                },
                "id": "65bb9f4b2883051661d9792c"
            },
            "amount": 516.342,
            "unit": "ug",
            "tissues": {
                "muscle": 516.342
            },
            "species": {
                "Narwhal": 516.342
            }
        },
        {
            "_id": "65bb9f5a2883051661d9ae70",
            "contaminant": {
                "_id": "65bb9f5a2883051661d9ae70",
                "name": "PFOS",
                "type": [⋯
                ],
                "twi": {⋯
                },
                "createdAt": "2024-02-01T13:40:42.770Z",
```

GET {{base_url}}/api/location

```
{
    "docs": [
        {
            "id": "65bb9f5a2883051661d9ae7d",
            "name": "Ittoqqortoormiit",
            "studies": [⋯
            ],
            "_status": "Private",
            "parent": {
                "id": "65bb9f4b2883051661d97923",
                "name": "Greenland",
                "_status": "Public",
                "breadcrumbs": [
                    {
                        "doc": "65bb9f4b2883051661d97923",
                        "label": "Greenland",
                        "id": "65ccc0dd6ffb3ef1e1d34b73"
                    }
                ],
                "createdAt": "2024-02-01T13:40:27.111Z",
                "updatedAt": "2024-02-14T13:32:13.440Z"
            },
            "breadcrumbs": [⋯
            ],
            "createdAt": "2024-02-01T13:40:42.858Z",
            "updatedAt": "2024-02-14T13:32:13.448Z",
            "species": [
                {
                    "id": "65bb9f5a2883051661d9ae90",
                    "name": "Polar Bear",
                    "taxon": "Ursus maritimus",
                    "location": {
                        "id": "65bb9f5a2883051661d9ae7d",
                        "name": "Ittoqqortoormiit",
                        "studies": [
                            "65bb9f5a2883051661d9ae77"
                        ],
```

Figure S16 API responses from custom and built-in endpoints using the Postman software. Left: diet intake (custom). Center: exposure intake (custom). Right: locations list (built-in).

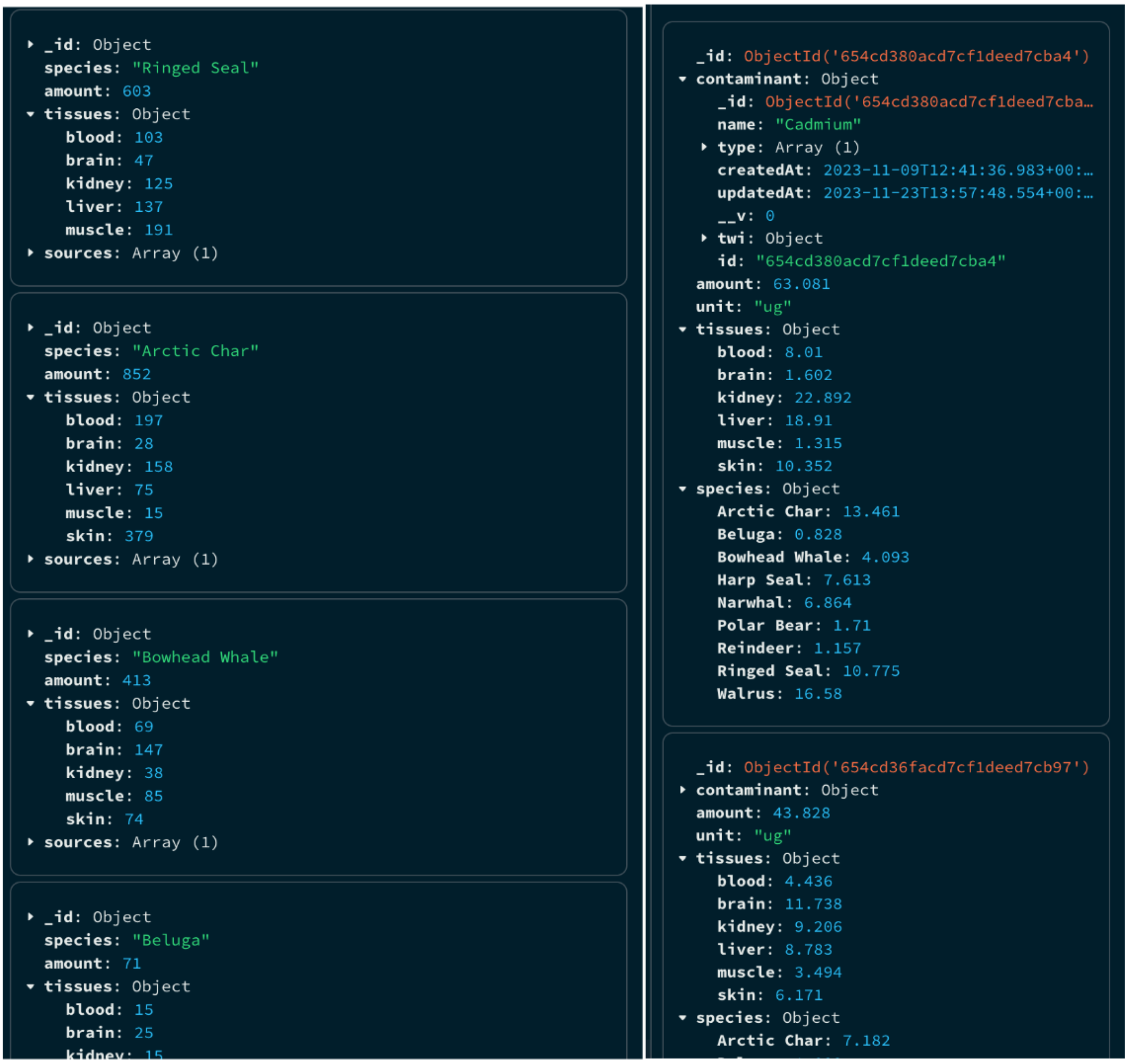


http://localhost:4000/api/graphql

```
{
  Diets(where: {
    AND: [
      {
        species: {
          equals: "Polar Bear"
        }
      },
      {
        tissues__tissueType: {
          equals: muscle
        }
      }
    ]
```

```
{
  "data": {
    "Diets": {
      "docs": [
        {
          "tissues": [
            {
              "amount": 9.400627164242287
            }
          ]
        },
        {
          "tissues": [
            {
              "amount": 8.318961253777015
            }
          ]
        },
        {
```

Figure S17 GraphQL playground. The main area showcases a split view with the query (left) and the response (right). Tabs to display documentation and schema from introspection are available on the right side.



```
▸ _id: Object
  species: "Ringed Seal"
  amount: 603
▾ tissues: Object
    blood: 103
    brain: 47
    kidney: 125
    liver: 137
    muscle: 191
▸ sources: Array (1)

▸ _id: Object
  species: "Arctic Char"
  amount: 852
▾ tissues: Object
    blood: 197
    brain: 28
    kidney: 158
    liver: 75
    muscle: 15
    skin: 379
▸ sources: Array (1)

▸ _id: Object
  species: "Bowhead Whale"
  amount: 413
▾ tissues: Object
    blood: 69
    brain: 147
    kidney: 38
    muscle: 85
    skin: 74
▸ sources: Array (1)

▸ _id: Object
  species: "Beluga"
  amount: 71
▾ tissues: Object
    blood: 15
    brain: 25
    kidney: 15
```

```
  _id: ObjectId('654cd380acd7cf1deed7cba4')
▾ contaminant: Object
    _id: ObjectId('654cd380acd7cf1deed7cba…
    name: "Cadmium"
  ▸ type: Array (1)
    createdAt: 2023-11-09T12:41:36.983+00:…
    updatedAt: 2023-11-23T13:57:48.554+00:…
    __v: 0
  ▸ twi: Object
    id: "654cd380acd7cf1deed7cba4"
  amount: 63.081
  unit: "ug"
▾ tissues: Object
    blood: 8.01
    brain: 1.602
    kidney: 22.892
    liver: 18.91
    muscle: 1.315
    skin: 10.352
▾ species: Object
    Arctic Char: 13.461
    Beluga: 0.828
    Bowhead Whale: 4.093
    Harp Seal: 7.613
    Narwhal: 6.864
    Polar Bear: 1.71
    Reindeer: 1.157
    Ringed Seal: 10.775
    Walrus: 16.58

  _id: ObjectId('654cd36facd7cf1deed7cb97')
▸ contaminant: Object
  amount: 43.828
  unit: "ug"
▾ tissues: Object
    blood: 4.436
    brain: 11.738
    kidney: 9.206
    liver: 8.783
    muscle: 3.494
    skin: 6.171
▾ species: Object
    Arctic Char: 7.182
```

Figure S18 Diet and Exposure custom endpoints responses, as depicted in the Compass app. Left: Diet intake response documents. Right: Exposure intake contaminant documents. A different dataset with additional species is used in this example, using randomized daily intake patterns, to better showcase the summarization of contaminant loads.

6.5 Appendix E – Supporting Figures

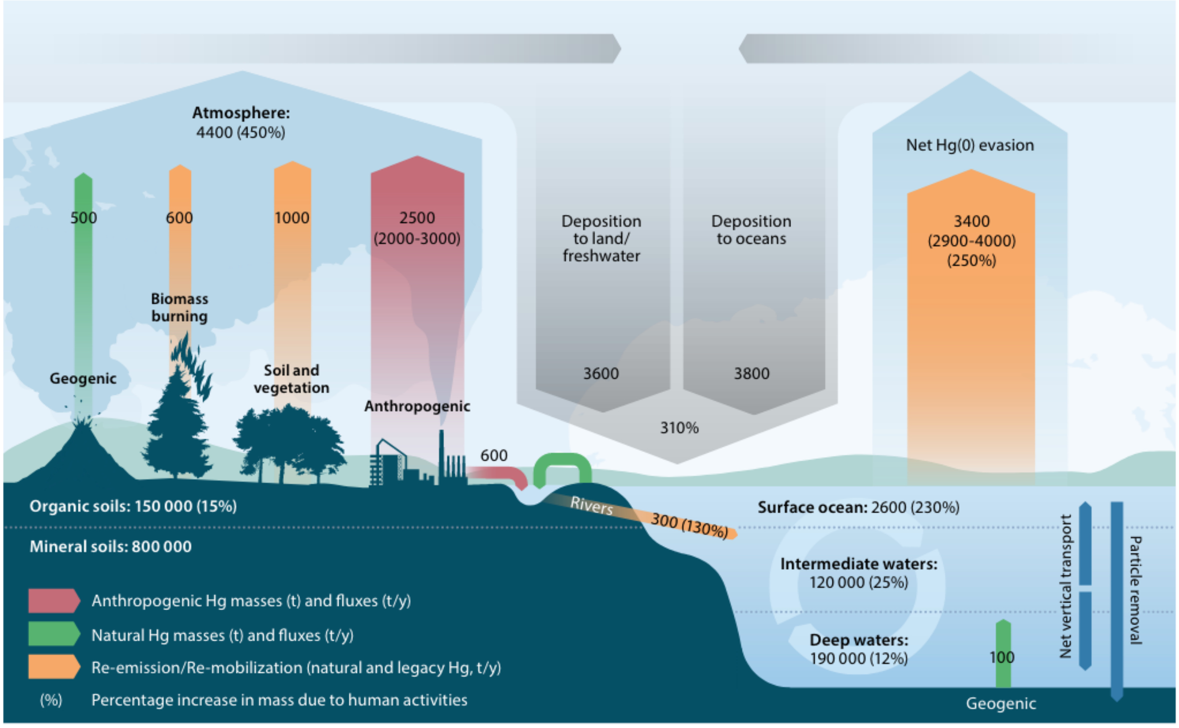


Figure S19 Estimated global mercury emissions and fluxes (ranges are in parentheses). Percentage values indicate the estimated increase since the pre-anthropogenic period (since ~1450AD). Taken as-is from AMAP, 2021b.

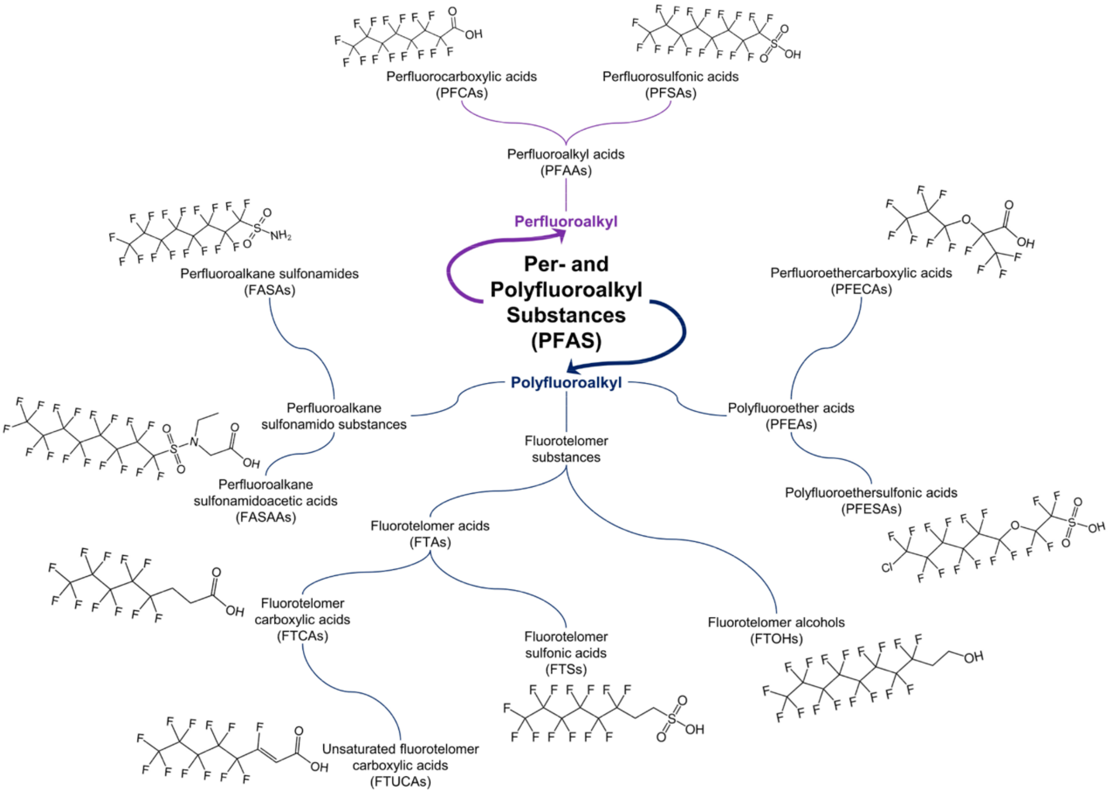


Figure S20 Structures various per- and poly-fluoroalkyl substances (PFAS). At the top, the two most common groups of immunotoxic PFAS: Perfluorocarboxylic acids (PFCAs) and Perfluorosulfonic acids (PFSAs). At the bottom right, the PFCA precursors fluorotelomer alcohols (FTOHs). Figure taken as-is from Brase et al., 2021.

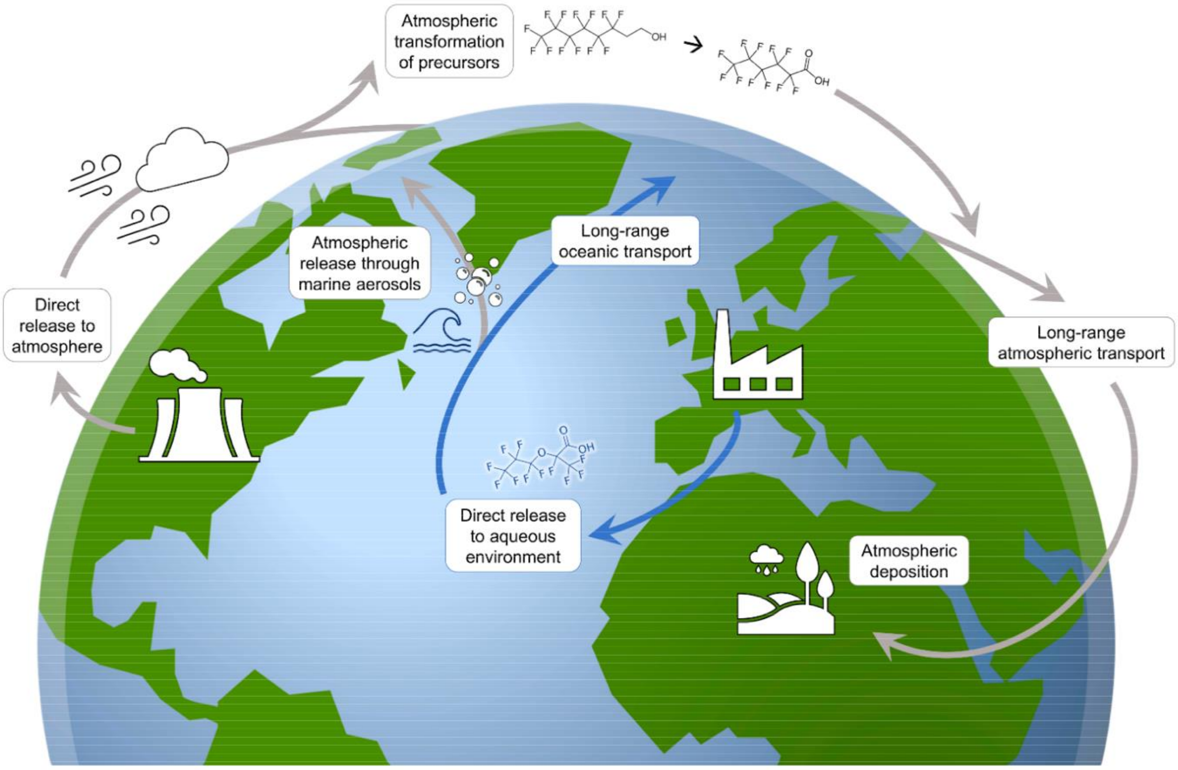


Figure S21 Simplified illustration of PFAS emissions and subsequent atmospheric and oceanic transport into the Arctic. Figure taken as-is from Brase et al., 2021.

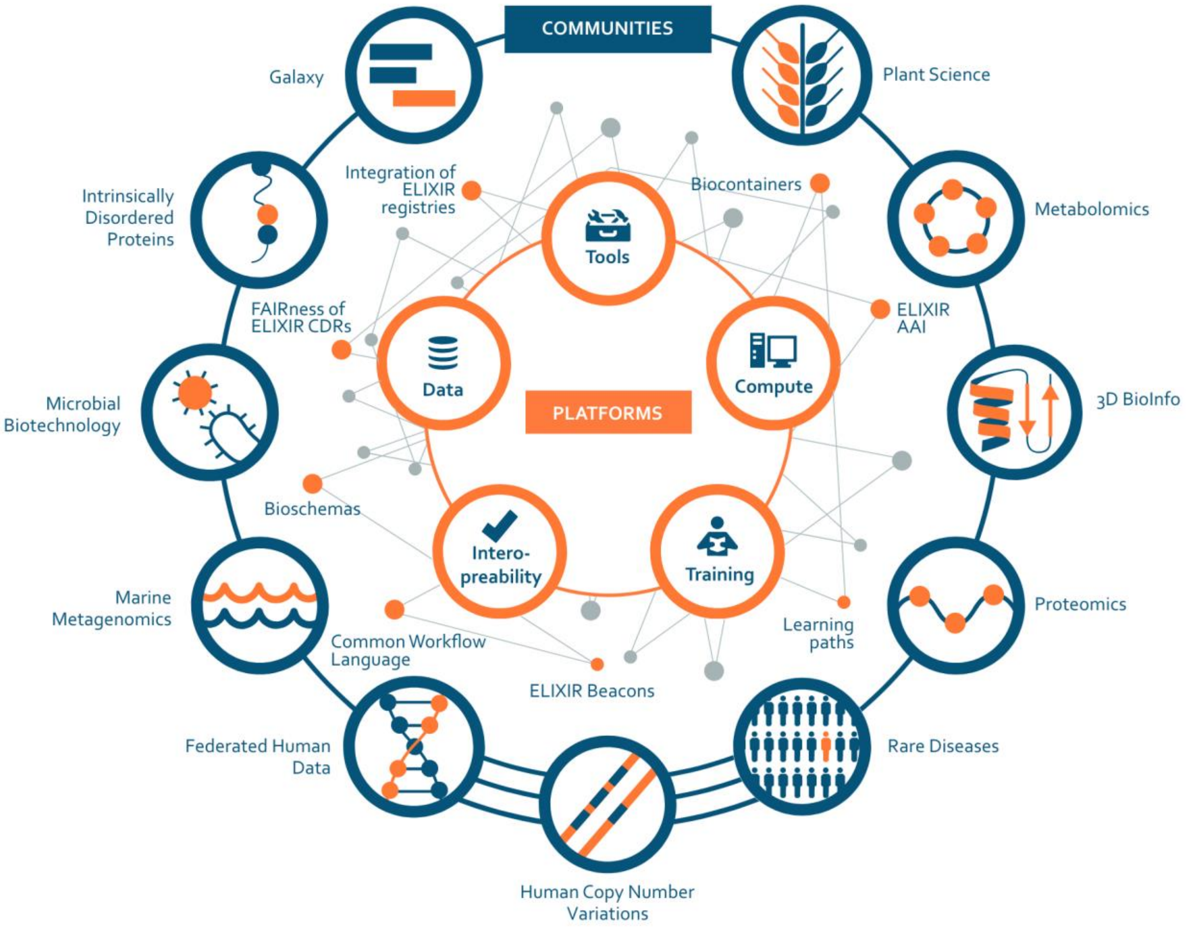


Figure S22 Communities and platforms are linked via studies in the ELIXIR research organization. Figure taken as-is from Harrow et al., 2021.

NTNU

Norwegian University of
Science and Technology